Proceedings of the International Workshop on

SUSTAINABLE DEVELOPMENT & CONCRETE TECHNOLOGY

Beijing, China

May 20–21, 2004

Edited by Kejin Wang

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Center for Transportation Research and Education
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Front cover: Pudong, the new area of Shanghai on the east bank of the Huangpu River, photo courtesy of Wei Qin; the Great Wall, an example of ancient Chinese military engineering; network of highways and bridges, Beijing, photo courtesy of China Highlights Travel Service. Back cover: concrete photo courtesy of the Portland Cement Association. Cover design by Mark Anderson-Wilk.

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Preface

In the past few decades, growing concern over global warming and other significant ecological changes has spurred much debate in all fields of science and engineering. The concrete industry has increasingly been considered one of the largest contributors to these ecological changes. Presently, annual worldwide concrete production is about 12 billion tons, consuming approximately 1.6 billion tons of portland cement, 10 billion tons of sand and rock, and 1 billion tons of water. The production of one ton of portland cement generates approximately one ton of carbon dioxide and requires up to 7000 MJ of electrical power and fuel energy. It is evident that the concrete industry significantly impacts the ecology of our planet.

The International Workshop on Sustainable Development and Concrete Technology is being held to address the role of portland cement concrete materials and construction in sustainable development. The main purpose of the workshop is to promote global interaction and research collaboration for a better understanding of sustainable development as applied to concrete technology. China's economic growth and its impact on the global environment have received a great deal of attention. China is now the world's largest cement producer and consumer. China's cement production in 2003 was over 800 million tons, more than one-third of the world's supply. Sustainable development in China is urgent.

The workshop is sponsored by the National Science Foundation, USA, and co-sponsored by American Concrete Institute International, USA, the Center for Advanced Cement-Based Materials, Northwestern University, USA, and many distinguished organizations in the People's Republic of China. The workshop is organized by Iowa State University, USA, and Tsinghua University, PRC, and hosted by Tsinghua University.

The international workshop includes two major themes: (1) critical issues of sustainable development and emerging technology for "green" concrete and (2) concrete durability and sustainable system. This volume of proceedings contains 31 papers presented at the workshop, about half of which are keynote and invited papers from eminent international experts. In addition to the paper sessions, the workshop includes a panel discussion on the future directions of sustainable development and international collaborations.

A field trip to the Three Gorges Dam is arranged at the end of the workshop, sponsored by China Yangtze Power Corporation Ltd. The project to build the world's largest dam combines a huge amount of construction material consumption with energy generation, natural disaster control, and environment protection issues. It provides a unique case study of sustainable development.

The workshop organizers would like to thank all sponsors, committee members, and hosts who made this workshop possible. Particular appreciation is made to the National Science Foundation (Grant CMS-0307261) and Program Director Dr. Perumalsamy N. Balaguru. Special thanks are also extended to all authors for their contributions and cooperation.

The editor is sincerely indebted to Iowa State University's Department of Civil, Construction and Environmental Engineering and Center for Transportation Research and Education, especially Mr. Mark Anderson-Wilk, for their support in producing this volume of workshop proceedings.

The organizers earnestly hope that this workshop will advance the emerging technologies for production of "green" concrete materials and "green" concrete structures. It is envisioned that the workshop will lead to a significant improvement in integration of infrastructure development with industrial ecology, resource management, information technology, and economy. The workshop will also assist in promoting international collaborations in education, research, and practice for global sustainable development. These proceedings will serve a useful resource for researchers and engineers involved in sustainable development activities.

Surendra P. Shah, Chair
Shuaib Ahmad, Co-chair
Peiyu Yan, Co-chair
Kejin Wang, Co-chair and Editor

Part I

Critical Issues of Sustainable Development and Emerging Technology for "Green" Concrete

HIGH-PERFORMANCE, HIGH-VOLUME FLY ASH CONCRETE FOR SUSTAINABLE DEVELOPMENT

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Abstract

For a variety of reasons, the concrete construction industry is not sustainable. First, it consumes huge quantities of virgin materials. Second, the principal binder in concrete is portland cement, the production of which is a major contributor to green-house gas emissions that are implicated in global warming and climate change. Third, many concrete structures suffer from lack of durability which has an adverse effect on the resource productivity of the industry. Because the high-volume fly ash concrete system addresses all three sustainability issues, its adoption will enable the concrete construction industry to become more sustainable.

In this paper, a brief review is presented of the theory and construction practice with concrete mixtures containing more than 50% fly ash by mass of the cementitious material. Mechanisms are discussed by which the incorporation of high volume of fly ash in concrete reduces the water demand, improves the workability, minimizes cracking due to thermal and drying shrinkage, and enhances durability to reinforcement corrosion, sulfate attack, and alkali-silica expansion. For countries like China and India, this technology can play an important role in meeting the huge demand for infrastructure in a sustainable manner.

1. Introduction

How to meet the housing and infrastructural needs of society in a sustainable manner is, unquestionably, the most important challenge confronting the concrete industry today. Among the sustainability issues, the three major ones that are widely discussed in the published reports may be summarized as follows:

Climate change—In many parts of the world, extreme weather patterns are occurring with greater frequency. Most scientists believe that this phenomenon is associated with the high emission rates of green-house gases, primarily carbon dioxide, the environmental concentrations of which has increased from 280 to 370 parts per million volume mainly during the industrial age (1, 2). The transportation industry and the portland cement industry happen to be the two largest producers of carbon dioxide. The latter is responsible for approximately 7% of the world's carbon dioxide emissions (2).

Resource productivity—The concrete industry is the largest consumer of virgin materials such as sand, gravel, crushed rock, and fresh water. It is consuming portland and modified portland cements at an annual rate of about 1.6 billion metric tons. The cement production consumes vast amounts of limestone and clay besides being energy-intensive.

Obviously, large amounts of energy and materials, in addition to financial resources, are wasted when structures deteriorate or fail prematurely which, in fact, has been the case with many recently built reinforced concrete bridge decks, parking garages, and marine structures throughout the world (3). Traditionally, most concrete structures are designed for a service life of 50 years. With the advent of high-performance concrete mixtures, some structures are now being designed and built for a service life of 100 years. In the long run, sustainable development of the concrete industry will not take place until we are able to make even more dramatic improvements in our resource productivity. In this context, it should be noted that the Factor Ten Club, a group of scientists, economists and business people have made a declaration that, within one generation, nations can achieve a tenfold increase in their resource productivity through a 90% reduction in the use of energy and materials (4).

Industrial ecology—Achieving a dramatic improvement in resource productivity through durability enhancement of products is, of course, a long-term solution for sustainable development. A short-term strategy that must be pursued simultaneously is to practice industrial ecology at a larger scale than is the case today. Simply defined, the practice of industrial ecology by a manufacturing industry involves the reclamation and re-use of its own waste products and, to the extent possible, the waste products of other industries which are unable to recycle them in their own manufacturing process.

Reportedly, over 1 billion tons of construction and demolition waste is generated every year. Cost-effective technologies are available to recycle most of the waste as a partial replacement for the coarse aggregate in fresh concrete mixtures. Similarly, industrial wastewaters and non-potable waters can substitute for municipal water for mixing concrete unless proven harmful by testing. Blended portland cements containing fly ash from coal-fired power plants, and ground-granulated slag from the blast-furnace iron industry provide excellent examples of industrial ecology because they offer a holistic solution for reducing the environmental impact of several industries.

The construction industry already uses concrete mixtures containing cement replacement materials, such as 15% to 20% fly ash or 30% to 40% slag by mass. As discussed in this paper, with conventional materials and technology, it is now possible to produce high-performance concrete mixtures containing 50% to 60% fly ash by mass of the blended cementitious material. Note that fly ash is readily available in most parts of the world. China and India, the two countries that consume large amounts of cement, together produce over 300 million tons of fly ash per year.

2. High-Performance Concrete

What is high-performance concrete? According to a recent paper by Aitcin (5), *what was known as high-strength concrete in the late 1970s is now referred to as high-performance concrete (HPC) because it has been found to be much more than simply stronger*. ACI defines HPC as a specially engineered concrete, one or more specific characteristics of which have been enhanced through the selection of component materials and mix proportions. Note that this definition does not cover a single product but a family of high-tech concrete products whose properties have been tailored to meet specific engineering needs, such as high workability, very-high early strength (e.g. 30-40 MPa compressive strength in 24 hours), high toughness, and high durability to exposure conditions.

A major criticism against the ACI definition of HPC is that durability of concrete is not mandatory; it is one of the options. The misconception that high-strength will automatically lead to high-durability has probably resulted in many cases of cracking and premature deterioration of HPC structures, as reported in the published literature (6, 7). The reason lies in the mix proportions used to achieve very high-strength; for example, commercial high-strength concrete mixtures are often designed to obtain 50-80 MPa compressive strength at 28-day and at times high early-strength values on the order of 25-40 MPa at 1-day, together with 150-200mm slump for ease of constructability if the structure is heavily reinforced. Typically, these mixtures are composed of a high cement content, viz 450-500 kg/m^3 portland or blended portland cement containing a relatively small amount of silica fume and fly ash or slag, a low water/cement on the order of 0.3 (with the help of a superplasticizing admixture), and an air-entraining agent when it is necessary to protect the concrete from cycles of freezing and thawing. Field experience shows (6, 7) that the foregoing high-strength concrete mixtures are prone to suffer early cracking from a variety of causes, such as a large thermal contraction due to the high portland cement content, a large autogenous shrinkage due to the low water-cementitious ratio, and a high drying shrinkage due to the high cement paste-aggregate ratio.

Aitcin (5) prefers to define HPC as a low water/binder concrete with an optimized aggregate-to-binder ratio to control its dimensional stability (i.e. drying shrinkage), and which receives an adequate water-curing (to control autogenous shrinkage). This definition adequately addresses the potential for lack of durability of HPC concrete except with massive structural members that may be subject to thermal cracking. In this regard, an earlier definition proposed by Mehta and Aitcin (8) stated that the term HPC should be applied to concrete mixtures possessing the following three characteristics: high workability, high strength, and high durability.

The above critical examination of the commercial practice and the perceived meaning of the term, *high-performance concrete*, is essential to answer the question whether or not HPC is a sustainable product. Most of the conventional HPC products will not qualify to be classified as "sustainable" because they are not likely to be highly durable and may contain a high content of portland cement and a relatively small amount of pozzalanic and cementitious by-products for cement replacement. However, the high-volume fly ash (HVFA) system, discussed next, represents an emerging technology for producing *sustainable HPC mixtures.*

3. High-Volume Fly Ash Concrete

Fly ash, a principal by-product of the coal-fired power plants, is well accepted as a pozzolanic material that may be used either as a component of blended portland cements or as a mineral admixture in concrete. In commercial practice, the dosage of fly ash is limited to 15%-20% by mass of the total cementitious material. Usually, this amount has a beneficial effect on the workability and cost economy of concrete but it may not be enough to sufficiently improve the durability to sulfate attack, alkali-silica expansion, and thermal cracking. For this purpose, larger amounts of fly ash, on the order of 25%-35% are being used.

Although 25%-35% fly ash by mass of the cementitious material is considerably higher than 15%-20%, this is not high enough to classify the mixtures as HVFA concrete according to the definition proposed by Malhotra and Mehta (9). From theoretical considerations and practical experience the authors have determined that, with 50% or more cement replacement by fly ash, it is possible to produce sustainable, high-performance concrete mixtures that show high workability, high ultimate strength, and high durability. The following text containing a brief description of the composition and properties of HVFA concrete is adapted from Malhotra and Mehta's book on HVFA concrete (9).

3.1 What is high-performance concrete?

The characteristics defining a HVFA concrete mixture are as follows:

- Minimum of 50% of fly ash by mass of the cementitious materials must be maintained.
- Low water content, generally less than 130 kg/m^3 is mandatory.
- Cement content, generally no more than 200kg/m^3 is desirable.

- For concrete mixtures with specified 28-day compressive strength of 30 MPa or higher, slumps >150 mm, and water-to-cementitious materials ratio of the order of 0.30, the use of high-range water-reducing admixtures (superplasticizers) is mandatory.
- For concrete exposed to freezing and thawing environments, the use of an air-entraining admixture resulting in adequate air-void spacing factor is mandatory.
- For concrete mixtures with slumps less than 150 mm and 28-day compressive strength of less than 30 MPa, HVFA concrete mixtures with a water-to-cementitious materials ratio of the order of 0.40 may be used without superplasticizers.

3.2 Mixture proportions

Adapted from a recent paper by Malhotra (10), typical range of component materials for different levels of strength in high-performance, HVFA concrete is shown in Table 1. Note that the control of water content is most essential because the amount of water is varied within a narrow range between 100-130 kg/m^3 by using a combination of one or more tools such as a superplasticizing admixture, a high-quality fly ash, and well-graded aggregate. Depending on the desired strength levels, the content and the fly ash/cement ratio of the binder can be varied. As the water content between the different strength levels does not vary much, it is necessary to increase the cementitious materials substantially to achieve higher strength. When very high strength is needed at an early age, it can be obtained by adopting one or more of the following methods: a higher ratio between portland cement and fly ash, substitution of a high-early strength portland cement for ordinary portland cement, and replacement of a portion of the fly ash with a more reactive pozzolan such as silica fume or rice-husk ash.

Table 1: Typical mix proportions for different strength levels

Strength level (MPa)	Low	Moderate	High
28 days	20	30	40
90 days to 1 year	40	50	60
Mix proportions (kg/m^3)			
Water	120-130	115-125	100-120
Cement, ASTM Type I/II	100-130	150-160	180-200
Fly ash, ASTM Class F	125-150	180-200	200-225
Water/cement	0.40-0.45	0.33-0.35*	0.30-0.32*
Coarse aggregate, 19 mm max.	1100-1200	1100-1200	1100-1200
Fine aggregate	800-900	800-900	800-900

* Moderate and high-strength concretes need a superplactisizer to obtain a low water/cement ratio. Also, some adjustments in water/cement will be needed when an air-entraining agent is used for protection against freezing and thawing cycles.

3.3 Mechanisms by which fly ash improves the properties of concrete

A good understanding of the mechanisms by which fly ash improves the rheological properties of fresh concrete and ultimate strength as well as durability of hardened concrete is helpful to insure that potential benefits expected from HVFA concrete mixtures are fully realized. These mechanisms are discussed next.

Fly ash as a water reducer

Too much mixing-water is probably the most important cause for many problems that are encountered with concrete mixtures. There are two reasons why typical concrete mixtures contain too much mixing-water. Firstly, the water demand and workability are influenced greatly by particle size distribution, particle packing effect, and voids present in the solid system. Typical concrete mixtures do not have an optimum particle size distribution, and this accounts for the undesirably high water requirement to achieve certain workability. Secondly, to plasticize a cement paste for achieving a satisfactory consistency, much larger amounts of water than necessary for the hydration of cement have to be used because portland cement particles, due to the presence of electric charge on the surface, tend to form flocs that trap volumes of the mixing water.

It is generally observed that a partial substitution of portland cement by fly ash in a mortar or concrete mixture reduces that water requirement for obtaining a given consistency. Experimental studies by Owen (10) and Jiang and Malhotra (12) have shown that with HVFA concrete mixtures, depending on the quality of fly ash and the amount of cement replaced, up to 20% reduction in water requirements can be achieved. This means that good fly ash can act as a superplasticizing admixture when used in high-volume. The phenomenon is attributable to three mechanisms. First, fine particles of fly ash get absorbed on the oppositely charged surfaces of cement particles and prevent them from flocculation. The cement particles are thus effectively dispersed and will trap large amounts of water, that means that the system will have a reduced water requirement to achieve a given consistency. Secondly, the spherical shape and the smooth surface of fly ash particles help to reduce the interparticle friction and thus facilitates mobility. Thirdly, the “particle packing effect” is also responsible for the reduced water demand in plasticizing the system. It may be noted that both portland cement and fly ash contribute particles that are mostly in the 1 to 45 μm size range, and therefore serve as excellent fillers for the void space within the aggregate mixture. In fact, due to its lower density and higher volume per unit mass, fly ash is a more efficient void-filler than portland cement.

Drying shrinkage

Perhaps the greatest disadvantage associated with the use of neat portland-cement concrete is cracking due to drying shrinkage. The drying shrinkage of concrete is directly influenced by the amount and the quality of the cement paste present. It increases with an increase in the cement paste-to-aggregate ratio in the concrete mixture, and also increases with the water content of the paste.

Clearly, the water-reducing property of fly ash can be advantageously used for achieving a considerable reduction in the drying shrinkage of concrete mixtures.

The significance of this concept is illustrated by data in Table 2 which shows mixture proportions of a conventional 25 MPa concrete compared to a superplasticized HVFA concrete with similar strength but higher slump. Due to a significant reduction in the water requirement, the total volume of the cement paste in the HVFA concrete is only 25% as compared to 29.6% for the conventional portland-cement concrete which represents a 30% reduction in the cement paste-to-aggregate volume ratio.

Table 2: Comparison of cement paste volumes

	Conventional concrete		HVFA concrete	
	kg/m^3	m^3	kg/m^3	m^3
Cement	307	0.098	154	0.149
Fly ash	–	–	154	0.065
Water	178	0.178	120	0.120
Entrapped air (2%)	-	0.020	-	0.020
Coarse aggregate	1040	0.385	1210	0.448
Fine aggregate	825	0.305	775	0.287
Total	**2350**	**0.986**	**2413**	**0.989**
w/cm	0.58	–	0.39	–
Paste: volume	–	0.296	–	0.254
Percent	–	30.0%	–	25.7%

Thermal cracking

Thermal cracking is of serious concern in massive concrete structures. It is generally assumed that this is not a problem with reinforced-concrete structures of moderate thickness, e.g. 50-cm thick or less. However, due to the high reactivity of modern cements cases of thermal cracking are reported even from moderate-size structures made with concrete mixtures of high-cement content that tend to develop excessive heat during curing. The physical-chemical characteristics of ordinary portland cements today are such that very high heat-of-hydration is produced at an early age compared with that of normal portland cements available 40 years ago. Also, high-early strength requirements in modern construction practice are usually satisfied by an increase in the cement content of the concrete mixture. Further, there is considerable construction activity now in the hot-arid areas of the world where concrete temperatures in excess of 60°C are not uncommon within a few days of concrete placement.

For unreinforced mass-concrete construction, several methods are employed to prevent thermal cracking, and some of these techniques can be successfully used for mitigation of thermal cracks in massive reinforced-concrete structures. For instance, a 40-MPa concrete mixture containing 350 kg/m^3 portland cement can raise the temperature of concrete by approximately 55-60°C within a week if there is no heat loss to the environment. However, with a HVFA concrete mixture containing 50% cement replacement with a Class F fly ash, the adiabatic temperature rise is expected to be 30-35°C. As a rule of thumb, the maximum temperature difference between the interior and exterior concrete should not exceed 25°C to avoid thermal cracking. This is because higher temperature differentials are accomplished by rapid cooling rates that usually result in cracking. Evidently, in the case of conventional concrete it is easier to solve the problem either by keeping the concrete insulated and warm for a longer time in the forms until the temperature differential drops below 25°C or by reducing the proportion of portland cement in the binder by a considerable amount. The latter option can be exercised if the structural designer is willing to accept a slightly slower rate of strength development during the first 28 days, and the concrete strength specification is based on 90-day instead of 28-day strength.

Water-tightness and durability

In general, the resistance of a reinforced-concrete structure to corrosion, alkali-aggregate expansion, sulfate and other forms of chemical attack depends on the water-tightness of the concrete. The water-tightness is greatly influenced by the amount of mixing-water, type and amount of supplementary cementing materials, curing, and cracking resistance of concrete. High-volume fly ash concrete mixtures, when properly cured, are able to provide excellent water-tightness and durability. The mechanisms responsible for this phenomenon are discussed briefly below.

When a concrete mixture is consolidated after placement, along with entrapped air, a part of the mixing-water is also released. As water has low density, it tends to travel to the surface of concrete. However, not all of this “bleed water” is able to find its way to the surface. Due to the wall effect of coarse aggregate particles, some of it accumulates in the vicinity of aggregate surfaces, causing a heterogeneous distribution of water in the system. Obviously, the interfacial transition zone between the aggregate and cement paste is the area with high water/cement and therefore with more available space that permits the formation of a highly porous hydration product containing large crystals of calcium hydroxide and ettringite. Microcracks due to stress are readily formed through this product because it is much weaker than the bulk cement paste with a lower water/cement.

It has been suggested that microcracks in the interfacial transition zone play an important part in determining not only the mechanical properties but also the permeability and durability of concrete exposed to severe environmental conditions. This is because the rate of fluid transport in concrete is much larger by percolation through an interconnected network of microcracks than by diffusion or capillary suction. The heterogeneities in the microstructure of the hydrated portland-cement paste, especially the existence of large pores and large crystalline products in the transition zone, are greatly reduced by the introduction of fine particles of fly ash. With the progress of the pozzolanic reaction, a gradual decrease occurs in both the size of the capillary pores and the crystalline hydration products in the transition zone, thereby reducing its thickness and eliminating the weak link in the concrete microstructure. In conclusion, a combination of particle packing effect, low water content, and pozzolanic reaction accounts for the eventual disappearance of the interfacial transition zone in HVFA concrete, and thus enables the development of a highly crack-resistant and durable product.

3.4 Concrete construction practice

Due to the high volume of fines and a low water content, fresh concrete mixtures of the HVFA system are generally very cohesive and show a little or no bleeding and segregation. They show excellent pumpability and workability at slumps as low as 75 mm, however higher slump values may be specified with heavily reinforced structures. The material moves well to fill space without much effort and behaves almost like a self-consolidating concrete. Consequently, the surface finish is usually smooth, pleasing, and without honeycombs and bugholes.

Due to the lower portland cement content, HVFA concrete mixtures may take one to two hours longer to set. Accelerating admixtures should not be used unless their compatibility with the actual concrete mixture has been adequately tested. In such cases, the use of a rapid-hardening portland cement offers a better solution.

Usually HVFA concrete mixtures do not suffer excessive slump loss in a short period. Jobsite retempering of ready-mixed HVFA concrete is permissible to restore severe slump loss with a small amount of superplacticizer or water, provided the water/cement does not exceed the specified limit.

Low water/cement, non-bleeding concrete mixtures are vulnerable to plastic shrinkage cracking as well as autogenous shrinkage cracking. With slabs-on-grade, concrete surfaces must be protected from any water loss by operating a water-fogger around the structure during the placement, or by covering the surface with a heavy plastic sheet immediately after the placement and screeding operations are over. A minimum of 7 days of moist-curing is mandatory to achieve the optimum strength and durability characteristics that are possible from the use of HVFA concrete. With slabs, foundations, piers, columns and beams, leaving the form work in place for at least a week is acceptable in lieu of moist-curing.

3.5 Field experience

Case histories of the application of HVFA concrete for a variety of structures in Canada and the United States are discussed in several reports. One of the first applications consisted of an unreinforced concrete pavement in Wisconsin in the 1970s (13). In Canada, beginning with a massive concrete foundation built in 1987 for testing of components for communication satellites, reinforced columns, beams, and floor slabs of an office complex were installed in 1988, and drilled caisson piles for a wharf in 1990. Details of their applications and others in Canada are described by Langley and Leaman (14). Mehta and Langley (15) have discussed the construction experience with a large (36 by 17 by 1.2 m), monolith, HVFA concrete foundation that has remained crack free until today (for almost three years after its installation). Similar experience with large foundation slabs, cast-in-place drilled piers, and caissons is reported from recently built structures in Houston and Chicago (15). Mehta (16) and Manmohan and Mehta (17) have also documented the construction experience with another HVFA concrete project involving a reinforced belt foundation, shear walls, and collector beams for the seismic upgrade of a building at the University of California campus at Berkeley.

3.6 Properties of concrete

Based on field experience and laboratory tests, the properties of HVFA concrete, when compared to conventional portland cement concrete, can be summarized as follows:

- Easier flowability, pumpability, and compactability.
- Better surface finish and quicker finishing time when power finish is not required.
- Slower setting time, which will have a corresponding effect on the joint-cutting and lower power-finishing times for slabs.
- Early-strength up to 7 days, which can be accelerated with suitable changes in the mix design when earlier removal of formwork or early structural loading is desired.
- Much later strength gain between 28 days and 90 days or more. (With HVFA concrete mixtures, the strength enhancement between 7 and 90-day often exceeds 100%, therefore it is unnecessary to overdesign them with respect to a given specified strength.)
- Superior dimensional stability and resistance to cracking from thermal shrinkage, autogenous shrinkage, and drying shrinkage. In unprotected concrete, a higher tendency for plastic shrinkage cracking.
- After three to six months of curing, much higher electrical resistivity, and resistance to chloride ion penetration, according to ASTM Method C1202.

- Very high durability to the reinforcement corrosion, alkali-silica expansion, and sulfate attack.
- Better cost economy due to lower material cost and highly favorable life-cycle cost.
- Superior environmental friendliness due to ecological disposal of large quantities of fly ash, reduced carbon-dioxide emissions, and enhancement of resource productivity of the concrete construction industry.

4. Concluding Remarks

Throughout the world, the waste disposal costs have escalated greatly. At the same time, the concrete construction industry has realized that coal fly ash is relatively inexpensive and widely available by-product that can be used for partial cement replacement to achieve excellent workability in fresh concrete mixtures. Consequently, in the modern construction practice 15%-20% of fly ash by mass of the cementitious material is now commonly used in North America. Higher amounts of fly ash on the order of 25%-30% are recommended when there is a concern for thermal cracking, alkali-silica expansion, or sulfate attack. Such high proportions of fly ash are not readily accepted by the construction industry due to a slower rate of strength development at early age.

The high-volume fly ash concrete system overcomes the problems of low early strength to a great extent through a drastic reduction in the water-cementitious materials ratio by using a combination of methods, such as taking advantage of the superplactisizing effect of fly ash when used in a large volume, the use of a chemical superplactisizer, and a judicious aggregate grading. Consequently, properly cured high-volume concrete products are very homogenous in microstructure, virtually crack-free, and highly durable. Because there is a direct link between durability and resource productivity, the increasing use of high-volume concrete will help to enhance the sustainability of the concrete industry.

In conclusion, the high-volume concrete offers a holistic solution to the problem of meeting the increasing demands for concrete in the future in a sustainable manner and at a reduced or no additional cost, and at the same time reducing the environmental impact of two industries that are vital to economic development namely the cement industry and the coal-fired power industry. The technology of high-volume fly ash concrete is especially significant for countries like China and India, where, given the limited amount of financial and natural resources, the huge demand for concrete needed for infrastructure and housing can be easily met in a cost-effective and ecological manner.

References

1. Dunn, S. "Decarbonizing the Energy Economy," *State of the World 2001: A Worldwatch Institute Report on Progress Toward a Sustainable Society*. W.W. Norton and Company, 2001, pp. 83-102.
2. Mehta, P.K. "Concrete Technology for Sustainable Development." *Concrete International* 21(11), 1999, pp. 47-52.
3. Mehta, P.K. "Durability: Critical Issues for the Future." *Concrete International* 19(7), 1997, pp. 69-76.
4. Hawken, P., E. Lovins, and H. Lovins. *Natural Capitalism: Creating the Next Industrial Revolution.* Little Brown and Co., 1999, 369 pp.
5. Aitcin, P.C. "The Art and Science of Durable High-Performance Concrete." *Proceedings of the Nelu Spiratos Symposium*. Committee for the Organization of CANMET/ACI Conferences, 2003, pp. 69-88.
6. Mehta, P.K., and R.W. Burrows. "Building Durable Structures in the 21st Century." *Concrete International* 23(3), 2001, pp. 57-63.
7. Krauss, P.D., and E.A. Rogalla. "Transverse Cracking in Mewly Constructed Bridge Decks." *National Cooperative Highway Research Project Report 380*. Transportation Research Board, Washington, DC, 1996, 126 pp.
8. Mehta, P.K., and P.C. Aitcin. "Principles Underlying the Production of High-Performance Concrete." *Cement, Concrete and Aggregates Journal* 12(2), 1990, pp. 70-78.
9. Malhotra, V.M., and P.K. Mehta. *High-Performance, High-Volume Fly Ash Concrete.* Supplementary Cementing Materials for Sustainable Development, Inc., Ottawa, Canada, 2002, 101 pp.
10. Malhotra, V.M. "High-Performance, High-Volume Fly Ash Concrete." *Concrete International* 24(7), 2002, pp. 30-34.
11. Owen, P.L. "Fly Ash and Its Usage in Concrete." *Journal of Concrete Society* 13(7), 1979, pp. 21-26.
12. Jiang, L.H., and V.M. Malhotra. "Reduction in Water Demand of Non Air-Entrained Concrete Incorporating Large Volume of Fly Ash." *Cement and Concrete Research* 30, 2000, pp. 1785-1789.
13. Naik, T.R., B.W. Ramme, R.N. Kraus, and R. Siddique. "Long Term Performance of High-Volume Fly Ash Concrete Pavements." *ACI Materials Journal* 100(2), 2003, pp. 150-155.
14. Langley, W.S., and G.H. Leaman. "Practical Uses for High-Volume Fly Ash Concrete." *AC, SP-178*. American Concrete Institute, 1998, pp. 545-574.
15. Mehta, P.K., and W.S. Langley. "Monolith Foundation: Built to Last a 1000 Years." *Concrete International* 22(7), 2000, pp. 27-30.
16. Mehta, P.K. "Use of Superplactisizers in High-Volume Fly Ash Concrete: U.S. Case Histories." *Proceedings of the Nelu Spiratos Symposium*. Committee for the Organization of CANMET/ACI Conferences, 2003, pp. 89-105.
17. Manmohan, D., and P.K. Mehta. "Heavily Reinforced Shear Walls and Mass Foundations Built With Green Concrete." *Concrete International* 24(8), 2003, pp. 64-70.

DEVELOPMENT OF "GREEN" CEMENT FOR SUSTAINABLE CONCRETE USING CEMENT KILN DUST AND FLY ASH

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Abstract

A research project was conducted to develop "green" cement for sustainable concrete using cement kiln dust (CKD) and Class F fly ash (FA). In the project, effects of mechanical, chemical and thermal activations on strength and other properties of CKD-FA binders were investigated. Different CKD-fly ash combinations, grinding equipment and methods, chemical additions, and elevated curing temperatures were considered. The set time, heat of hydration, and strength of CKD-fly ash pastes were evaluated. The hydration products and microstructure of the binder pastes were studied. The results indicate that when blend proportion and activation are properly applied, the binder made with CKD and fly ash will have satisfactory strength and performance, which provides potential applications for the new cementitious product.

1. Introduction

Portland cement concrete is the most widely used construction material in the world. Each year, the concrete industry produces approximate 12 billion tons of concrete and uses about 1.6 billion tons of portland cement worldwide. In addition to consuming considerable amounts of nature materials (limestone and sand) and energy, producing each ton of portland cement releases one ton of carbon dioxide (CO_2) into the environment. Concerns for the sustainable development in the cement and concrete industries are increasingly addressed [1, 2.].

One of the immerging concrete technologies for sustainable development is to use "green" materials for construction. The "green" materials are considered as materials that use less natural resource and energy and generate less CO_2. They are durable and recyclable and require less maintenance [3]. The purpose of the present research was to develop non-clinker "green" cement using two industry wastes: cement kiln dust (CKD) and fly ash (FA).

CKD contains partially calcined materials with some hydraulic and cementitious properties. It also has high alkali, chloride, and sulfate content, which may cause problems in cement performance. FA is mainly composed of vitrified (amorphous) alumina-silicate melt in addition to a small amount of crystalline minerals, such as quartz, mullite, mica etc. Due to the high degree of polymerization at which tetrahedral silicate is bridged with oxygen, most fly ashes, especially Class F FA, react with water very slowly at a room temperature. Some research has indicated that, if the two materials are appropriately blended, the alkalis from CKD may activate hydration of FA, and the blends may create a cementitious material in which the waste material deficiencies will be converted into benefits [4,5].

In the present research, different activation methods were employed to activate hydration of CKD-FA binders. The effects of raw material characteristics, blend proportions, and activation methods on the binder performance were investigated. Some of the results are presented below.

2. Experimental Work

2.1. Materials and proportions

Table 1 provides the chemical compositions of CKDs and fly ashes used, where Type I ordinary portland cement (OPC) is listed as a reference. CKD 1 and FA 1 were used for chemical and thermal activation studies with a CKD 1:FA1 ratio of 50:50. CKD 2 and FA 2 were used for mechanical activation (grinding) study with a CKD2:FA2 ratio of 35:65. The median particle size (50% passing) of OPC, CKD 1, FA 1, CKD 2 and FA 2 are 25, 53, 10, 8, and 30 microns, respectively.

Table 1: Chemical composition of cementitious materials (% by weight)

	OPC	CKD1	FA1	CKD2	FA2
SiO_2	20.35	11.5	46.80	17.67	51.65
Al_2O_3	5.24	4.38	23.89	5.06	23.52
Fe_2O_3	3.58	2.04	15.77	2.75	9.39
CaO	64.29	56.0	4.74	56.99	4.73
MgO	1.13	1.34	0.91	0.91	1.07
SO_3	2.56	16.7	1.18	6.55	1.42
K_2O	0.60	5.86	1.56	3.43	2.32
Na_2O	0.11	1.02	0.79	0.30	1.73
$(Na_2O)_{eq}$	0.50	4.80	1.80	2.56	3.26
Cl^-	–	0.73	–	0.38	–
LOI	1.10	6.00	2.36	8.00	3.34

Note: $(Na_2O)_{eq} = Na_2O + 0.658\ K_2O$.

2.2. Activation methods

Three activation methods are used for accelerating CKD-FA binder hydration: chemical, thermal, and mechanical activations. In addition, 2% and 5% (by weight of binder) of NaOH was added into the CKD-FA binder systems for chemical activation. Curing temperatures of 38°C and 50°C were considered for thermal activation and the results were compared with that from curing temperature of 24°C. Different grinding regimes were selected for mechanical activation, and they were (1) simple blending (B), (2) ball mill grinding (G), (3) vibratory mill grinding, and (4) combined grinding using ball and vibratory mill grinding (C). Grinding aid (A) and high-speed mixing (H) were also applied.

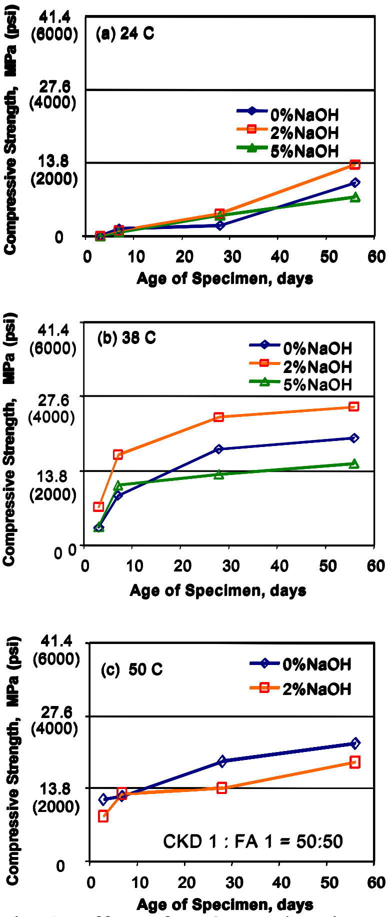

Fig. 1: Effect of NaOH and curing temperature on binder strength

2.3. Test methods

The binder hydration process was characterized set time, strength, heat of hydration tests, x-ray diffraction (XRD), and thermogravimetric analysis (TGA) of pastes. Detailed information on the test methods can be found in references [6, 7].

3. Results and Discussions

3.1. Effects of NaOH addition and elevated curing temperature on strength

Fig. 1 demonstrates effect of NaOH addition and elevated curing temperature on binder strength development. As observed in Figs. 1a and b, when the curing temperature is 24°C and 38°C, addition of 2% NaOH increases binder strength. The binder made with 50% CKD-50% FA-2% NaOH and cured at 38°C has the highest strength of all samples, approximate 27 MPa (4000 psi) at age of 56 days. Addition of 5% NaOH tends to increase binder strength at early age (before 7 days); but decreases binder strength at later age. As previous research indicated, excessive NaOH addition may result in undesirable morphology and non-uniformity of hydration products in the pastes, thus reducing binder strength [8]. The present research (to be discussed later) also revealed that addition of NaOH generally decreased ettringite formation in a CKD-FA and system.

At the curing temperature of 50°C (Fig. 1c), addition of even 2% NaOH caused reductions in the binder strength at both early and later ages. Combination of NaOH addition and elevated curing temperature (at 50°C) appeared not to be preferred for the CKD-FA binder strength development. It was observed that the effectiveness of activation, in terms of strength improvement, resulting from elevated curing temperature was much higher than that from NaOH addition. When a proper CKD-to-FA ratio and activation method were employed (such as a binder made with 50% CKD-50% FA-2% NaOH and cured at 38°C), compressive strength of the CKD-FA binder was comparable with that of OPC.

3.2. Effects of NaOH addition and elevated curing temperature on hydration
Fig. 2 presents XRD patterns of CKD-FA pastes with 0 or 2% NaOH addition cured at normal (24°C) and elevated (38°C) temperature. Note that the major crystalline hydration product of the CKD-FA binders was ettringite. Alkali (sodium/potassium) sulfate crystals are often found in the pastes having NaOH addition. Other compounds, such as $CaCO_3$ and SiO_2, were actually present in the binder raw materials.

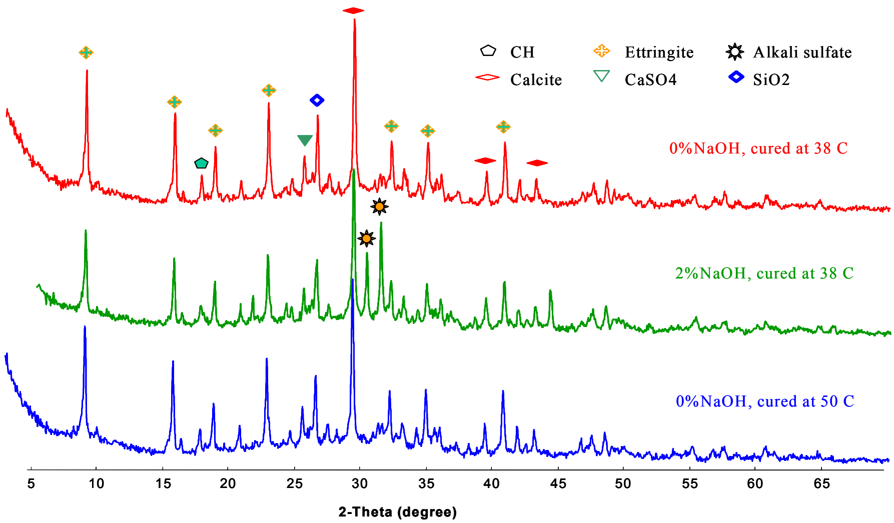

Fig. 2: Effects of NaOH addition and curing temperature on XRD pattern of pastes (CKD 1 : FA 1 = 50 : 50)

In a CKD-FA system, sulfate content was high due to composition of CKD, and aluminate content might be low due to slow hydration of the Class F fly ash. Therefore, the ettringite formed in a CKD-FA system was quite stable at the age of 28 days, or even at 120 days. As a result, the ettringite in a CKD-FA system contributed to both early and later strength of the binders [9].

Closely examining the ettringite peaks in the XRD patterns, the investigators found that when curing temperature increased from 38°C to 50°C, the intensity of ettringite in a CKD-FA paste slightly increased at 7 days but decreased at 28 days and the XRD peak also became flatter. It is believed that a high curing temperature may promote early hydration but prevent hydration products from diffusing away from the hydrated grain, thus impairing crystal growth at late age. When NaOH was added in a CKD-FA binder, the intensity of ettringite of the paste decreased at both 7 and 28 days. NaOH addition may accelerate chemical dissolution but depress crystal (ettringite and calcium hydroxide) formation during the binder hydration [6].

TGA tests further evidenced that ettringite was the major hydration product of the CKD-FA binders. Table 2 presents the effects of NaOH addition and elevated curing temperature on the weight loss of pastes under the TGA tests at 45-100°C. This weight loss is mainly associated with the decomposition of ettringite (together with other sulfate phases) in the paste samples. The test data indicated that if no NaOH was added in a CKD-FA paste, curing temperature of 38°C provided the sample with the largest amount of ettringite formation. In addition, the curing temperature had little effects on the height and location of the DTG peaks of the pastes.

Table 2: Amount of ettringite (or sulfate compounds) in CKD-FA pastes

Mix	NaOH (%)	Curing temp. (°C)	Weight loss of sample (%, TGA test at 45-100°C)	DTG peak temp. (°C)
1	0	24	9.116	82.5
2	0	38	9.833	82.0
3	0	50	9.427	81.9
4	2	24	8.799	79.4
5	2	38	9.993	77.0
6	5	24	8.498	73.2

Note: CKD 1: FA 1 = 50:50; w/b = 0.52; at 28 days.

For a given curing temperature (24°C), the amount of weight loss due to ettringite/sulfate phase decomposition decreased with increased NaOH addition. This indicated an ettringite depression due to NaOH addition, which was consistent with XRD results. In addition, as the amount of NaOH increased, the temperature for decomposition of the ettringite/sulfate phases in the tested samples decreased, which implied that the different types of ettringite formed in the pastes. At the curing temperature of 38°C, amount of weight loss within the TGA test temperatures of 45-

100°C slightly increased when 2% NaOH was added to the binder system. This was possibly related to the amount of alkali sulfate formed in the system.

3.3. Effects of grinding on binder properties

Grinding was expected to activate the materials mechano-chemically, through reducing particle size and introducing surface defects and electrostatic charges. Fig. 3 shows the effects of grinding methods and time on the particle size distributions of mix I (CKD2 : FA2 = 35 : 65). The ball mill grinding results demonstrated that the binder fineness increased with grinding time; however, after 8 hours of ball mill grinding, the material reached the upper limit of the possible fineness and the rate of binder fineness increase became dramatically slow (Fig. 3a). There was a substantial shift in particle size distribution between binder with 4-hour vibratory mill grinding (I-4VA) and 4 hour ball mill grinding (I-4GA), which indicated that vibratory grinding was more efficient than ball mill grinding. Addition of grinding aid increased the grinding efficiency. The binders with 4 hour vibratory grinding (I-4VA), 8 hour combined grinding (I-4CA), and 12 hour ball mill grinding (I-12GA) had the smallest medium particle size among the binders tested, which was 3.0-3.1 μm compared with 9.98 μm of the simply blended binder. Note that the 8 and 12 hour ball mill grinds resulted in nearly identical particle size distributions. Between these grinding times, surface defects might be formed by the additional grinding and mechano-chemical activation took place.

XRD tests were performed to verify that the particle size reduction alone is not the sole factor in determining if mechano-chemical activation occurred, and the amount of crystalline and amorphous material in the materials might also change due to grinding process. The results indicated that at a given test condition, the baseline of the XRD curves was approximately the same for all of the binders, but the intensity of peaks in the XRD curves varied with grinding methods. The increased reactivity of the tested materials could be determined by decreased crystalline phases. It was observed that the crystalline peaks of the binder with 4-hour ball mill grinding (I-4GA) were lowered when compared to the blend binder (no grinding), and the binder having the lowest crystalline peaks, or the most highly reactive one, was that ground with 4-hour vibratory mill (I-4VA) (Fig. 4).

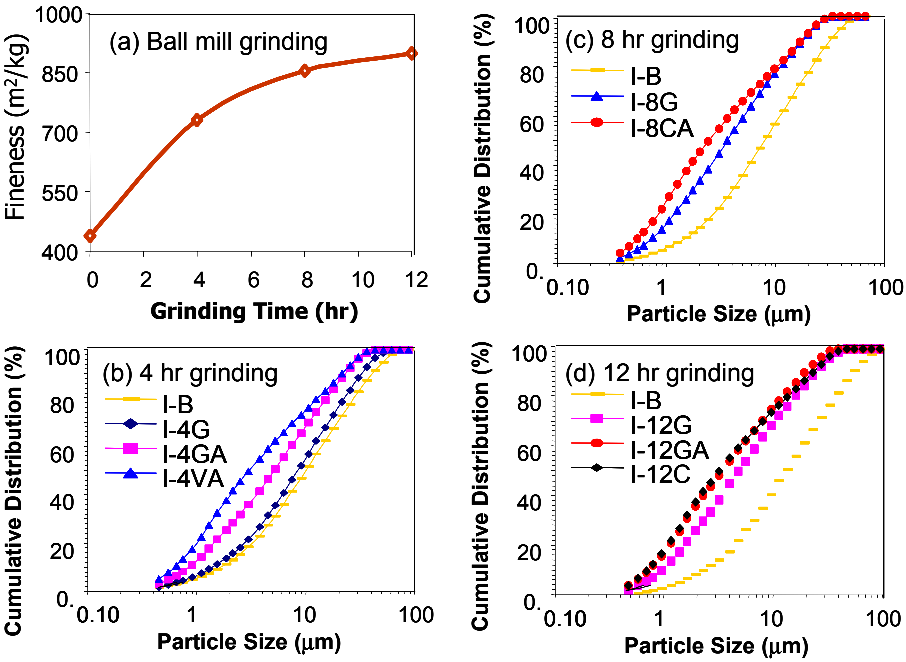

Fig. 3: Effects of grinding on particle size of CKD-FA binder
(I = mix with CKD 2 : FA 2 = 35 : 65; B = simple blending; G = ball mill grinding,
V = vibratory mill grinding; C = combined grinding using ball and vibratory mills; A = grinding aid)

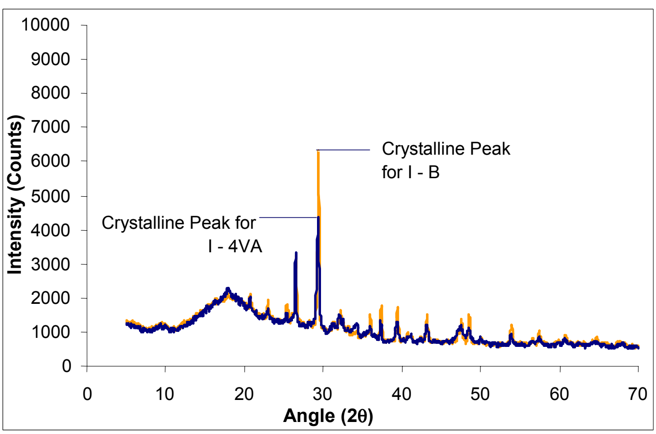

Fig. 4: Effect of grinding process on XRD pattern

Table 3 demonstrates effects of grinding methods on CKD-FA binder properties. It is observed that all ground binders had earlier, faster, and higher heat of hydration than those of the simply blended binder (B). As the ball mill-grinding time increased from 4 hours (4G) to 8 hours (8G), the paste initial set time significantly decreased and total heat of the paste slightly increased. The strength of the pastes decreased with the grinding time, which is possibly due to particle agglomeration of the binder. The pastes made of the binder with grinding aid (4GA) had lower strength than the paste without grinding aid (4G) even though the former one had finer particles and higher value of the total heat evolved, which was probably due to the air entrainment of the grinding aid. Among all, the binder having 4 hour vibratory mill grinding (4VA) had the earliest initial set, the highest strength and total heat of hydration, and the fastest heat evolution. Followed was the binder subjected to 8 hour combined mill grinding (8CA). No clear relationship was observed between the particle size and set time or strength. This implies that the improve binder performance were attributed to the combined effect of particle size reduction, surface defects, and electrostatic charges resulting from grinding.

Table 3: Set time, strength, and heat of hydration of CKD-FA pastes

Grinding methods (CKD2:FA2 =65:35)	Medium particle size (μm)	Initial set (hrs)	28-day compressive strength (psi)	Total heat evolved in 3 days (kJ/kg)	Max. rate of the heat evolution (kJ/kg-hr)	Time at the max. rate of heat (hrs.)
B	9.98	-	850	160	2.9	18.8
4G	8.47	34.5	1620	193	3.8	14.7
8G	4.48	27	1180	200	3.7	14.6
12G	4.37	-	920	200	-	-
4GA	5.13	17.5	1150	283	-	-
4VA	3.04	11.5	2800	290	7.7	14.6
8CA	3.02	16.5	2780	279	6.6	16.6

4. Conclusions

- The major crystalline hydration product of a CKD-FA binder is ettringite. The ettringite formed in a CKD-FA system appeared stable at the age over 100 days.
- Curing at elevated temperature had more significant influence on CKD-FA binder strength development than on OPC strength development and appeared more effective for CKD-FA binder strength improvement than NaOH addition.
- NaOH addition might accelerate chemical dissolution but depressed crystal (ettringite) formation during the binder hydration. With an increased amount of NaOH addition, the ettringite formed in CKD-FA pastes decomposed at a reduced temperature.
- Grinding process reduced not only the particle size but also the crystalline phases of the materials, thus improving binder reactivity. Vibratory grinding

for 4 hours provided the most success for mechano-chemical activation among all grinding methods used.

- Satisfactory strength of a CKD-FA binder could be achieved when proper CKD-to-FA ratio and activation methods are employed.

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References

1. Metha, P.K. "A Concrete Technology for Sustainable Development: An Overview of Essential Principles." *CANMET/ACI International Symposium on Concrete Technology for Sustainable Development*, Vancouver, 1999.
2. Bjork, F. "Concrete Technology and Sustainable Development." *CANMET/ACI International Symposium on Concrete Technology for Sustainable Development*, Vancouver, 1999.
3. Edvardsen, C., and K. Tollose. "Environmentally 'Green' Concrete Structures." *Proceedings of the FIB Symposium: Concrete and Environment*, Berlin, October 2001.
4. Bhatty, M.S.Y. "Use of Cement Kiln Dust in Blended Cements." *World Cement* 15(4), 1984, pp. 126-128 and 131-134.
5. Bhatty, M.S.Y. "Properties of Blended Cements Made with Portland Cement, Cement Kiln Dust, Fly Ash, and Slag." *Proceedings of the Imitational Congress on the Chemistry of Cement,* Theme 3, Vol. 1, IV, Brazil, 1986, pp. 118-127.
6. Wang, K., S.P. Shah, and A. Mishulovich. "Effects of curing temperature and NaOH addition on hydration and strength development of clinker free CKD-fly ash binders." *Cement and Concrete Research*, in press.
7. Babaian, P.M., K. Wang, A. Mishulovich, S. Bhattacharja, and S.P. Shah. "Effect of Mechano-Chemical Activation on Reactivity of Cement Kiln Dust: Fly Ash Systems." *ACI Material Journal* 100(1), Jan.-Feb. 2003, pp. 55-62.
8. Gebauer, J. "Alkali in Clinker: Influence on Cement and Concrete Properties." *Conference of the National Building Research Institute*, Pretoria, South Africa, March 1981.
9. Tang, F.J., and S.W. Tresouthick. "Hydration and Performance of Cements with Various Amounts and Forms of Added Sulfate." *Research and Development Information Serial No. 1887A*. Portland Cement Association, 1992.

THE ADVANCES AND BARRIERS IN APPLICATION OF NEW CONCRETE TECHNOLOGY

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Abstract

Numerous advances in all areas of concrete technology including materials, mixture proportioning, recycling, structural design, durability requirements, testing and specifications have been made. Throughout the world some progress has been made in utilizing these innovations but largely these remain outside routine practice.

The high performance concrete (HPC) for transportation structures, e.g., bridges and pavements, is gaining wider acceptability in routine practice. HPC provides enhanced strength and durability properties and contributes towards long lasting structures and pavements. The constructability can also be enhanced by proper mixture proportioning and testing. Most HPC mixture include recycled materials e.g. fly ash, ground granulated blast furnace slag (GGBFS) or silica fume.

The use of recycled materials in construction is an issue of great importance in this century. Utilization of fly ash and GGBFS in concrete addresses this issue. The replacement of portland cement by fly ash or GGBFS reduces the volumes of portland cement used is a major benefit. The reduction of portland cement production will reduce carbon dioxide (CO_2) emissions, reduce energy consumption and reduce the rate of global warming. Utilization of fly ash and GGBFS usually provides cost savings as well as improved concrete properties.

The case histories discussed demonstrate the practical uses of supplementary cementitious materials—e.g., fly ash, GGBFS, and silica fume—for various types of bridges and pavements in wide ranging environmental conditions. The successful utilization of supplementary cementitious materials requires proper mixture proportioning, testing, placement and curing.

Lack of widespread transfer of developed and available new concrete technology is a major problem in most countries. The practicing engineer's (user) involvement through research, development and technology transfer stages is a key to successful

application of new concrete technology in routine design and practice. The past experience has shown that successful technology transfer occurs when there is a pressing national need, champions of technology are created, champion and organizations involved persist, practical demonstrations of technology are conducted to demonstrate benefits, and regulatory requirements are implemented. The new concrete technology must fulfill a need to be successful. The user (owner, designer, construction engineer) involvement is vital to success. The user starts and ends technology process. Examples of successful concrete technology transfer efforts are discussed.

1. Introduction

Developing and maintaining world's infrastructure to meet the future needs of industrialized and developing countries is necessary to economically grow and improve the quality of life. The quality and performance of concrete plays a key role for most of infrastructure including commercial, industrial, residential and military structures, dams, power plants and transportation systems. Concrete is the single largest manufactured material in the world and accounts for more than 6 billion metric tons of materials annually. In the United States, federal, state, and local governments have nearly $1.5 trillion dollars in investment in the U.S. civil infrastructure. The worldwide use of concrete materials accounts for nearly 780 billion dollars in annual spending.

The industrialized and developing world is facing the issues related to new construction as well as repair and rehabilitation of existing facilities. Rapid construction and long term durability are requirements on most projects. Initial and life-cycle costs play a major role in today's infrastructure development.

There have been number of notable advancements made in concrete technology in the last fifty years. Some of these advances have been incorporated in routine practices. But, in general the State-of-practice has lagged far behind the state-of-art. This is particularly true for public sector projects. There is an increasing concern in most of the world that it takes unduly long time for successful concrete research products to be utilized in practice. Even though some advances have been made in quick implementation of new concrete technology, significant barriers to innovation and implementation remain. Continued coordination of ongoing international research and educational programs is needed.

This paper shares Federal Highway Administration's (FHWA) experience with regard to incorporation of new technology for concrete bridges and pavements. FHWA's experience in concrete research and technology transfer is described in the following sections.

2. Advances in Concrete Technology

Numerous advances in all areas of concrete technology including materials, mixture proportioning, recycling, structural design, durability requirements, testing and specifications have been made. Innovative contracting mechanisms have been considered, explored and tried. Some progress has been made in utilizing some of these technology innovations, but largely these remain outside routine practice. The following sections describe some of the innovations.

2.1. Concrete materials

The development of chemical admixtures has revolutionized concrete technology in the last fifty years. The use of air entraining admixtures, accelerators, retarders, water reducers and corrosion inbitititors are commonly used for bridges and pavements. The use of self-consolidating concrete is beginning (mostly used for precast elements). Shrinkage reducing admixtures are rarely used for bridges and pavements. Supplementary cementitious materials e.g. fly ash, ground granulated blast furnace slag (GGBFS) and silica fume are routinely used.

2.2. Use of recycled materials in concrete

The use of recycled materials generated from transportation, industrial, municipal and mining processes in transportation facilities is a issue of great importance. Recycled concrete aggregates and slag aggregates are being used where appropriate. As the useable sources for natural aggregates for concrete are depleted utilization of these products will increase. Utilization of fly ash and GGBFS in concrete addresses this issue in addition to improving concrete properties. The replacement of portland cement by fly ash or GGBFS reduces the volumes of cement utilized which is a major benefit since the cement manufacture is a significant source of carbon dioxide emissions worldwide. Silica fume is a comparatively expensive product and it is added in smaller quantities in concrete mixture rather than as a cement replacement.

2.3. Concrete mixture proportioning

Continuous gradation and consideration of workability during laboratory testing are slowly gaining acceptance in practice. The utilization of laboratory as well as full-scale trial batches are used on major projects.

2.4. Concrete mechanical properties

Higher strength concrete for bridges are commonly used for columns and beams. Higher strength concrete usually provide higher abrasion resistance and where appropriate this is considered in the bridge deck and pavement designs.

2.5. Concrete durability properties

Concrete durability requirements are specified on most major bridge and pavement projects. Typically the requirements are based on "Rapid Chloride Permeability

Test." This is a surrogate procedure which measures flow of electrical current. The lack of better laboratory and field tests has hindered progress in this area.

2.6. Concrete tests
The utilization of advanced test procedures e.g. various shrinkage tests, air-void analyzer and non-destructive tests have become widespread. The non-destructive tests including maturity test are gaining wider acceptability. Workability test for stiff concrete mixes is being evaluated by several organizations.

2.7. Concrete construction control
In-situ concrete testing, effective curing practices and utilization of computer software to monitor concrete strength development as well as minimizing cracking potential are used on major transportation projects.

2.8. Specifications
Performance related specifications rather than prescriptive specifications for concrete have been developed but not widely used. The use of incentive/disincentive clauses in specifications tend to improve concrete quality.

3. Advances in Application of New Concrete Technology

The advances in applying new concrete technologies in transportation facilities are numerous. The following case histories will provide a good overview of the state-of-practices for concrete bridges and concrete pavements.

3.1. High performance concrete (HPC) bridges
In 1993, FHWA initiated a national program to implement the use of HPC in bridges. The bridges are located in different climatic regions of the United States and use different types of superstructures. These bridges demonstrate practical applications of HPC. The concrete mixtures utilized for the superstructure elements (deck and girders) and substructure elements (piers and abutments) included supplementary cementitious materials (fly ash, silica fume, GGBFS). The cementitious materials were used to provide required durability and/or strength characteristic. Following are characteristics:

- Specified design strengths. For prestressed concrete girders range from 8,000 psi to 14,700 psi (55 to 101 Mpa).
- Specified rapid chloride permeability for bridges decks range from 1,000 to 2,500 coulombs.
- Specified compressive strength for deck concrete range from 4,000 to 8,000 psi (28 to 55 Mpa).
- Required strength and/or durability requirement was met or exceeded.

- Total cementitiious materials contents range from 765 to 1000 lb/cu. yd. (454 to 593 kg/cu.m).
- Fly Ash content range from 200 to 316 lb/cu.yd (231 to 59 kg/cu.m).
- The water–cementitious materials ratio ranges from 0.24 to 0.35.

New York State Department of Transportation, Florida Department of Transportation, and Virginia Department of Transportation utilize HPC in routine practice.

3.2. High performance concrete pavements

The goal of the FHWA High Performance Concrete Pavement Program is a develop an integrated system for the design and construction of portland cement concrete (PCC) pavements that will perform better under the traffic conditions today and in the future. Improved durability, better designs and the innovative materials will help to minimize and extend pavement service life.

Fly ash is routinely use in pavement concrete mixes for jointed plain concrete and continuously reinforced concrete pavements. Both Class C and Class F ashes are used and typically the amount of fly ash used may vary from less than 5 to more than 40 percent by mass of the cement plus fly ash. The percentage depends on fly ash and cement properties and desired concrete properties. Many fly ashes reset with available alkalies in concrete which makes them less available to react with aggregate. The state DOTs of Virginia, Illinois, Iowa, Indiana, Nebraska, Texas, Wisconsin and Kansas are among those which encourage the use of fly ash in concrete pavements.

GGBFS is utilized for paving mixes by several state DOTs including North Carolina, Ohio, Delaware and Virginia. GGBFS preblended with portland cements or added separately in the concrete mix is used. Preblended GGBFS with portland cement is available in proportions of 25%-70% of the total cementitious materials.

Silica fume is rarely used on the paving projects because of cost considerations. In the past, Maine Department of Transportation has utilized silica fume for medians and sidewalks on urban roads. Silica fume provides excellent abrasion resistance and a few northern States are consisting its use on roads with significant winter usage by vehicles employing chains and/or studded tires.

Concrete pavement can be designed with two lifts with wet on wet construction. In such a design, the lower lift can be designed economically with higher volumes of fly ash or/or GGBFS.

3.3. Implementation of pavement research projects

HIPERPAV—In 1993, FHWA recognized the industry concern with the potential for early-age cracking on fast track paving projects. This was a result of projects built in the mid-1980s and reported in the joint industry FHWA Special Project Report SP –201 (1). There was similar concern at the time of maintaining the bond of bonded concrete overlays (BOLs). To respond to this concern, a research project was formulated to develop information on factors that had the potential to influence both early-age uncontrolled full depth cracking and the effect of early traffic on the bond of BOLS. This project had the object o the developing a set of guidelines for mixture proportioning, pavement design ad construction of enable to user to avoid these early-age problems. Since temperature was envisioned as the primary influencing factor, the project was entitled "Fast- Track Paving: Temperature control and Opening to Traffic of bonded Concrete Overlays".

FHWA's Mobile Concrete Laboratory (MCL) was involved in the field testing and monitoring of fast track paving projects and the MCL staff identified the need for concrete temperature monitoring and "opening of traffic criteria. "FHWA's MCL engineers approached FHWA's research and development engineers and a research project was initiated. The practitioners were included on the technical panel and participated throughout the research and development stages. When it became apparent that written guidance would be too voluminous and impractical and a computer software approach was must, the practitioners readily agreed to this approach. This lead to successful deployment and delivery by the practitioners. The practitioners and researchers continue to collaborate on further refinements of the software.

Workability—Workability of fresh concrete depends on its rheological properties. This rheological behavior is defined by two characteristics of the concrete, i..e yield stress and plastic viscosity. Yield stress is the effort needed to initiate movement of the fresh concrete, and correlates well with slump. Plastic viscosity is the flow characteristics of the concrete while moving, and for low stiffness concretes can be determined by various rheometers currently available. However, for higher stiffness mixes (such as used with slipform paving) there are currently no laboratory or field devices available for measuring plastic viscosity, Therefore, the FHWA formulated a project to develop a test for measuring plastic viscosity, in order that workability of slipform paving concrete could be determined and controlled. The objective of this project was develop a practical, reliable test for measuring paving concrete workability in the laboratory or in the field.

FHWA's researchers discussed the research feasibility for such a test for stiff concrete paving mixes prior to project initiation. The practitioners have remained engaged through the research and prototype development state. In fact, the practitioners have suggested further modifications to the test apparatus (e.g. weight reduction for field use). The modifications have been included in three prototype units being used for deployment.

Air Void Analyzer—In the mid 1980s, researchers in Europe were challenged to improve quality assurance in concrete construction by innovation testing of plastic concrete. The efforts in Denmark resulted in the development and evaluation of the fresh concrete air void analyzer (AVA). This device can characterize the air void structure (volume, size and spacing) of fresh concrete. The clear advantage of the AVA is its ability to characterize the air void structure on fresh concrete in less than 30 minutes. With this information, adjustments can be made in the production process during concrete placement. Since 1995, the AVA has been used commercially in a number of European countries.

The FHWA first purchased an AVA test unit in 1993. Field trials and comparisons with standard ASTM test procedures (ASTM C457) were made. The results compared well. FHWA has been actively promoting the technology since 1993. The implementation was difficult and slow till 1999 when a number of State Departments of Transportation as well as industry recognized inadequate air entrainment in several newly built transportation facilities and inadequacies of traditional test procedures e.g. pressuremeter . This recognition has prompted several State highway agencies and industry to purchase the equipment. The American Association of State Highway and Transportation Official have listed AVA technology as a priority item for implementation. This case history demonstrates the importance of having a champion (FHWA) promote the technology with persistence and the necessity of perceived need on the part of intended user.

4. Barriers in Applications of New Concrete Technology

In order to improve the durability of concrete buildings, bridges, pavements and other structures, not only must the technology or state of the knowledge be advanced, but in addition, that knowledge must of transferred to those doing the work, so that the advancement becomes state of the practice. This “technology transfer” or implementation of the results of research into routine use in concrete mixtures, structural design and construction practices is a challenge that has often lagged considerably behind the actual technical advancements. Research projects need to be developed and conducted with implementation of the results in mind. It is of vital importance to involve the practitioners and users of the research projects in all the activities from formulation of research ideas and plans through product development, delivery and deployment. This involvement and resultant buy-in from the future users of the technology from the time of research project initiation leads to quicker technology transfer and implementation.

Once the research has been completed, a number of possible implementation mechanisms need to be considered in order to select the right approach for successful transfer of the technology to the practitioner. The best approach will depend on the form of the research results. The processes used to bring techniques for improvement in concrete performance and durability through research to practice were discussed in previous sections. Innovation cycle begins and ends with user involvement.

Other barriers in the successful implementation of new concrete technologies are as follows:

- No perceived need on the part of the intended user.
- Inadequate Research and Development
- No Champion
- Too complex
- Poor economics
- Institutional opposition
- Lack of persistence

5. Conclusions and Recommendations

- Significant advances have been made in concrete technology during the last fifty years.
- Many of the innovations have been incorporated in the routine practice.
- Some of the successful examples are discussed in this paper.
- Major barriers in application of new concrete technology remain.
- Technology transfer is not easy.
- In order to speed implementation, research project objectives and scope should fully consider the potential end-use of the research results.
- Practitioner's input into the formation and conduct of research project is critical to the transition to practice.
- User participation from the early research project stage results in quicker product implementation in routine concrete design and construction practice. The practitioners become "technology champions" through early and continuous involvement in the project.
- Researchers, implementers, and users must be a cohesive team in order to convince others to try new technology.
- Multiple strategies including information dissemination, training workshops, field demonstration projects, hands-on training, equipment loan programs, technical support and educational courses should be considered for research product implementation.
- Adult education and marketing techniques play a major role in technology implementation. This is particularly true for civil engineering design and construction technologies.

- Delivery and full implementation is a long-term process and may require several years of effort. The researchers and implementation team need to continue to be involved in the technology transfer efforts with enthusiasm and confidence for a sustained period.

References

1. Federal Highway Administration. *Accelerated Rigid Paving Techniques, State-of-the-Art Report*. Special Project 201. FHWA, U.S. Department of Transportation, Washington, DC, December 1994.
2. Wong, G. Sam, et al. *Portland Cement Concrete Rheology and Workability, Final Report*. Report No. FHWA-RD-00-025. FHWA, U.S. Department of Transportation, Washington, DC, April 2001, 117 pp.

WHAT ROLE COULD CONCRETE TECHNOLOGY PLAY FOR SUSTAINABILITY IN CHINA?

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Abstract

There is currently a large increase in infrastructure construction in China. Concrete is the main construction material for most of the structures. The concrete technology has a good opportunity to be developed more quickly for vast markets. Concrete technology for sustainable development in China also plays a very important role for sustainability in the world. As discussed by P. K. Mehta [1], there are some essential principles for sustainable development: conservation of concrete-making materials, enhancement of durability of concrete structures, and holistic approach to concrete technology research and education. An overview and some cases about mentioned essential principles and what we could do in this field are presented in this paper.

1. Introduction

China is one of the big developing countries in the world. There has been a large increase in infrastructure construction in the last 20 years. Concrete is the main construction material for all infrastructures. We can find this trend from the increase of cement output: 700 million tons of cement were manufactured and consumed in 2002. This is about half of the cement output in the world. Hence, the concrete technology has a good chance of being developed more quickly in vast markets. It also shows that concrete technology for sustainable development in China plays a very important role for sustainability in the world.

In this paper, we link the state of the art in China, give an overview and some cases about three essential principles for sustainable development, and explain what we could do in this field.

2. Conservation of Concrete-Making Materials

Portland cement concrete is presently the most widely used manufactured material. One of the important reasons is that its raw materials—rock and clay—are available almost everywhere. As mentioned above, about 700 million tons of the cement were manufactured and consumed in China in 2002. At the same time, along with the vigorous development of electric power plants and ironworks, more than 150 million tons of coal ash and about 80 million tons of blast furnace slag were produced per year. Most of the latter was used in manufacturing normal and blended cement in our country since the end of the 1950s. Until recently, because cement with high early strength is favored on the market, a water-cement ratio 0.44 was replaced by 0.50 for grading cement by the new national standard corresponding to ISO standard. Ground slag powder is increasingly used as supplementary material in concrete.

Fly ash is the primary supplementary material used for concrete. It is mainly used for massive concrete, in particular for dam construction, to reduce thermal cracking. It was also utilized for blended cement manufacturing as one of the raw materials. In the past, it was applied for compensating output of cement industry to meet the need of construction and as an economical replacement of cement in cast-in-place and pre-cast concrete. Beginning from pouring, various admixtures were added to the concrete mixture, especially superplasicized mixture with HRWR, by pumping or slipform paving. Fly ash is looked upon as a material for improving workability of mixtures.

Recently, ready-mixed concrete stations have been established in urban areas, including in small cities in outlying provinces. At the same time, bulk transportation of cement and fly ash has also been developed. These progresses drive effective application of fly ash in concrete. In some large urban areas, such as Shanghai, Beijing, Guangzhou, general cast-in-place concrete for building and other elements with 30% or more (by weight) of fly ash in cementitious materials are not unusual up to the end of 20th century. The resource of fly ash around those metropolises has been limited. Providing fly ash from hundreds of kilometers away has become common practice.

The author was involved with four sections of freeway about 100km long in south China. The pavement and deck of the bridge were poured by the mixture with 20%-35% (by weight) of fly ash in cementitious materials, on a short testing section of about 150m long, the concrete for pavement with 48.5% of fly ash content in cementitious materials near by Zhanjiang (Fig. 1). The enterprise and staff benefit very much from using mixtures with fly ash because it could not only reduce cement content and the wear off of a shell of a very expensive imported internal vibrator, but also improve the quality of pavement by making it smother and having less cracks.

Fig. 1: Photograph of the testing section of fly ash concrete pavement

Although fly ash concrete is increasingly utilized, the rate of consumption of fly ash by the cement and concrete industry is estimated to be very low, and some serious problems still exist in our country. Examples of such problems are as follows: (1) In the north of China, a number of electric power plants are located often not far from coal mines, but far from large urban areas and big projects. At the same time, many cement factories are also centralized in that region around mines, so in large urban areas, lack of fly ash resources has often been encountered. Freight of fly ash increases its cost, and economic interest has been reduced in using fly ash concrete. (2) There is "a misconception among some engineers from developing countries that the use of fly ash in concrete increases the danger of reinforcement corrosion because the pozzolanic reaction reduces the pH" [2]. There is another similar misconception in

China that the use of fly ash in concrete makes the pavement poor in abrasion resistance. Both of them result from accelerated evaluation testing method in laboratory, and they visibly block fly ash application in concrete. (3) There are some institutional barriers, but change is happening. For example, the maximum fly ash content 25%-50% by mass of cementitious material (for reinforced concrete only 15%-25%) is prescribed in a new specification published by the National Transportation Department in 2000, and the other specification will be replaced with performance-based items on fly ash content in concrete.

The author believes that the most effective approach for application of fly ash, especially in the region of centralized coal mines, electric power plants, and cement factories, is producing high-volume fly ash cement (HVFA blended cements). The author appreciates the work carried out by Malhotra [4], because it could visibly reduce the production of cement clinker while maintaining the target production of cement to meet the demand of the construction industry. Of course, it will take time to persuade consumers and to accept certain specification. First, a cement performance standard ASTM C1157M has to be established.

Aggregate is the major constituent of concrete. Due to depleted reserves and environmental pressures, the availability of “good” aggregates, particularly in many urban areas, decreased. As for the recycling of old, demolished concrete as aggregate for new concrete, the author believes that this is a very remote possibility, and it needs longer time to realize in China because of a number of reasons.

3. Enhancement of Durability of Concrete Structures

Of course, enhancement of durability of concrete structures is related to sustainable development. Similar to the situation in the United States and other countries, premature deterioration of infrastructures happened throughout China, especially in recent years. For example, in Fig. 2, the baluster of an intersection in downtown Beijing has seriously been deteriorated. This intersection was only built within the last 20 years. When deteriorations appeared on parts of this intersection, a heated debate happened between researchers. Some argued that the deterioration was due to an alkali-silica reaction, and others considered corrosion of reinforcing steel or deicer salt scaling. The author believes, however, that poor uniformity of the concrete is the main reason of deterioration. A part of concrete was vibrated and densified. The rest of the concrete was segregated, and honeycomb could be found by eye on the surface of concrete.

Fig. 2: Deteriorated baluster on an intersection

Fig. 3: Pavement cracks on a highway

Another example concerns concrete pavement. This is a section of pavement of freeway between Shenzhen and Shantou in south China. The pavement was built from concrete with fly ash (containing on average 35%-37% by weight of cementitious materials), which improved the quality of aggregate. On this section of freeway, even microcracking, was not found on the surface of pavement after three years of opening to traffic. Otherwise, no break off happened when up to 200mm settlement of roadbed presented. On the border of this section, cracking on the surface of pavement appeared very soon after paving by other contractors without adding fly ash to concrete. One year later, however, cracking gradually appeared on the no-crack section along the direction of traffic. More serious cracking emerged on the other section of pavement from Beijing to Zhuhai, completed by the same contractor, only a half year after paving in winter with advanced slipform paver. It extended quickly in several months through most of that section (Fig. 4). The concrete for this section had only 20% of fly ash in cement. The author was invited to visit those sections of pavement to analyze the direction and location of cracking on surface, and he made following comments:

Fig. 4: Pavement cracks on a highway

- The base of the pavement was built with high stiffness; the deformation of the pavement concrete was limited strictly by base.
- The strength of concrete on pavement increased fast because of using high strength cement at early age.
- Imported slipform paver could perform paving two lanes simultaneously (9m width), and then longitudinal joint became pseudo-joint. The pavement on two lanes restricted each other because of concrete's shrinkage deformation. Intense elastic tension stress formed at early age before opening to traffic because of mentioned above three reasons.

- Most of the cracks occurred basically on the main lane outboard, but not on the overtaking lane inboard. It means that vehicle load (large vehicle loads are very usual now for truck traffic in China) and settlement of road base are also important reasons of cracks on pavement.

Of course, there are combinations of reasons that induce cracking. Fresh concrete changed from very stiff to plastic with poor uniformity since 1970s, which became the hidden trouble of concrete structure's durability in China. On the other hand, since the 1990s, as Mehta and Burrows said [4], "the use of high strength cements and concrete mixtures to support the high speed of modern construction is the most predominant factor in the cracking of concrete structures at early ages," and "today's reductionistic concreting practice, driven solely by demand of high-speed construction, is generally responsible for excessive cracking and for reported epidemic of durability problems." Unfortunately, this holistic model of concrete durability is rarely accepted in our country. Premature cracking and deterioration of concrete pavement is widely attributed by many persons to the large vehicle loads. However, the change from concrete to asphalt pavement in recent years will not help to prolong the service life of highway or to reduce the life-cycle cost.

4. Holistic Approach to Concrete Technology—Research and Education

In the field of research of concrete technology, the reductionist approach is presented everywhere. For example, since the 1960s or earlier, the alkali-silica reaction (ASR) between certain reactive forms of silica present in aggregate particles and a highly alkaline solution resulting from the hydration of high-alkali cement has been

Fig. 5: Bleeding and segregation of mixtures during concreting

studied by researchers in China. More than 1% alkali contained in most cement production is manufactured by factories in north China. Until the 1980s, hardly any example was found that concrete deterioration results from ASR. Up to the 1990s, a number of examples of ASR, and even of alkali-carbonate reaction, were found. So, the adoption of a no-risk ASR policy in China has led to rejection of high-alkali cement and many deposits of aggregates that were found to be reactive in laboratory testing. In order to please some agencies specifying the use of cements having a low alkali content so as to avoid potential, or very often imaginary, alkali aggregate reactions, some cement companies are selling cement with an unnecessary low alkali content. During recent years, the author has heard several times that compatibility problem between cement and naphthalene-based superplasticizer appeared in concrete proportioning work for project. This results in bleeding and segregation of mixtures during concreting. (Fig. 5) The results were obtained at the University of Sherbrooke by Jiang et al. [5]. It seems to indicate, from a rheological point of view, that for many types of cement there is an optimal amount of soluble alkalis. This ideal alkali soluble content is not reached with some modern types of cement because of concern about ASR. In fact, high volume fly ash concrete or slag concrete should be the best and most economic solution for ASR and other concrete durability problems, but a holistic approach for research should first be mastered.

The author teaches concrete technology with holistic approach both for undergraduate students (“Construction Materials” course) and graduate students (“Advances in Concrete Materials and Engineering” course). The author worked as an operator of concrete production and concreting in situ for some years after graduating from the university, and after that he worked as a researcher in research institute for about 20 years. In 1993, the author returned to the university and worked as a teacher. The author agrees with “holistic model of concrete deterioration” [7] described in the book *Concrete Technology: Past, Present, and Future* [6]. He uses a number of examples to explain to students the reasons of cracks in concrete structures, why the concrete with high volume of fly ash or slag has better crack resistance compared with Portland cement concrete, the relationship between cracking of concrete and durability of concrete structures, etc.

China, the big developing country, has about one fourth of the world population. With growing population, industrialization, and urbanization, some conflicts appear between natural resource, environmental capacity, and the development of the national economy. The paradigm shift in scientific research and education has to be changed from a reductionist to a holistic model. China has a civilization spanning several millennia, and Confucian thinking emphasizes the unification of nature and humans. The author hopes that mentioned paradigm shift will be realized through our effort as soon as possible. It might take a long time, but the movement in the right direction is more important.

References

1. Mehta. P.K. “Concrete Technology for Sustainable Development: An Overview of Essential Principles. *International Symposium on Sustainable Development of Cement and Concrete Industry*, October 1998. Ottawa, Canada.
2. Malhotra. V. M. “High-Performance High-Volume Fly Ash Concrete.” *Concrete International*, July 2002.
3. Mehta. P.K., and R.W. Burrows. “Building Durable Structures in the 21st Century.” *Concrete International*, March 2001.
4. Malhotra, V. M. “Performance of Lab-Produced HVFA-Blended Cements in Concrete.” *Concrete International*, April 2001.
5. Aïtcin, P.-C. “Cements of Yesterday and Today; Concrete of Tomorrow.” *Cement Concrete Research,* September 2000.
6. *Concrete Technology: Past, Present, and Future.* Proceedings of the V. M. Malhotra Symposium, ACI SP-144, 1994.
7. Mehta. P.K. “Concrete Technology at the Crossroads: Problems and Opportunities.” C*oncrete Technology: Past, Present, and Future.* Proceedings of the V.M. Malhotra Symposium, ACI SP-144, 1994.

UTILIZATION OF SOLID WASTES (WASTE GLASS AND RUBBER PARTICLES) AS AGGREGATES IN CONCRETE

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Abstract

Post-consumer glass represents a major component of solid waste. On the other hand, more than 100 million tons of coal combustion ash are generated in the U.S. annually, of which 60 million tons are fly ash. To deal with these problems, two new materials were developed: "glascrete" and "ashcrete." They have the potential of being made almost entirely from recycled materials: crushed mix-color waste glass as aggregate and activated fly ash (or portland cement) as cementitious binder. The combination of waste glass with portland cement or with activated fly ash offers an economically viable technology for high-value utilization of the industrial wastes. Disposal of waste tires is another serious environmental problem in the U.S. Two innovative materials were developed for utilization of rubber particles in concrete: rubber modified concrete (RMC) and sulfur rubber concrete (SRC). In RMC, the strength loss of the concrete is minimized, and the toughness of the concrete is enhanced by surface treatment of the rubber particles using coupling agents. In SRC, waste rubber particles are mixed in sulfur concrete, and the partial vulcanization process between the rubber and hot sulfur improves the strength of SRC.

1. Introduction

Conversion of three types of solid wastes (i.e., waste glass, fly ash, and rubber particles) into construction materials will be discussed in this paper. But, our focus will be made on the utilization of waste glass and rubber particles as aggregates in concrete.

Post-consumer glass represents a major component of solid waste. Current collection methods for glass products are quite limited, therefore, only a small fraction of the solid waste can be recycled directly to the primary market—the bottling and container industry. The problem is very severe in large metropolitan areas such as New York City, Los Angeles, and Chicago. In New York City, for example, more than 100,000 tons of mixed-color glass is collected annually. This amount does not include the waste glass collected by industrial and commercial companies. On the other hand, the United States generates more than 100 million tons of coal combustion ash annually, of which 60 million tons are fly ash. Only about 27% of the fly ash produced is reused or recycled, and the rest is land filled. Two new materials, called "glascrete" and "ashcrete" were developed to solve the problems. Glascrete has attractive appearance due to the smooth and colorful glass aggregates, which makes it suitable for various architectural and decorative applications. Ashcrete has high strength and very high early strength, which make it unique for applications in precast concrete industry.

The literature review shows that in the waste glass market there are more than 70 potential secondary uses of glass [1, 2, 3]. The most important ones are glasphalt, fiberglass, clean fill, and drainage. There are some advantages for using mixed color glass aggregate in concrete, especially for some architectural applications. However, being a reactive material, when glass aggregates are added into portland cement concrete, they inevitably result in a long-term durability problem, called alkali-silica reaction (ASR). The product of ASR is called ASR gel, which swells with the absorption of moisture. Sometimes the generated pressure due to ASR gel is sufficient to induce the development and propagation of fractures in concrete. Therefore, the major problem that we need to solve for utilization of glass aggregate in portland cement concrete is how to reduce the long-term damage of concrete due to ASR expansion.

Waste tires are another major environmental problem for many metropolitan areas in the U.S. There are more than 242 million scrap tires, approximately one tire per person, generated each year in the U.S. The steady stream of scrap tires, plus 2-3 billion waste tires that have already accumulated in stockpiles and uncontrolled tire dumps, have created a significant disposal problem. In the state of Colorado, more than 2 million waste tires generated per year. It is one of the long-term goals for many state governments to develop more effective uses and markets for the large quantities of waste tires.

Some researchers have tried to use recycled rubber particles as aggregates in portland cement concrete [4, 5, 6, 7, 8]. The advantages of the rubber modified concrete (RMC) can be summarized as (1) The toughness and ductility of RMC are usually higher than that of regular concrete, which makes it suitable for many applications; (2) The density of RMC is lower than the density of regular concrete; and (3) Comparing with other recycling methods, such as using waste tires as fuel in cement plants, RMC makes a fully use of the high energy absorption feature of the rubber particles. The disadvantages of RMC are (1) the strength of RMC is usually lower than the strength of regular concrete; and (2) The durability of RMC is not well understood.

In the following sections, we will introduce most recent research results obtained by several research groups in the United States.

2. Glascrete: Portland Cement Concrete with Waste Glass as Aggregates

The partial replacement of natural aggregate by waste glass in portland cement concrete was studied by Meyer and his co-workers [9, 10]. As mentioned earlier, the main problem to be confronted here is the ASR expansion. The research showed that there are several approaches that can effectively control the expansion of ASR due to glass aggregate, in addition to the conventional approaches used to minimize ASR expansion of regular portland cement concrete, such as using silica fume and various additives.

First, the particle size of glass aggregate was found to have a major influence on ASR expansion. Since the ASR reaction is clearly a surface-area dependent phenomenon, one would expect the ASR associated expansion to increase monotonically with aggregate fineness. However, there exists a size of the aggregate at which the maximum expansion occurs. This is called "pessimum" size. For regular soda lime glass, the pessimum size is about #16 or #30 mesh size. For aggregate finer than the pessimum size, the ASR expansion decreases with further decrease in particle size. In fact, when waste glass was ground to mesh size #50 or finer, no expansion of the glascrete mortar bars was observed. This means that the ASR expansion increases with increasing fineness of glass particles up to a certain point, and then decreases afterwards [11, 12]. The practical implication of this finding is that waste glass, ground to at least mesh size #100, is not likely to cause unacceptable expansion due to ASR.

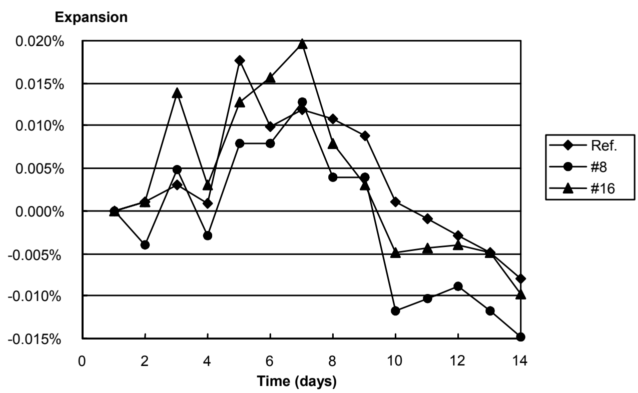
Types of glass were found to have a significant effect on the ASR expansion. Various types of glass aggregate were tested including soda-lime glass (used in most beverage containers), Pyrex glass, and fused silica. The maximum expansions of mortar bars made with different glass aggregate types differ by almost one order of magnitude. Window glass, plate glass, and windshield glass were found to cause negligible ASR expansion in the ASTM C1260 test.

Colors of glass are also important for ASR expansion. Clear glass (the most common kind in waste glass) was found to be most reactive, followed by amber (brown) glass. Green glass did not cause any expansion. Depending on the size of glass particle, green glass of fine particles can reduce the expansion. This implies that finely ground green glass has the potential for an inexpensive ASR suppressant. The green color comes from added Cr_2O_3 in the glass. However, when chromium oxide is added directly into the concrete mix, the ASR expansion of the concrete is not reduced. So, the ASR suppressing mechanisms of Cr_2O_3 in green glass needs to be further studied.

3. Ashcrete: Activated Fly Ash with Glass Aggregates

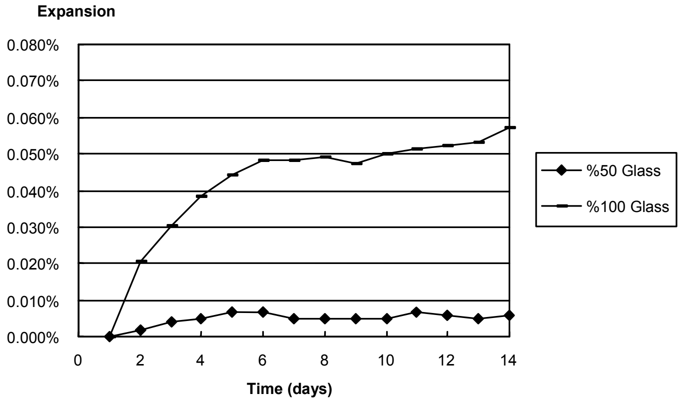
The glass aggregates were also used in a relatively new cementitious material, called ashcrete, or chemically activated fly ash (CAFA), or water-glass activated fly ash (WAFA) [13, 14, 15, 16]. It is a low-cost and environmentally friendly cementitious material and has great potential for various applications in construction, especially for precast concrete. Ashcrete consists of activation chemicals, Class-F fly ash, coarse and fine aggregates without any portland cement.

Fig. 1 Ashcrete with 10% glass aggregates, #8 and #16



The same tests for glascrete were performed on ashcrete with the same glass aggregates [15]. Ashcrete binder seems to reduce expansion of ASR. Not only is the maximum expansion of ashcrete much smaller than that of regular concrete, also the expansion time histories for ashcrete exhibit different behavior. For the portland cement concrete (i.e., glascrete), the expansion increases continuously during the 14 day testing period. For ashcrete, almost all curves showed that expansions increase for a certain period and thereafter decrease continuously. After about ten days, the net expansions turned negative, i.e. instead of expanding, the specimens shrank (see Fig. 1).

Fig. 2 Ashcrete with 50% and 100% glass aggregates

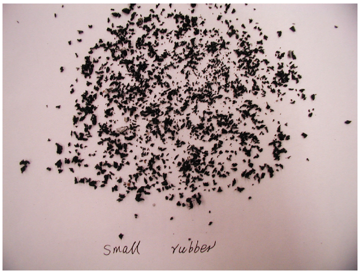


Experimental investigations similar to those described above for glascrete were conducted for the ashcrete to study the effect of glass particle size, glass type, color and content [15]. The test results showed that (a) unlike in the glascrete, green glass is not effective in suppressing ASR expansion; (b) ashcrete with Pyrex glass or fused silica as aggregate resulted in higher ASR expansion than if window glass aggregate was used; and (c) 100% of natural aggregate can be replaced by waste glass, and the resulting ASR expansion of ashcrete is below the limit of 0.1% considered by ASTM C1260 as critical (see Fig. 2). The most important conclusion is that ASR-related expansion does not appear to be a problem for ashcrete with the waste glass aggregates.

4. Rubber Modified Concrete (RMC)

A systematic experimental study was performed recently for improving strength and toughness of rubber modified concrete [17, 18, 19]. Two types of rubber particles of different sizes (large and small) were used to study the size effect on mechanical properties of RMC (see Fig. 3 for the rubber particles). The average size of large particles is 4.12 mm, and the average size of small particles is 1.85 mm. The test results indicated that particle sizes used in this study has no effect on compressive strength, brittleness and toughness of RMC.

(a)



(b)

Fig. 3: (a) Large rubber particles with average size of 4.12 mm
(b) Small rubber particles with average size of 1.85 mm

Low water-cement ratio significantly increases the strength of rubber-modified mortars (RMM). An 8% silica fume pretreatment on the surface of rubber particles can improve properties of RMM. On the other hand, directly using silica fume to replace equal amount (weight) of cement in concrete mix has the same effect.

In general, the bond between rubber particles and concrete can be enhanced by increasing electrostatic interactions and/or facilitating chemical bonding. In this study [17, 18, 19], rubber particles were pretreated by coupling agents, and the method was found to be very effective to improve mechanical properties of the RMC. Three coupling agents: PAAM, PVA and silane were tested. Although PAAM is quite effective to improve the interface strength between rubber particles and cement matrix, it has adverse effect on the workability of the RMC when the rubber content is above 10% of total aggregate by volume. Both PVA and silane are very effective in improving the compressive strength of the RMC. There is no adverse effect on workability of the RMC. PVA is more effective than silane for improving the compressive strength of the RMC. The overall results show that using proper coupling agents to treat the surface of rubber particles is a promising technique, which produces a high performance material suitable for many engineering applications.

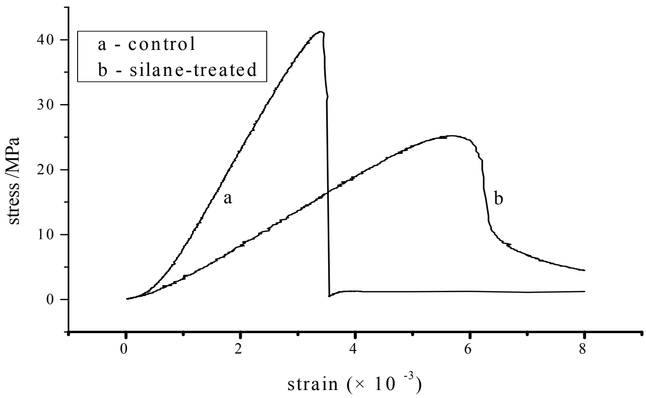


Fig. 4: Stress-strain curves of the regular concrete (control) and silane-treated RMC (10% rubber content) under compression

Results of tension test, fatigue test and ultrasound velocity test showed that the RMC has higher energy dissipation capacities than regular concrete, that is, the RMC has high toughness and high ductility. Fig. 4 shows that there is a considerable increase in the strain corresponding to the maximum stress, from 0.0034 for regular concrete (shown as "control"in Fig. 4) to 0.0061 for the silane-treated RMC. Also, from the peak stresses and the post-peak curves, one can see that regular concrete is very brittle, and silane-treated RMC is less brittle (i.e. softening behavior). As a result, there is an increase in the toughness and ductility. The failure modes of the RMC indicate that the RMC samples can withhold very large deformation and still keep their integrity.

5. Sulfur Rubber Concrete

Sulfur rubber concrete (SRC) is an innovative idea [17, 20]. In sulfur rubber concrete, melted element sulfur, instead of portland cement, serves as the binder. This is why the concrete is called sulfur rubber concrete, because there is no portland cement in it. Production of sulfur concrete is a hot mix procedure similar to the process for manufacturing of asphalt concrete. Sulfur concrete can be manufactured in a modified asphalt batch plant or a continuous mix facility.

When rubber is used in the sulfur concrete to replace some of the natural aggregates, the hot mix process for the sulfur concrete makes the rubber aggregates undergo a vulcanization process, i.e., reacting to sulfur under temperature about 140°C. Although the reaction kinetics does not allow complete vulcanization happening on the surface of rubber particles under the concrete mixing condition, the sulfur matrix still shows good affinity to the rubber. This characteristic helps to establish a better bond between the two phases (see Fig. 5) than the bond between rubber and portland cement paste. As a result, the strength of the sulfur rubber concrete is higher than the strength of the regular concrete with rubber aggregates.

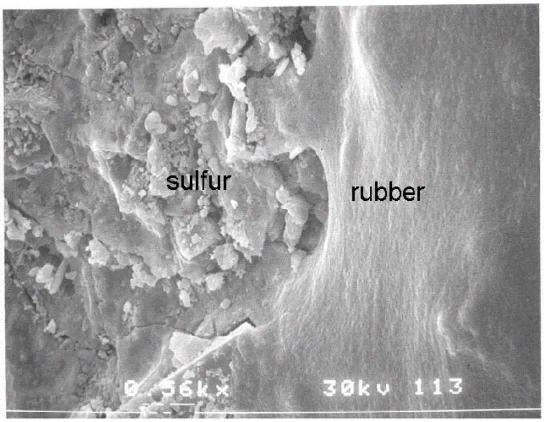


Fig. 5: The interface between rubber particle and sulfur matrix

For preparing the sulfur rubber concrete, all raw materials, i.e. sulfur, natural aggregates, rubber particles, and mineral fillers need to be heated to 130°C to 146°C. Sulfur rubber concrete is characterized by its high strength, high abrasion resistance and high chemical corrosion resistance. On the other hand, the sulfur cement that bonds the aggregates in the concrete has thermoplastic properties. Consequently, the concrete can be crushed, re-melted and reformed without loss of strength or other properties. In another words, it can be completely recycled. Though its cost of one-time application is higher, the cost for recycling process will be much lower.

In this study, various rubber contents (from 0% to 50% replacement rates of natural aggregate), different micro fillers (fly ash and portland cement), different mixing temperatures, and processing techniques (wet and dry processes) were used for manufacturing of the SRCs. The wet process involves mixing sulfur binder with rubber particles first and holding the mixture at a certain temperature for a period of time. Then, the natural aggregates will be added to the rubber-sulfur mixture. The dry process involves mixing the rubber particles with natural aggregate first and then adding the sulfur binder into the aggregate mixture. The important goal in mix design for SRC is to obtain a proper hierarchical size distribution of all constituent phases. Fig. 6 shows the test data of the study [20]. One can see that fly ash is a better micro filler comparing with portland cement. More importantly, although high rubber content reduces the strength of SRC, the SRCs with rubber content in the range of 10%-30% have sufficient strength for many applications, provided that proper micro fillers and processing techniques are used.

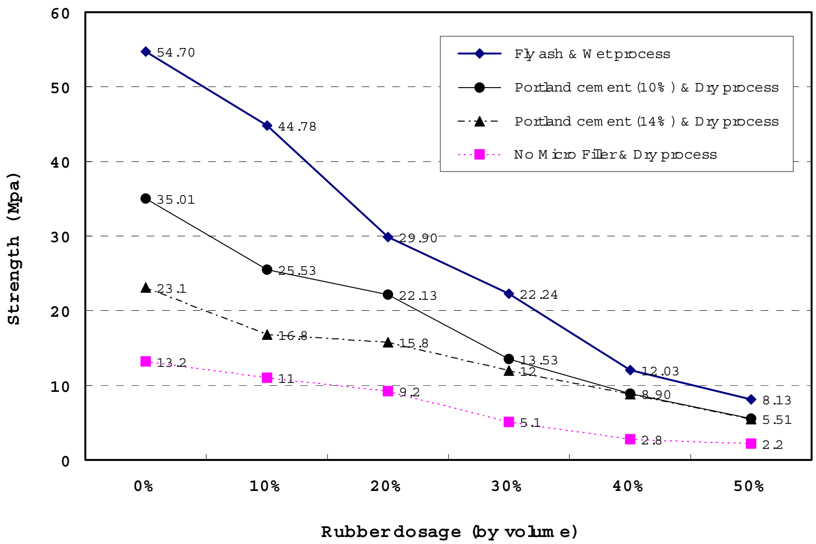


Fig. 6: Strengths of SRC in terms of rubber contents, types of micro fillers, and processing techniques

6. Conclusions

In order to re-utilize solid wastes, such as crushed mixed color glass, fly ash and rubber particles from waste tires, extensive experimental studies were performed for developing four different types of new concretes, glascrete, ashcrete, rubber modified concrete, and sulfur rubber concrete. The experimental results show that each of the concretes has some unique properties, with potentials to be utilized in various applications.

References

1. Hughes, C.S. *Feasibility of Using Recycled Glass in Asphalt*. Report VTRC 90-R3. Virginia Transportation Research Council, Charlottesville, VA, 1990.
2. Shin, C.J., and Sonntag, V. "Using Recovered Glass as Construction Aggregate Feedstock." *Transportation Research Record* 1437, 1994, 8-18.
3. Collins, R.J., and Ciesielski, S. "Recycling and Use of Waste Materials and By-Products in Highway Construction." *Synthesis of Highway Practice 199*. National Cooperative Highway Research Program, Washington, DC, 1994.

4. Eldin, N.N., and Senouci, A.B. “Rubber-tire Particles as Concrete Aggregate.” *Journal. of Materials in Civil Engineering*, ASCE, 5(4), 1993, 478–496.
5. Biel, T.D., and Lee, H. “Use of Recycled Tire Rubbers in Concrete.” Proceedings of the ASCE 3rd Materials Engineering Conference, *Infrastructure: New Materials and Methods of Repair*, 1994, 351–358.
6. Schimizze, R., et al. “Use of Waste Rubber in Light-Duty Concrete Pavements.” Proceedings of the ASCE 3rd Materials Engineering Conference, *Infrastructure: New Materials and Methods of Repair*, 1994, 367–374.
7. Topcu, I.B. ‘Assessment of the brittleness index of rubberized concretes’, *Cement and Concrete Research* 27(2), 1997, 177-183.
8. Segre, N., and Joekes, I. ‘Use of Tire Rubber Particles as Addition to Cement Paste’, *Cement and Concrete Research*, 30, 2000, 1421-1425.
9. Meyer, C., and Xi, Y. “Use of Recycled Glass and Fly Ash for Precast Concrete.” *Journal of Materials in Civil Engineering*, 11(2), May 1999, 89-90.
10. Jin, W., Meyer, C., and Baxter, S. “Glascrete: Concrete with Glass Aggregate.” *ACI Materials Journal* 97(2), March-April 2000, 208-213.
11. NYSERDA (New York State Energy Research and Development Authority). *Use of Recycled Glass for Concrete Masonry Blocks*. Report 97-15, Nov. 1997.
12. NYSERDA (New York State Energy Research and Development Authority). *Use of Recycled Glass and Fly Ash for Precast Concrete*. Final Report 98-18, Oct. 1998.
13. Samadi, A., Xi, Y., Martin, J.P., and Cheng, J. “A Unique Concrete Made with Fly Ash and Solium Silicate Solution.” Presented at the April Meeting of the American Ceramics Society, Cincinnati, OH, 1995.
14. Silverstrim, T., Rostami, H., Xi, Y., and Martin, J. “High Performance Characteristics of Chemically Activated Fly Ash (CAFA).” *Proceedings of the PCI/FHWA International Symposium on High Performance Concrete*, New Orleans, Louisiana, Oct. 20-22, 1997, 135-147.
15. Xie, Z.H., Wen, X., and Xi, Y. “ASR Potentials of Glass Aggregates in Water-Glass Activated Fly Ash and Portland Cement Mortars.” *Journal of Materials in Civil Engineering*, ASCE, 2003, 67-74.
16. Xie, Z., and Xi, Y. “Hardening Mechanisms of An Alkaline Activated Class-F Fly Ash.” *Cement and Concrete Research* 31, 2001, 1245-1249.
17. Xi, Y., Li, Y., Xie, Z.H., and Li, Z.J. *High Toughness of Rubber-Modified Concrete (RMC)*. Final Report CU/SR-XI-2003/002. Colorado Commission of Higher Education, 2003a, 63 p.
18. Li, Y., and Xi, Y. “Microstructure and Properties of Rubber-Modified Portland Cement Mortar.” To be submitted to *ACI Materials Journal*, 2003a.
19. Li, Y., and Xi, Y. “Improving Strength and Toughness of Rubber-Modified Concrete.” Submitted to *Cement and Concrete Research*, 2003b.
20. Xi, Y., Li, Y., Xie, Z.H., and Lee, J.S. “Mix Designs and Processing Techniques for Sulfur Rubber Concrete.” Submitted to *Cement and Concrete Research*, 2003b.

DEVELOPMENT OF SUSTAINABLE CEMENTITIOUS MATERIALS

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Abstract

In this paper, two types of sustainable cementitious composites, geopolymer and magnesium phosphate cement, are introduced. The geopolymer is a type of amorphous alumino-silicate products and magnesium cement is MgO based cementitious material. Geopolymer can be synthesized by polycondensation reaction of geopolymeric precursor, and alkali polysilicates. The MgO cement can be obtained by properly mixing MgO particles, fly ash, and phosphate. Comparing to portland cement, geopolymers and magnesium phosphate cement are energy efficient and environment friendly. Thus they are sustainable cementitious materials. In the paper, the recent developments of these two materials at HKUST are presented. The investigation shows that these two materials have superior properties to the portland cement such as high early strength, excellent volume stability, better durability, good fire resistance, and easy manufacture process.

1. Introduction

Portland cement (PC) concrete is the most popular and widely used building materials, due to its availability of the raw materials over the world, its ease for preparing and fabricating in all sorts of conceivable shapes. The applications of concrete in the realms of infrastructure, habitation, and transportation have greatly prompted the development of civilization, economic progress, stability and of the quality of life [1]. Nowadays, with the occurrence of high performance concrete (HPC), the durability and strength of concrete have been improved largely. However, due to the restriction of the manufacturing process and the raw materials, some inherent disadvantages of portland cement are still difficult to overcome. There are two major drawbacks with respect to sustainability. (1) About 1.5 tones of raw materials is needed in the production of every ton of PC, at the same time, about one ton of carbon dioxide (CO_2) is released into the environment during the production. Therefore, the production of PC is extremely resource and energy intensive process.

(2) Concrete made of PC deteriorates when exposed to the severe environments, either under the normal or severe conditions. Cracking and corrosion have significant influence on its service behavior, design life and safety.

Here, two different cementitious materials will be discussed. One is geopolymer and the other is magnesium phosphate cement (MPC). Compared with portland cement, the above two cements possess some common and individual characters, respectively. Their properties are very favorable to the sustainable development of our modern society.

1.1 Advantages and applications of geopolymer

Compared with portland cement, geopolymers possess the following characteristics:

- Abundant raw materials resources: any pozzolanic compound or source of silicates or almino-silcates that is readily dissolved in alkaline solution will suffice as a source of the production of geopolymer.
- Energy saving and environment protection: geopolymers don not require large energy consumption. Thermal processing of natural alumino-silicates at relative low temperature (600° to 800°) provides suitable geopolymeric raw materials, resulting in 3/5 less energy assumption than portland cement. In addition, a little CO_2 is emitted.
- Simple preparation technique: Geopolymer can be synthesized simply by mixing alumino-silicate reactive materials and strongly alkaline solutions, then curing at room temperature. In a short period, a reasonable strength will be gained. It is very similar to the preparation of portland cement concrete.
- Good volume stability: geopolymers have 4/5 lower shrinkage than portland cement.
- Reasonable strength gain in a short time: geopolymer can obtain 70% of the final compressive strength in the first 4 hours of setting.
- Ultra-excellent durability: geopolymer concrete or mortar can withdraw thousands of years weathering attack without too much function loss.
- High fire resistance and low thermal conductivity: geopolymer can withdraw 1000° to 1200° without losing functions. The heat conductivity of geopolymer varies form 0.24w/m·k to 0.3w/m·k, compared well with lightweight refractory bricks (0.3 w/m·k to 0.438 w/m·k).

Geopolymer, with properties such as abundant raw resource, little CO_2 emission, less energy consumption, low production cost, high early strength, fast setting. These properties make geopolymer find great applications in many fields of industry such as civil engineering, automotive and aerospace industries, non-ferrous foundries and metallurgy, plastics industries, waste management, art and decoration, and retrofit of buildings.

(1) Toxic waste treatment. Immobilization of toxic waste may be one of the major areas where geopolymer can impact significantly on the statues quo. The molecular structure of geopolymer is similar to those of zeolites or feldspathoids, which are known for their excellent abilities to adsorb and solidify toxic chemical wastes such as heavy metal ions and nuclear residues. It is the structures that make geopolymer a strong candidate for immobilizing hazardous elemental wastes. Hazardous elements present in waste materials mixed with geopolymer compounds are tightly locked into the 3-D network of the geopolymer bulk matrix.

(2) Civil engineering. Geopolymer binders behave similarly to portland cement. It can set and harden at room temperature, and can gain reasonable strength in a short period. Some proportions of geopolymer binders have been tested and proved to be successful in the fields of construction, transportation and infrastructure applications. They yield synthetic mineral products with such properties as high mechanical performance, hard surface (4-7 on the Mohs Scale), thermal stability, excellent durability, and high acid resistance. Any current building component such as bricks, ceramic tiles and cement could be replaced by geopolymer

(3) Global warming and energy saving. It is well known that a great amount of CO_2 is emitted during the production of portland cement, which is one of the main reasons for the global warming. Studies have shown that one ton of carbon dioxide gas is released into the atmosphere for every ton of portland cement which is made anywhere in the world. In contrast, geopolymer cement is manufactured in a different way than that of portland cement. It does not require extreme high temperature treatment of limestone. Only low temperature processing of naturally occurring or directly man-made alumino-silicates (kaoline or fly ash) provides suitable geopolymeric raw materials. These lead to the significant reduce in the energy consumption and the CO_2 emission. It is reported by Davidovits [8] that about less 3/5 energy was required and 80%-90% less CO_2 is generated for the production of geopolymer than that of portland cement. Thus it is of great significance in environmental protection for the development and application of geopolymer cement.

(4) High temperature and fire resistance. Geopolymer cement possesses excellent high temperature resistance up to 1200° and endures 50kW/m^2 fire exposure without sudden properties degradation. In addition, no smoke is released after extended heat flux. The merits make geopolymer show great advantages in automotive and aerospace industries. At present, some geopolymer products have been used in aircraft to eliminate cabin fire in aircraft accidents.

(5) Archaeological analogues. It is proved that the micro-structure of hardened geopolymer materials is quite similar to that of ancient constructs such as Egyptian pyramid, Roman amphitheater. Consequently, many experts suspended that these

ancient constructs might be cast in place through geopolymerization, rather than made of natural stones. To confirm the viewpoint, many scientists make much attempt to explain the unsolved enigma for some ancient long-term constructs by means of geopolymer theories in recent years.

1.2 Advantages and applications of MPCs

MPCs are artificial stone made from acid-base reaction of magnesia and phosphates. They possess some properties that portland cements do not possess according to the previous studies. Therefore, they can be utilized in the field in which portland cements are not suitable [9-34]. (1) Very quick setting, high early strength. (2) Recycling lot of non-contaminated industrial waste to building material. (3) Recycling organic waste to building materials. (4) Stabilization of toxic and radioactive waste. (5) Very good durability, including chemical attack resistance, deicer scaling resistance, permeation resistance.

The applications of MPCs include following aspects:

(1) Due to its rapid setting and high early strength, magnesium phosphate cement (MPC) has been utilized in raped repair of concrete structure, such as highway, airport runway, and bridge decks for many years. It can save a lot of waiting time and cost caused by long disrupting time by use other materials. If the interrupt period is too long for the busy highway, airport runway, and bridges, etc., it will cause lose of millions dollars. By using MPC materials, the interrupt time of transportation can be greatly shortened. Therefore, the valuable time and resource can be saved.

(2) MPC can incorporate with lot of non toxic industrial waste, such as Class F fly ash (FA) and translate it into useful construction materials. The addition FA in MPC can be over 40% by mass of MPC, about two times comparing with PC. In addition, MPC can combine the FA that is not suitable incorporated in PC because of its high carbon content and other impurities. Besides FA, even acid blast furnace slag, red mud (the reside of alumina industry), even tails of gold mine can also be utilized in MPC at large amount. These wastes are difficult to use in PC concrete in a considerable amount.

(3) Due to the high alkali environment of PC (pH over 12.5), when they are use as reinforcement, some components natural fibers, notably lignin, and hemicelluose will be susceptible to degradation. However, the lower alkalinity of MPC matrices (pH value 10 to 11) makes them potentially better suited to vegetable fiber reinforcement. Furthermore, the sugar in some natural fibers, such and sugarcane and corn stalk can prohibit the setting of PC, and weakens the bonding between portland cement and fiber. But, the set of MPC is not influenced by sugar.

(4) Management and stabilization of toxic and radioactive wastes, including solids and liquids. The wastes cane be micro and /or macro-encapsulated and chemically bonded by MPC, form a strong, dense and durable matrix that stores the hazardous and radioactive contaminants as insoluble phosphates and microencapsulates insoluble radioactive components. The waste forms are not only stable in groundwater environments, but also are non-ignitable and hence safe for storage and transportation.

(5) Very suitable for repairing of the deteriorated concrete pavements in the cold areas. MPC can develop strength at low temperature due to its exothermic hydration and low water to binder ratio. At the same time, MPCs possess a higher deicer scaling property than portland cement.

(6) The raw material of MPC is hard burnt magnesia. In fact, it is a refractory material. Therefore, MPC can be designed to be fire proof and/or as cold setting refractory according to the practical need.

2. Summary on Geopolymer Development

2.1 Work done by others

Since France scientist Davidovits invented geopolymer materials in 1978 [35], great concerns on the development of geopolymer have been received across the world. More than 28 international scientific institutions and companies have presented updated research and published their results in public journals. These works mainly focus on the following aspects:

(1) Solidification of toxic waste and nuclear residues

Davidovits et al. [36] firstly began to investigate the possibilities of heavy metal immobilization by commercial geopolymeric products in the early 1990s. The leachate results for geopolymerization on various mine tailings showed that over 90% of heavy metal ions included in the tailings can be tightly solidified in 3D framework of geopolymer. In the middle of 1990s, J.G.S. Van Jaarsveld and J.G.S. Van Deventer et al. [37-40] also set out to study the solidification effectiveness of geopolymer manufactured from fly ash. The bond mechanism between heavy metal ions and geopolymer matrix is also simply explained on the basis of the XRD, IR, MAS-NMR and leaching results. Recently, the European research project GEOCISTEM [41] successfully tested geopolymerization technology in the context of the East-German mining and milling remediation project, carried out by WISMUT. Another research project into the solidification of radioactive residues was jointly carried out by Cordi-Geopolymer and Comrie Consulting Ltd., and was documented in reference [42].

(2) Fire resistance

Recently The Federal Aviation Administration (FAA), USA, and the Geopolymer Institute of Cordi-Geopolymere SA, France [43], have jointly initiated a research program to develop low-cost, environmentally-friendly, fire resistant matrix materials for use in aircraft composites and cabin interior applications. The flammability requirement for new materials is that they withstand a 50 kW/m^2 incident heat flux characteristic of a fully developed aviation fuel fire penetrating a cabin opening, without propagating the fire into the cabin compartment. The goal of the program is to eliminate cabin fire as cause of death in aircraft accidents. As with this program, the fire resistance properties of geopolymer reinforced by various types of fiber such as carbon fiber, glass fiber, SiC fiber etc. were tested and the fire-proof mechanics were also analyzed. In addition, the comparisons were made among geopolymer composite and carbon-reinforced polyester, vinyl, epoxy, bismaleinide, cyanate ester, polyimide, phenolic, and engineering thermoplastic laminates. The test results showed that these organic large molecular polymers ignited readily and released appreciable heat and smoke, while carbon-fiber reinforced Geopolymer composites did not ignite, burn, or release any smoke even after extended heat flux exposure. On the basis of these fireproof studies, some non-flammable geopolymer composites for aircraft cabin and cargo interiors were produced and introduced on November 18, 1998, in Atlantic City, NJ, USA.

(3) Archeological research

In the 1970s Professor J. Davidovits proposed a controversial theory that documented in a book [44] and has since gained widespread support and acceptance. He postulated that the great pyramids of Egypt were not built by natural stones, but that the blocks were cast in place and allowed to set, creating an artificial zeolitic rock with geopolymerization technology. He collected a great amount of evidences which come from old ancient Egyptian literatures and samples in sites to confirm his geopolymerization theory. From then on, many experts began to focus their concerns on geopolymer studies. Some related papers [45-55] and patents were also published.

2.2 Work done by us

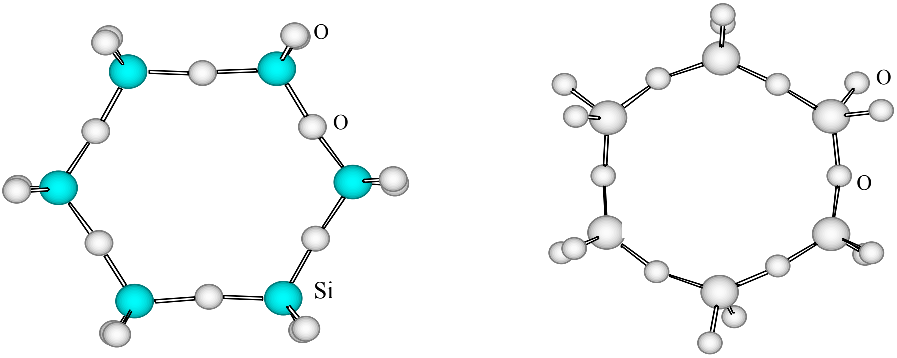
In 2002, Prof. Sun Wei from Southeast University and Prof. Zongjin Li from Hong Kong University of Science and Technology jointly applied for a research project to systematically investigate the synthetic mechanism, structural nature, proportional design method, mechanical and durability performance of geopolymer manufactured with naturally occurring and man-made alumino-silicate materials in China. Subsequently, the project (No.50278018) was approved by the China National Science Fund Committee. In fact, studies on geopolymer started in the early 2000. Many works on geopolymer have been done in three years. The following summarizes some of the experimental results.

(1) Reaction mechanism

Much attempt on formation mechanism has been made since the invention of geopolymer. However, only one described formation mechanism was proposed by Davidovtis. He believed that the synthesis of geopolymer consist of three steps. The first is dissolution of alumino-silicate under strong alkali solution. The second is reorientation of free ion clusters. The last is polycondensation. But each step includes many pathways. Taking dissolution step for example. It includes 8 pathways according to the thermodynamics. Different pathway can create different ion clusters that directly determine the final properties of geopolymer. Thus it is very important to understand the actual pathway for producing geopolymer in order to gain insight into the mechanism of geopolymerization. However, until now, these studies are not still done. It is because that the forming rate of geopolymer is very rapid, as a result, these three steps take place almost at the same time, which make the kinetics of these three steps inter-dependent. Thus it is impossible to separate these steps in experimental studies. This leads to the use of molecular simulation to solve these problems.

In our studies, two 6-membered-rings molecular structural models to represent the chemical structure of metakaolinite (main raw material for synthesizing geopolymer) were established in order to quantitatively analysis the formation process of geopolymer, as shown in Fig. 1(a), and Fig. 1(b). Based on these two 6-membered-rings models, all possible dissolution pathways of metakaoline under strongly alkali environment were numerically simulated using quantum mechanics, quantum chemistry, computation chemistry and thermodynamics theories. All possible pathways (Eqs. (1) to (8)) involved in the formation process of geopolymer were analyzed, and the enthalpies of each possible pathway were also calculated (Table 1). As a result, the optimum pathways in theory, that is the actually occurring pathways in the geopolymerization process, were determined. During molecular simulation, some interesting phenomena were found, and were explained by experimental results.

$$(Si(OH)_2O)_6+3NaOH \Rightarrow (OH)_3Si\text{-}(Si(OH)_2O)_3\text{-}Si(OH)_3+HO\text{-}Si{\equiv}(ONa)_3+H_2O \quad \Delta E1 \tag{1}$$
$$(Si(OH)_2O)_6+3KOH \Rightarrow (OH)_3Si\text{-}(Si(OH)_2O)_3\text{-}Si(OH)_3+HO\text{-}Si{\equiv}(OK)_3+H_2O \quad \Delta E2 \tag{2}$$
$$Si(OH)_2O)_6+4NaOH \Rightarrow (OH)_3Si\text{-}(Si(OH)_2O)_3\text{-}Si(OH)_2\text{-}ONa+HO\text{-}Si{\equiv}(ONa)_3+2H_2O \quad \Delta E3 \tag{3}$$
$$Si(OH)_2O)_6+4KOH \Rightarrow (OH)_3Si\text{-}(Si(OH)_2O)_3\text{-}Si(OH)_2\text{-}OK+HO\text{-}Si{\equiv}(OK)_3+2H_2O \quad \Delta E4 \tag{4}$$
$$(Al^-(OH)_2O)_6+3NaOH \Rightarrow (OH)_3Al^-\text{-}(Al^-(OH)_2O)_3\text{-}Al^-(OH)_3+HO\text{-}Al^-{\equiv}(ONa)_3+H_2O \quad \Delta E5 \tag{5}$$
$$(Al^-(OH)_2O)_6+3KOH \Rightarrow (OH)_3Al^-\text{-}(Al^-(OH)_2O)_3\text{-}Al^-(OH)_3+HO\text{-}Al^-{\equiv}(OK)_3+H_2O \quad \Delta E6 \tag{6}$$
$$(Al^-(OH)_2O)_6+4NaOH \Rightarrow (OH)_3Al^-\text{-}(Al^-(OH)_2O)_3\text{-}Al^-(OH)_2\text{-}ONa+HO\text{-}Al^-{\equiv}(ONa)_3+2H_2O \quad \Delta E7 \tag{7}$$
$$(Al^-(OH)_2O)_6+4KOH \Rightarrow (OH)_3Al^-\text{-}(Al^-(OH)_2O)_3\text{-}Al^-(OH)_2\text{-}OK+HO\text{-}Al^-{\equiv}(OK)_3+2H_2O \quad \Delta E8 \tag{8}$$



(a) 6-member rings structure cluster of SiO_4 tetrahedron

(b) 6-member rings structure cluster of AlO_4 tetrahedron

Fig. 1: Molecular structure representing model of metakaolinite

(2) Microstructure characterization

The structure characteristics of products directly determine the final mechanical and durability properties. The case is also true for geopolymer. Many researchers have investigated its microstructure using different advanced techniques. But because geopolymer is a type of amorphous 3D materials with complex composition, It is very difficult to quantitatively measure the exact arrangement and chemical atmosphere of different atomic in geopolymer. If we want to solve this difficulty, we should have to turn to statistical theories for establishing its molecular model. But unfortunately, until now, these studies are not still been done. Therefore, the structural nature of geopolymer is not yet understood thoroughly.

In our studies, many microstructure techniques, such as XRD, IR, XPS, MAS-NMR, ESEM-EDXA and TEM were used to investigate the structural characterization in atomic, molecular, nanometer, micrometer and centimeter scales. The relationship between geopolymers and the corresponding zeolites were also investigated. The inter-transformation between geopolymers and zeolites can be realized under specified conditions. On basis of these results, the micro-structure of geopolymers can be clearly characterized: geopolymer is an amorphous 3D alumino-silicate material, which is composed of AlO_4 and SiO_4 tetrahedra lined alternatively by sharing all oxygen atoms. Positive ions (Na^+, K^+) are present in the framework cavities to balance the negative charge of Al^{3+} in four-fold coordination. In addition, 3D statistical models (Fig. 2) were also simulated according to the decomposition results of MAS-NMR spectra.

Table 1: Reaction heat of single 6-member rings structure model under strongly alkaline solution.

a. Single 6-member rings of SiO_4 tetrahedra

The molecular structural unit	Formation enthalpy (a.u)	Reaction enthalpy (kJ/mol)			
		ΔE1	ΔE2	ΔE3	ΔE4
$(Si(OH)_2O)_6$	-1491.44763	-5.48908	12.12039	-36.22681	-19.22697
$(OH)_3Si\text{-}(Si(OH)_2O)_3\text{-}Si(OH)_3$	-1294.64502				
$(OH)_3Si\text{-}(Si(OH)_2O)_3\text{-}Si(OH)_2\text{-}ONa$	-1385.43022				
$(OH)_3Si\text{-}(Si(OH)_2O)_3\text{-}Si(OH)_2\text{-}OK$	-1370.88091				
$HO\text{-}Si{\equiv}(ONa)_3$	-500.93548				
$HO\text{-}Si{\equiv}(OK)_3$	-437.84919				
NaOH	-119.29816				
KOH	-104.13922				
H_2O	-59.25069				

b. Single 6-member rings of AlO_4 tetrahedra

The molecular structural unit	Formation enthalpy (a.u)	Reaction enthalpy (kJ/mol)			
		ΔE5	ΔE6	ΔE7	ΔE8
$(Al^{-}(OH)_2O)_6$	-619.66576	-299.7974	-245.78806	-302.69174	-235.0346
$(OH)_3Al^{-}\text{-}(Al^{-}(OH)_2O)_3\text{-}Al^{-}(OH)_3$	-776.45042				
$(OH)_3Al^{-}\text{-}(Al^{-}(OH)_2O)_3\text{-}Al^{-}(OH)_2\text{-}ONa$	-839.39222				
$(OH)_3Al^{-}\text{-}(Al^{-}(OH)_2O)_3\text{-}Al^{-}(OH)_2\text{-}OK$	-810.58557				
$HO\text{-}Al^{-}{\equiv}(ONa)_3$	-441.65654				
$HO\text{-}Al^{-}{\equiv}(OK)_3$	-342.17037				
NaOH	-119.29816				
KOH	-104.13922				
H_2O	-59.25069				

(3) Mechanical properties
More concerns have been received on the solidification of heavy metal ion and nuclear waste and fire resistance since 1990, but at present, less experimental data is available for the systematical investigation on mechanical properties and durability.

Up to now, more than 100 geopolymer concrete specimens were prepared to study mechanical behaviors such as compressive, flexural, splitting tensile, shear strength and their stress-strain responds. PSS geopolymer concrete has the highest mechanical performance among various geopolymer concretes, next to PSDS, and PS has the lowest strength.

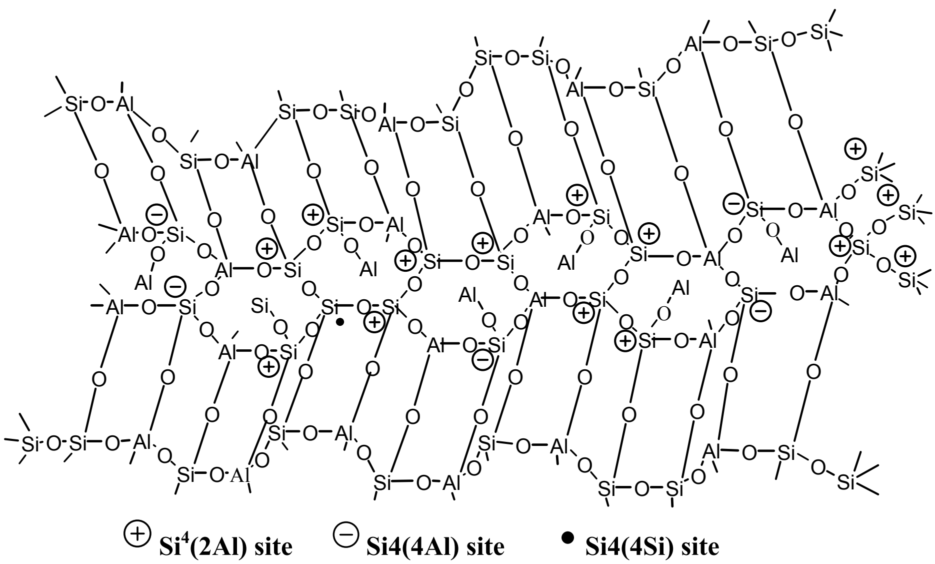


Fig. 2: Statistical structure model of K-Geopolymer

Another 147 geopolymer concrete or mortar specimens were also produced to investigate the durability properties such as chloride ions permeability, resistance to freezing and thawing cycles, resistance to chemical attack including HCl, H_2SO_4 and Na_2SO_4 attack, long-term volume stability, and alkali aggregate reaction (AAR). At present, the durability tests are still under way.

3 The Development of MPCs

3.1 Work done by others

The phosphate bonding has been known for about a century, since the advent of dental cement formulations. In refractory industry, the properties of cold-setting and heat-setting compositions were used as chemically bonded refractory. According to the comprehensive studies of Kingery in 1950, The phosphate bonding can be classified as (1) zinc-phosphate bond, (2). Silicate-phosphoric acid bond, (3) oxide-phosphoric acid bond, (4) acid phosphate bond, and (5) metaphosphate/polyphosphate bond [9]. The oxides such as magnesium, aluminum, zirconium, will react with phosphoric acid or acid phosphate at room temperature, forming a coherent mass, setting quickly and giving high early strength. The hydration system based on magnesia and ammonia phosphate [9-34] had drawn most of the attention in the past years.

From 1970s, many patents using the reaction of magnesia and acid ammonia phosphate have been granted for rapid repair of concrete. The variation in patents arises from the use of different raw materials, inert materials to reduce cost, and retarders to control the reaction rate. Most claims are supported by a few examples cited in the patents without systematic scientific approach. From the middle of 1980s, systematic studies about the system of magnesia and ammonia phosphate were made by researchers [9-32]. The hydration products, setting process, and strength development were the main content among those previous investigations. Very few papers focused on the durability of the system [17, 21, 32]. Entering the middle of 1990s, it was found that MPC can incorporate with lot of industrial waste and solidify toxic waste [33-35]. Therefore, MPC became a forceful candidate for sustainable development. The benefits in environment may be obtained from two aspects, (1) the non-toxic industrial waste can be recycled to useful building materials, and (2) many toxic and radioactive wastes treated difficultly with traditional process can be treated by MPC easily. This function endues MPC more promising use in the future, especially to the sustainable development of the modern society.

About the durability of MPCs, research work had been done by other investigators mainly includes, superior durability such as freezing-thawing and scaling resistance, protection steel from corrosion, better bond properties with waste organic materials, transfer non-contaminated industrial wastes into useful construction materials, and stabilization of toxic or radioactive wastes.

The deterioration of concrete pavements is mainly cause by frost action in cold areas. It is severely amplified by the use of deicer chemicals. The repair material must possess high frost/deicer-frost resistance. The result shown that MPC have very high deicer-frost resistance [17, 32]. The scaling does not occur on the surfaces of MPC materials until 40 freeze-thaw cycles. The regime of freeze-thaw cycling was achieved with cooling rate of about 0.5^{o}C/min. for 4 hours at -20±2^{o}C and then thawed for 4 hours at 20±5^{o}C. A 3% NaCl solution was used as the deicer solution. The studies shown that the freezing thawing resistance of MPCs was basically equal to the well air-entrained PC concrete in general.

Steel corrosion in PC concrete was a very serious problem. However, MPC is inhibitor of corrosion of steel, forming an iron phosphate film at the surface of the steel. The pH of hardened MPC mortar is 10 to 11, this may be considered as contributing to inhibition of reinforcing steel corrosion. In addition, the ratio of permeability of MPC to PC concrete is 47.3%, or more than double in resistance to permeation [17]. Abrasion resistance test shown that MPC mortar possesses approximately double the abrasion resistance compared with slab-on-grade floor concrete and to be nearly equal to that of pavement concrete [17, 21]. With respect to chemical corrosion resistance, in the case of continuous immersion of specimens in sulphate solution and potable water, results indicate that MPC mortar patches will practically remain durable under sulfate and moist conditions.

A wide range of waste particle sizes can be utilized when producing structural products using the MPC. Styrofoam materials are the candidate for optimal results. The styrofoam articles can be completely coated with a thin, impermeable layer of the MPC. The uniform coating of the styrofoam particles not only provides structural stability but also confer resistance to fire, chemical attack, humidity and other weathering conditions. The styrofoam insulation material provides superior R values. Furthermore, wood waste (suitable size range from 1 to 5 mm long, 1 mm thick and 2 to 3 mm wide) can be bonded with MPC to produce particleboard having flexural strength. For example, samples containing 50wt% of wood and 50wt% of binder display approximately 10.4 MPa in flexural strength. Samples containing 60wt% and 70wt% of wood exhibit flexural strength of 2.8 and 2.1 MPa, respectively. Once the wood and binder is thoroughly mixed, the samples are subjected to pressurized molding on the order of approximately 18.3 MPa, and for approximately 30 to 90 minutes.

With the progress of modern civilization, the living conditions had been greatly improved; at the same time, however, a large amount of industrial waste (including toxic and nontoxic) had been produced. MPC can bind lot of bind non-toxic industrial waste to useful construction materials. If the wastes were toxic, MPC can solidify and stabilize them. There is a significance to recycle and/or stabilize the waste, especially under the condition of natural resources becoming more and more deficient. The waste in various forms in aqueous liquids, inorganic sludge, particles, heterogeneous debris, soils, and organic liquids. However, there was only a few part of the total waste can been recycled, such as fly ash, red mud was manufactured blended portland cement or concrete. Most of the wastes need to be solidified and stabilized. Because of the divers nature of the physical and chemical composition of these wastes, no single solidification and solidification technology can be used successfully treat and dispose of these wastes. For example, the low-level wastes contain both hazardous chemical and low-level radioactive species [33]. To stabilize them requires that contaminants of two kinds be immobilized effectively. Generally, the contaminants are volatile compounds and hence cannot be treated effectively by high-temperature processes.

In a conventional vitrification or plasma hearth process, such contaminants may be captured in secondary waste stream or off-gas particulates that need further low-temperature treatment for stabilization. Also some of these waste streams may contain pyrophorics that will ignite spontaneously during thermal treatment and thus cause hot spots that may require expensive control system and equipment with demanding structure integrity on. Therefore, there is a critical need for a low-temperature treatment and stabilization technology that will effectively treat the secondary wastes generated by high-temperature treatment process and waste that are not amenable to thermal treatment. Now, those wastes can be successfully solidified by magnesia phosphate cement, or chemically bonded phosphate ceramics (CBPC) [33]. Other forms of waste, such as ashes, liquids, sludge and salts can be also solidified by MPC.

MPC is very extremely insoluble in ground water and this will protect ground water from contamination by the contained wasted. The long-term leaching tests conducted on magnesium phosphate systems shown that these phosphate are insoluble in water and brine. The radiation stability of MPC is excellent [34]. Changes in the mechanical integrity of the materials were not detected after gamma irradiation to cumulative dosage of 10^8 rads.

3.2 Work done by HKUST

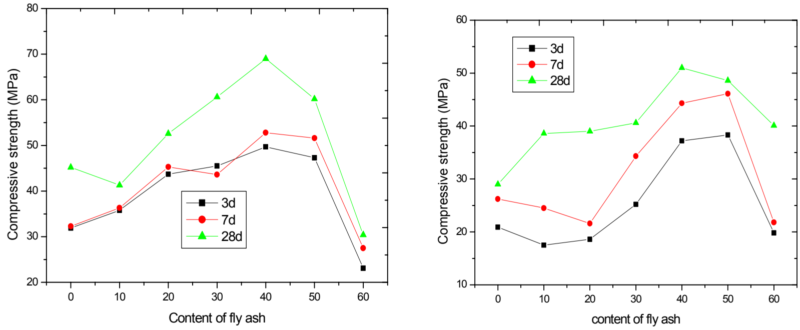
From the late of 2001, we started the project of new MPC system based on potassium phosphate. The main advantages of new system are binding lot of industrial waste and no ammonium gas was emitted. Up to now, the mechanical and chemical properties, hydration process and mechanism, durability and binding properties with old PC concrete had been investigated. Here the mechanical property and durability will be mainly introduced.

3.2.1 Mechanical properties

(1). Strength development of MPC made of different hard burnt magnesia

Two kinds of hard burnt magnesia and a Class F fly ash (FA). The magnesia contains 89.6% magnesium oxide was named M9, whose average size of particle was 30.6 μm. The other contains 71.6% magnesium oxide was named M7, whose average size of particle was 59.8 μm.

Compressive strength versus fly ash content for MPC mortars at 3, 7, and 28 days is presented in Fig. 3 for M7 and M9 series. From the figures, it can be seen that for the two series, the MPC mortars with 30%-50% fly ash exhibit higher strength than the sample without fly ash, and the highest strength occurred at the samples with 40% fly ash. To the mortars made from M9, from 10%-40% of FA, the strength gradually increases with the addition of fly ash at all ages (except M9F1 at 28 days has lower strength than that of M9F0). When the fly ash content surpasses 40%, the strength decreases. But, the strength of sample with 50% fly ash is still comparable to that of sample with 30% fly ash.

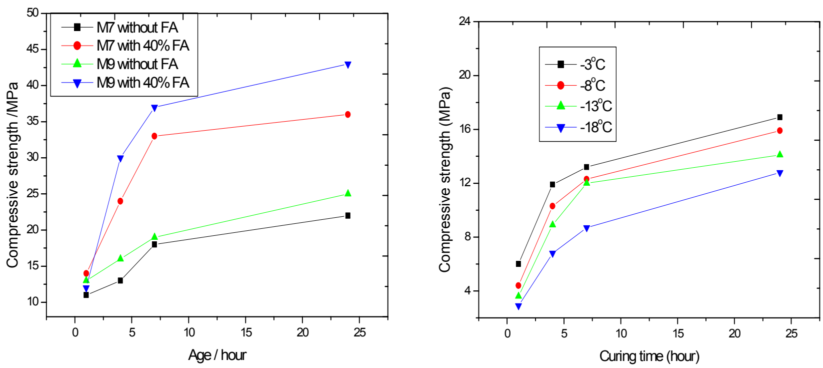


(a) M9 series sample (b) M7 series sample

Fig. 3: Strength development of MPC mortar sample

The modulus of elasticity of MPC mortar M9F0 and M9F4 was determined at age of 7 days. The elastic modulus of M9F0 and M9F4 is 27.47 and 31.85 GPa, respectively.

The compressive strength of MPC mortar at 1, 4, 7, and 24 hours under room temperature is shown in Fig. 4 (a). The specimens containing 40% FA had very fast development of strength than the specimens not containing FA, And Fig. 4 (b) was the strength development of MPC (AF content was 40%) mortar at 1, 3, 7, and 24 hours under negative temperature (After the specimens were formed they were put into the environmental chamber immediately together with molds. And they were de-molded after one hour.) The test results show that FA has the effect of reinforcement to strength, even if MPC mortar were cured under very low temperatures.



(a) Cured in room temperature (b) Cured in negative temperatures

Fig. 4: Early strength development of MPC under different temperatures

3.2.2 Durability

(1) Deicer frost scaling resistance

The deicer used here is calcium chloride ($CaCl_2$) and the concentration in water is 4% by weight of water. The MPC mortar sample and PC mortar samples together immersed completely in $CaCl_2$ solution in a plastic box, which has no cover. Then the box was placed inside the environmental room, KATO for freezing and thawing. After these samples were frost (-18^oC) for 16 hours, they were removed from the environmental room and placed in laboratory air at normal condition for 8 hours, which is a freezing-thawing cycle. Add water each cycle as necessary to maintain the proper depth of solution. Repeat the cycle daily. The surfaces of samples were flushed off thoroughly at the end each 5 cycles. Compressive strength was determined of MPSC mortar after following every curing stage: (I) The sample of MPSC mortar formed after 3 days, and 7 days for PC mortar; (II) These samples were suffered 30 freezing-thawing (FT) cycles; (III) The same above samples were cured 30 days under normal conditions; (IV) After that, the samples were tested after aging 60 days under normal condition.

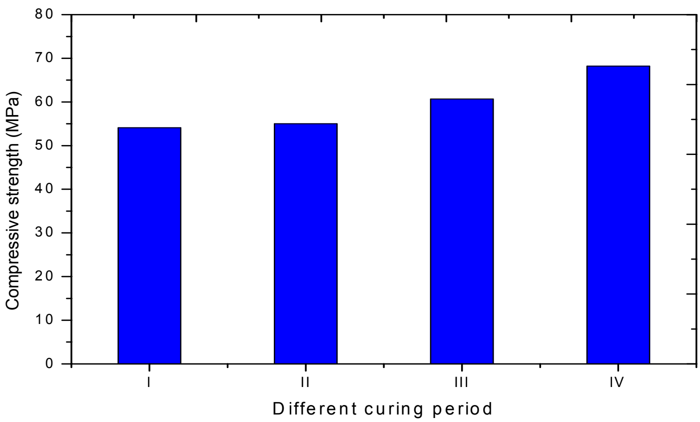


Fig. 5: Strength of MPC after FT salt scaling cycles

The compressive strength of MPC mortar was 54.1 MPa after hydration 3 days, and strength of PC mortar was 59.8 MPa for after hydration 7 days. They had the comparable strength when they were suffered FT cycles at same time. After 30 FT cycles, the surface of PC mortar samples were severe scaled and cannot be used to determine compressive strength (due to the very rough surfaces). However, the surface of MPC mortars is intact, smooth as the surfaces before FT cycles. This indicates that MPSC mortar has a superior deicer scaling resistance to PC mortar. The compressive strength test result, Fig. 5, showed that the strength of MPC sample increased a little after 30 FT cycles, comparing to the 3-day strength. Furthermore, the strength can increase continually when MPSC samples were set in normal condition after the FT cycles. This shows that the microstructure of MPC mortar was not damaged also after 30 FT cycles.

The resistance of concrete to freezing and thawing mainly depends on its degree of saturation and the pore system of the hardened cement paste. If concrete is never going to be saturated, there is no danger of damage from freezing and thawing. Even in a water cured specimen, not all residual space is water-filled and indeed this is why such a specimen does not fail on first freezing. Space available for expelled water must by close enough to the cavity in which ice is being formed, and this is the basis of air entrainment: if the hardened cement paste is subdivided into sufficiently thin layers by air bubbles, it has no critical saturation.

When the dilating pressure in the concrete exceeds its tensile strength, damage occurs. The extent of the damage varies from surface scaling to complete disintegration as ice is formed, starting at the exposed surface of the concrete and progressing through its depth. Each cycle of freezing causes a migration of water to locations where it can freeze. These locations include fine cracks, which become enlarged by the pressure of the ice and remain enlarged during thawing when they become filled with water. Subsequent freezing repeats the development of pressure and its consequences. When salts are used for deicing road or bridge surface, some of these salts become absorbed by the upper part of the concrete. This produces a high osmotic pressure, with a consequent movement of water toward the coldest zone where freezing takes place, which aggravates the scaling condition of concrete.

The reason of MPSC mortar posseses higher deicer scaling resistance than PC mortar can be attributed two aspects. First is less water inside the former than in the latter. Usually, the water to binder ratio of MPSC mortar was around 0.20, but for portland cement mortar it was around 0.44. Therefore, the former has denser microstructure than the latter. MIP test result indicates that the total porosity of MPC paste is about 9 percent by volume, while the total porosity of PC paste is about 20 percent by volume. The second reason is that there are many closed pores inside the MPC paste, very like the entrained PC concrete. These closed pores can prohibit water permeates into the inner of MPC matrix. The specimens were far from saturation of water.

(2) Wet-dry cycles in fresh water and natural sea water

The compressive strengths were determined at the end of each following curing stages: (I) After the MPC mortar samples were formed 3 days; (II) They were immersed in fresh water (FW) and sea water (SW) respectively, under room temperature. One wet-dry cycle kept 24 hours, including 12 hours in air and immersing in water 12 hours. The samples were put in water and taken out manually every day during wet-dry cycle; (III) Then those samples were set in lab air for another 30 days and test strength; (IV) After that, the samples were immersed in FW and SW for another 60 days, respectively.

Fig. 6 shows the strength development after wet-dry cycles in FA and SW. After 30 wet-dry cycles in FW and SW, the strength of MPC samples even increased a little. After then, the strengths of MPSC mortars recovered and continued increasing when set in lab air for another 30 days. However, when the MPSC samples were immersed in FA and SW for 60 days again, the strength reduced. The result shows that there is no inverse effect under the wet-dry cycle in FW or SW. However, the strength reduced some when they were immersed in water for a long time, though the deduction of strength was not larger 17.0%. MPCs were suitable utilized in the environments that are dry or wet-dry alternatively.

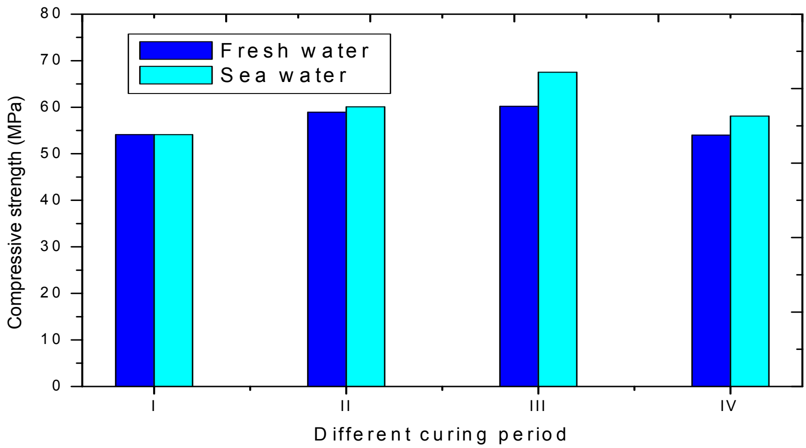


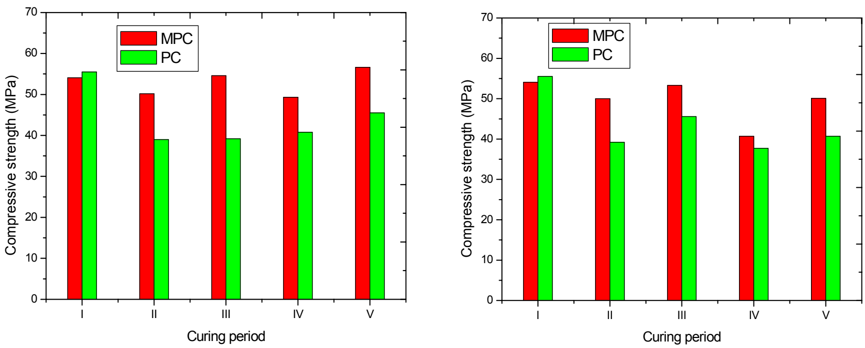
Fig. 6: Strength of MPC after wet-dry cycles in fresh water and sea water

(3) Sulfate attack resistance test
The compressive strength was determined after each following stage: (I) After 3 days formed for MPC, 7 days for the PC mortar samples after they were molded, respectively; (II) The MPC mortars were immersed completely in solution of sodium sulfate (NS) and magnesium sulfate (MS) respectively, their concentration is 5 wt%. MPC mortars were immersed 30 days in the two solutions; (III) The same samples set in normal condition for another 30 days; (IV) Afterwards, all the mortars immersed in the corrosive solutions for 60 days; (V) At last, those specimens were set in lab air for 90 days.

After immersing 30 days in the NS solutions, comparing with the strength at 3 days, the strength of MPC sample increased. But, after 30 days immersed in solution of

MS, strength of CON decreased 7.2%. However, the strength loss of PC mortar is 29.4%; see Fig. 7.

After then, the corroded samples set in normal condition, the strengths of MPC mortar increase continually, and surpass their strengths at 3d. However, the strength of PC sample basically did not recover anymore. This indicated that the microstructure of MPSC can recover when separated from the attacking agents; however, the microstructure of PC had been damaged in the attacking agents. Then, these samples were immersed the sulfate solution again for another 30 day, respectively. The strength of MPC and PC decreased once more. However, after the specimens were put in lab air for another 90 days, the strength of MPC recovered much more (even catch up with the un-eroded specimens), the strength of PC mortar only recovered a little. From the results, it can be deduced that MPC sample has more resistance to NS attach than MS attack. In spite of which type of sulfate solution, MPC posses high salt attack resistance than PC mortar in the present research.



(a) After attacked in NS (b) After attacked in MS

Fig. 7: Strength development after attacked by sulfate solutions

4. Conclusions

Geopolymer is a type of amorphous alumino-silicate cementitious material. Geopolymer can be synthesized by polycondensation reaction of geopolymeric precursor, and alkali polysilicates. Comparing to portland cement, the production of geopolymers consume less energy and almost no CO_2 emission. Geopolymers are not only energy efficient and environment friendly, but also have a relative higher strength, excellent volume stability, better durability, good fire resistance, and easy manufacture process. Thus geopolymer will become one of the perspective sustainable cementitious materials in 21st century.

As a new sustainable cementitious materials, MPCs have much beneficial advantages in environments. Not only non-toxic wastes can be transferred into useful building materials, but also the toxic and/or radioactive waste can be solidified and stabilized safely with MPCs. Furthermore, MPC can incorporated with natural organic fibers to form composites, light weight or insulation materials. These natural organic fibers are not suitable bonding with portland cement. This is very meaning to the recycling of agricultural organic fibers in larger degree.

MPCs are high early strength and quick setting, very suitable to repair highways, airport runways, and bridges that are busy for transportation. The short waiting time for repairing means that saving lot of costs. In addition, MPCs have very good durability. Such as higher freezing-thawing and scaling resistance, low permeability, higher abrasion resistance, higher ability of sulfate attack resistance. MPCs are very suitable utilized in severe environments, such as frosty areas and corrosive conditions.

References

1. Mehta, P. K. Advanced cements in concrete technology, *Concrete Internationa*l, June 1999, 69-76.
2. J. Davidovits. "Geopolymers and geopolymeric new material." *Journal of Thermal Analysis* Vol. 35, 1998, 29-441.
3. J. Davidovits. Geopolymer chemistry and properties. *Proceedings of the First European Conference on Soft Mineralogy*, Vol.1, 1988, 25-48.
4. J. Davidovits. Recent progresses in concretes for nuclear waste and uranium waste containment. *Concrete Internationa*l, Vol.16, No. 12, 1994, 53-58.
5. J. Davidovits. High alkali cements for 21st century concretes. C*oncrete Technology, Past, Present, and Future*, ed. P.K. Mehta, pp. 383-397, American Concrete Institute, Detroit ,SP-144, 1994.
6. R.E. Lyon, A Foden, P.N. Balaguru, M. Davidovits, and J. Davidovits. Fire-resistant Aluminosilicate Composites. *Journal Fire and Materials*, Vol. 21, 1997, 67-73.
7. J. Davidovits. Technical data sheet for geopolymeric cement type (Potassium, Calcium)-Poly(sialate-siloxo), Proceedings of Geopolymere '99, GEOCISTM, GLOBAL WARMING, NASTS award, 1994.
8. J. Davidovits. Properties of geopolymer cements. *Alkaline Cements and Concretes,* KIEV Ukraine, 1994, 9.
9. Kingery, W. D. Fundamental study of phosphate bonding in refractories: I, literature review. *Journal of the American ceramic society* 33(8), 1950, 239-50
10. Suguma, T., and Kukacka, L. E. Magnesium monophosphate cements derived from diammonium phosphate solutions. *Cement and concrete research* 13, 1987, 407-416.

11. Suguma, T., and Kukacka, L. E. Characteristics of magnesium polyphosphate cements derived from ammonium polyphosphate solutions. *Cement and Concrete Research* 13, 1987, 499-506.
12. Abdelrazig, B. E. I., and Sharp, J. H. A discussion of the papers on magnesia-phosphate cements. *Cement and Concrete Research* 15, 1985, 921-922.
13. Popovics, S; Rajendran, N., and Penko, M. Rapid hardening cements for repair of concrete. *ACI Materials Journal*, Jan-Feb. 1987, 64-73.
14. Abdelrazig, B.E. I, and Sharp, J. H. Phase changes on heating ammonium magnesium phosphate hydrates. *Thermochimica Acta* 129, 1988, 197-215.
15. Ramey, E. G., Moore, Raynond. K., Parker, Frazier. J.R., and Strickland, A. Mark. Laboratory evaluation of four raped setting concrete patching materials. *Transportation Research Record* 1041, 47-52.
16. Abdelrazig, B.E. I., and Sharp, J. H., and El-Jazairi, B. The chemical composition of mortars made from magnesia-phosphate cement. *Cement and Concrete Research* 18, 1988, 415-425.
17. Yoshizake, Y; Ikeda, K; Yoshida, S; and Yoshizumi, A. Physicochemical study of magnesium-phosphate cement. *MRS Int'l. Mtg. On Adv.*. Vol. 13, 1989, 27-38.
18. Abdelrazig, B.E. I., Sharp, J. H. and El-Jazairi, B. The microstructure and mechanical properties of mortars made from magnesia-phosphate cement. *Cement and Concrete Research* 19, 1989, 247-258.
19. Sarker, A. K. Phosphate cement-based fast-setting binders. *Ceramic Bulletin* 69(2), 1990, 234-238.
20. Sarker, A. K. Hydration/dehydration characteristics of struvite and dittmarite pertaining to magnesium ammonium phosphate cement systems. *Journal of Materials Science* 26, 1991, 2514-2518.
21. Seehra, S. S., Gupta, S. and Kumar, S. Rapid setting magnesium phosphate cement for quick repair of concrete pavements – characterization and durability aspects. *Cement and Concrete Research* 23, 1993, 254-266.
22. Bensted, J. A discussion of the paper "Rapid setting magnesium phosphate cement for quick repair of concrete pavements: characterization and durability aspects". *Cement and Concrete Research* 24, 1994, 595-596.
23. Sarker, A. Investigation of reaction/bonding mechanisms in regular and retarded magnesium phosphate cement systems. *Cement Technology*, 1994, 281-288
24. Hall, David. A; and Stevens, Ronald. Effect of water content on the structure and mechanical properties of magnesia-phosphate cement mortar. *Journal of the American Ceramic Society* 81(6), 1998, 1550-56.
25. Yang, Quangbing, and Wu, Xueli. Factors influencing properties of phosphate cement-based binder for rapid repair of concrete. *Cement and Concrete Research* 29, 1999, 389-396.
26. Soudee, E., and Pera, J. Mechanism of setting reaction in magnesia-phosphate cements. *Cement and Concrete Research* 30, 2000, 315-321.

27. Yang, Quangbing, Zhu, Beirong, Zhang, shuqing, and Wu, Xueli. Properties and applications of magnesia-phosphate cement mortar for raped repair of concrete. *Cement and Concrete Research* 30, 2000, 1807-1813.
28. Jiang, H.Y., and Zhang, L. M. Research of magnesium phosphate cement. *Journal of Wuhan University of Technology* 23(1), 2001, 32-34.
29. Jiang, H. Y., Liang, B., and Zhang, L.M. Investigation of MPB with super early strength for repair of concrete. *Journal of Building Materials* 4(2), 2001, 196-198.
30. Hall, David. A, Stevens, R., and El-Jazairi, B. The effect of retarders on the microstructure and mechanical properties of magnesia-phosphate cement mortar. *Cement and Concrete Research* 31, 2001, 455-465.
31. Soudee, E., and Pera, J. Influence of magnesia surface on the setting time of magnesia-phosphate cement. *Cement and Concrete Research* 32, 2002, 153-157.
32. Yang, Quangbing, Zhang, Shuqing, and Wu Xueli. Deicer- scaling resistance of phosphate cement-based binder for rapid repair of concrete. *Cement and Concrete Research* 32, 2002, 165-168.
33. Singh, D., Wagh, A., Cunnane, J., and Mayberry, J. Chemically Bonded Phosphate Ceramics for Low-Level Mixed-Waste Stabilization. *J. Environ. Sci. Health*, A32(2), 1997, 527-541.
34. Wagh, A., Strain, R., Jeong, S., Reed, D., Krouse T., and Singh, D. Stabilization of Rocky Flats Pu-Contaminated Ash within Chemically Bonded Phosphate Ceramics, *J. Nucl. Mat*., 265, 1999, 295-307.
35. J. Davidovits. Geopolymer cement to minimize carbon-dioxide greenhouse-warming. *Ceramic Transactions*, Vol. 37, 1993, pp.165-182.
36. J. Davidovits. 'Gopolymers: Inorganic polymeric new materials'. *Journal of. Materials Education*, Vol.16, 1994, 91-139.
37. J. Davidovits, Douglas C. Comrie, John H. Paterson, and Douglas J. Ritcey. Geopolymeric concretes for environmental protection. *Concrete International: Design & Construction*, Vol.12, No.7, July 1990, pp. 30-40.
38. J.G.S. Van Jaarsveld, and J.S.J. Van Deventer. The effect of metal contaminants on the formation and properties of waste-based geopolymers. *Cement and Concrete Research.* 29, 1999, 1189-1200.
39. J.G.S. Van Jaarsveld, J.S.J. Van Deventer,and L. Lorenzen. Factors affecting the immobilization of metals in geopolymerized fly ash. *Metallurgical and Materials Transactions B*. Vol. 29B, Feb. 1998, 283-291.
40. J.G.S. Van Jaarsveld, J.S.J. Van Deventer. The potential use of geopolymeric materials to immobilize toxic metals: Part I. Theory and Applications. *Minerals Engineering,* Vol. 10, No. 7, 1997, 659-669.
41. J.G.S. Van Jaarsveld, J.S.J. Van Deventer, and A. Schwartzman. The potential use of geopolymeric materials to immobilize toxic metals: Part II. Material and Leaching Characteristics. *Minerals Engineering,* Vol. 12, No. 1, 1999, 75-91.

42. European R&D project BRITE-EURAM BE-7355-93: Cost-effective Geopolymeric cement for innocuous stabilization of toxic elements (GEOCISTEM). Final Report, April 1997.
43. Comrie Preliminary examination of the potential of geopolymers for use in mine tailings management, D. Comrie Consulting Ltd., Mississauga, Ontario, Canada, 1988.
44. Lyon, R.E. Technical Report DOT/FAA/CT-94/60, 1994.
45. J. Davidovits, and M. Morris. *The pyramids: An enigma solved*, Hippocrene Books, Inc., New York, 1988.
46. J. Davidovits. Ancient and modern concretes: what is the real difference? *Concrete International: Design & Construction*, Vol.9, No. 12, Dec. 1987, pp. 23-35.
47. Margie Morris. The cast-in-place theory of pyramid construction. *Concrete International: Design & Construction*, Vol.13, No. 8, 1991, pp. 29, 39-44.
48. Margie Morris. Archaeology and technology. *Concrete International: Design & Construction*, Vol. 9, No.12, Dec.1987, pp. 29-35.
49. Campbell D.H., and Folk R.L. The ancient pyramids—concrete or rock. *Concrete International: Design & Construction*, Vol.13, No.8, 1991, pp. 28-39.
50. J. Davidovits. Great pyramids debate. *Concrete International*, Vol. 14, No.2, 1992, 17-18.
51. M. Morris. Geopolymeric pyramids—A rebutal to Folk R.L., Campbell D.H. *Journal of Geological Education*, Vol.40, 1992, 28-39 and 344-346.
52. Folk R.L., and Campbell D.H. Are the pyramids built of poured concrete blocks? *Journal of Geological Education*, Vol.40, 1992, 25-34 and 344.
53. Harrell, J.A., and Penrod B.E. The great pyramid debate –Evidence from the Lauer sample. *Journal of Geological Education*, Vol.41, 1993, 358-363.
54. Mckinney R.G. Comments on the work of Harrell and Penrod. *Journal of Geological Education*, Vol.41, 1993, p. 369.
55. M. Morris. How not to analyze pyramid stone. *Journal of Geological Education*, Vol.41, 1993, pp. 364-369.

PROPERTIES OF LIGHTWEIGHT CONCRETE MANUFACTURED WITH FLY ASH, FURNACE BOTTOM ASH, AND LYTAG

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Abstract

Fly ash (FA), furnace bottom ash (FBA) and Lytag (LG) were used in the current study to replace ordinary portland cement (OPC), natural sand (NS) and coarse aggregate (CA), respectively, and thereby to manufacture lightweight concrete (LWC). Two control mixes containing no replacement materials were designed with a 28-day compressive strength of 20 N/mm^2 and 40 N/mm^2. For each compressive strength, three different mixes, viz. (a) 100%OPC+100%NS + 100%CA, (b) 100%OPC + 100%FBA + 100%LG and (c) 70%OPC + 30%FA + 100%FBA + 100%LG, were manufactured with slump in the range of 30 ~ 60 mm. The density, compressive strength, pull-off surface tensile strength, air permeability, sorptivity and porosity of the concretes were investigated.

The results indicated that it is possible to manufacture lightweight concrete with density in the range of 1560-1960 kg/m^3 and 28-day compressive strength in the range of 20-40 N/mm^2 with various waste materials from thermal power plants. However, the introduction of FBA into concrete would cause detrimental effect on the permeation properties of concrete. With part of OPC replaced with FA, the strength decreased, but the permeability of the resulting concrete improved.

1. Introduction

Lightweight concrete (LWC) has been successfully used since the ancient Roman times and it has gained its popularity due to its lower density and superior thermal insulation properties [1]. Compared with normal weight concrete (NWC), LWC can significantly reduce the dead load of structural elements, which makes it especially attractive in multi-storey buildings. However, most studies on LWC concern "semi-lightweight" concretes, i.e. concrete made with lightweight coarse aggregate and natural sand. Although commercially available lightweight fine aggregate has been used in investigations in place of natural sand to manufacture the "total-lightweight" concrete [2, 3], more environmental and economical benefits can be achieved if waste materials can be used to replace the fine lightweight aggregate.

Lytag is one of the most commonly used lightweight aggregates, which is manufactured by pyro-processing fly ash (FA), while FA and furnace bottom ash (FBA) are two waste materials from coal-fired thermal power plants. They are, respectively, lighter than traditional coarse aggregate, OPC and natural sand. The previous investigations carried out by the authors on using FBA from a thermal power plant in Northern Ireland as a sand replacement material indicated that FBA could be a potential fine aggregate in NWC for certain applications [4, 5]. However, the application of FBA in structural LWC is not well defined. Therefore, the current study investigates the possibility of manufacturing structural LWC with FA, FBA and Lytag

2. Experimental Program

2.1 Materials

The cement used was the Class 42.5N portland cement supplied by Blue Circle, U.K., complying with BS 12: 1991 [6].

For the control mixes, the coarse aggregate used was 10 mm crushed basalt and the fine aggregate used was medium graded natural sand complying with BS 882: 1992 [7]. Both materials are from the local sources in Northern Ireland. They were oven dried at 40^{o}C for 24 hours and cooled to 20^{o}C before using in the manufacture of concrete. The FA and FBA used were supplied by Kilroot Power Station in Northern Ireland, U.K. The FBA was dried firstly in an oven at 105^{o}C for 24 hours and then allowed to cool for 24 hours at 20^{o}C. The FBA that passed 5 mm sieve (hereafter FBA sand) was used to replace natural sand. The Lytag used was with a size of 8 mm and was supplied by Finlay Concrete Products, Northern Ireland, U.K. It was also oven dried at 40^{o}C for 24 hours and cooled to 20^{o}C before casting. Table 1 reports the chemical compositions of OPC, FA, FBA and Lytag. The specific gravity and 1-hour water absorption of basalt, natural sand, FBA sand and Lytag are reported in Table 2. Fig. 1 presents the particle size distribution of basalt, natural sand, FBA sand and Lytag.

2.2 Mix proportions

Two control mixes containing OPC, basalt and natural sand were designed for a 28-day compressive strength of 20 N/mm^2 (Series M) and 40 N/mm^2 (Series H) respectively, for a slump in the range of 30-60 mm. For each control mix, 30% of OPC, 100% of natural sand, and 100% of basalt were then replaced with FA, FBA, and Lytag, respectively. The binder content (OPC or OPC + FA) was kept the same as that of the control mix for each series when the natural sand and basalt were replaced with FBA and Lytag, respectively.

Table 1: Chemical composition of cement, PFA, FBA, and Lytag

Oxide composition (%)	OPC	FA	FBA	Lytag
SiO_2	20.6	59.01	61.78	53.19
Al_2O_3	5.7	22.8	17.8	26.3
Fe_2O_3	2.9	8.8	6.97	10.26
CaO	63.6	2.38	3.19	2.02
MgO	1.8	1.39	1.34	1.45
Na_2O	0.12	0.74	0.95	0.96
K_2O	0.75	2.8	2	3.99
SO_3	3.2	0.27	0.79	-
Cl	0.01	0.01	-	-
LOI	1.5	6.7	3.61	4

Table 2: Property of aggregates

Property	Basalt	Natural sand	FBA sand	Lytag
Specific gravity (S.S.D.)	2.91	2.66	1.58	1.52
1-hour water absorption (%)	1.1	1.1	32.2	12.31

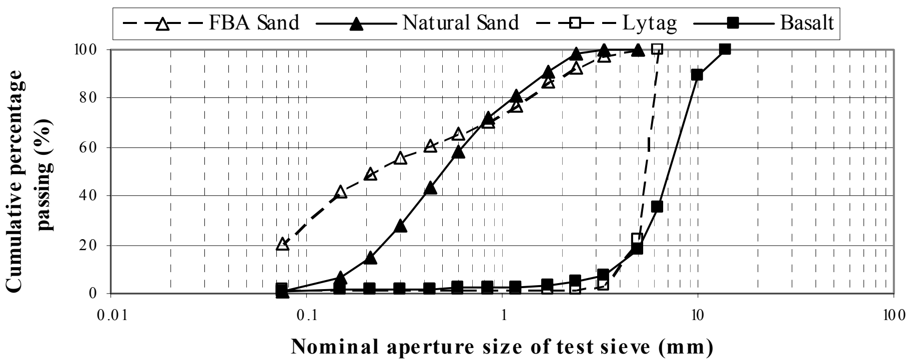


Fig. 1: Particle distribution of FBA sand, natural sand, Lytag, and basalt

For each series, three different mixes were studied. Mix 1: 100%OPC+100%NS+100%CA (control). Mix 2: 100%OPC+100%FBA+100%LG. Mix 3: 70%OPC+30%FA+100%FBA+100%LG. The water content (and therefore W/C) of Mix 2 and Mix 3 was adjusted by carrying out trials so that the workability measured in terms of slump was in the range of 30-60mm. The volume ratio between the fine aggregate and the coarse aggregate for each test series was kept the same as that obtained for the respective control mix. The resulting mix proportions, which were used in this investigation, are reported in Table 3.

Table 3: Mix proportions (kg/m^3) and properties of fresh concretes

Mix No	W/C	Cement	FA	Free Water	Sand	FBA	Basalt	Lytag	Measured Slump (mm)	Measured Air Content (%)
M1	0.65	330	-	215	820	-	1040	-	27	2
M2	0.4	330	-	132	-	552	-	616	51	5
M3	0.32	231	99	106	-	562	-	627	43	5
H1	0.47	460	-	215	715	-	1025	-	50	1.2
H2	0.32	460	-	147	-	477	-	602	30	5
H3	0.29	322	138	133	-	473	-	599	34	5

2.3 Batching and mixing

For each mix, the required quantities of the constituents were batched by weight. The water required for 1-hour absorption by the aggregates (basalt, natural sand, FBA sand and Lytag) was added to the mix water in addition to the free water shown in Table 3. Different mixing procedures were used for NWC and LWC, which are described below.

Mixing procedure for NWC (control): The manufacturing of NWC was carried out based on reference 8. Approximately half the basalt, all the natural sand and the remaining basalt were added, in this order, evenly into the pan. The aggregates were mixed for 30 seconds. The mixing was continued and about half the mixing water (i.e. free water as shown in Table 3 plus that required for 1 hour water absorption) was added during the next 15 seconds. After mixing for a total of 3 minutes, the mixer was stopped and the contents were left covered for 15 minutes. The cement was then added evenly over the aggregate. The mixer was started and the mixing was continued for 30 seconds. The mixer was then stopped and any material adhering to the mixer blades were cleaned off into the pan. Without delay, the mixing was recommenced and the remaining mixing water was added over the next 30 seconds. The mixing was continued for 3 minutes after all the materials were added.

Mixing procedure for LWC: The procedure given in the Lytag Information Document [9] was used to modify the manufacturing procedure for the LWC. About half the mixing water (free water as shown in Table 3 plus that required for 1 hour water absorption) was added. Then all the Lytag and all the FBA were added in this order, evenly into the pan [9] and mixed for 3 minutes. The mixer was stopped and left covered for 15 minutes. Thereafter, the procedure was the same as that for the NWC.

2.4 Specimen preparation and curing

For each mix, nine 100-mm size cubes were cast to determine the compressive strength at the age of 3, 7, and 28 days. At 28 days, the same cubes used for compressive strength were also used to test the density at saturated-surface dried (SSD) condition. Three 250x250x110-mm slabs were cast to investigate pull-off tensile strength, permeation properties and porosity of the concrete at the age of 28 days.

All specimens were cast in two layers and compacted on a vibrating table until air bubbles appearing on the surface stopped. They were left in the mould in the laboratory at 20(±1)^{o}C for one day and then removed from the moulds. After that, they were cured in water at 20(±1)^{o}C for two days, and then wrapped in polythene sheet and left in the laboratory at 20(±1)^{o}C until they were tested. (The three-day specimens were tested immediately after removing from the water bath, instead of wrapping in polythene sheet.)

2.5 Details of tests

For each mix, the air content and workability (in terms of slump) of the fresh concrete were measured. The air content was measured by following a procedure given in BS 1881: part 106: 1983 [10]. The slump test was carried out in accordance with BS 1881: Part 102: 1983 [11].

At the age of 3, 7, and 28 days, the compressive strength was determined by crushing three 100-mm cubes in accordance with BS 1881:Part 116: 1983 [12] and an average of the three values was obtained. Prior to the compressive strength test at the age of 28 days, the cubes were used to test the SSD density by following BS 1881: Part 114: 1983 [13].

At the age of 28 days, the slabs were dried at 40(±1)^{o}C and 22(±1)% Relative Humidity (RH) in a drying cabinet for two weeks and then cooled to room temperature 20(±1)^{o}C for one day. The air permeability and water absorption (sorptivity) were tested on three slabs per mix by using the "Autoclam Permeability System" [14] on the mould finished face and average values of both the air permeability and the sorptivity were calculated. The surface tensile strength was measured by carrying out the Limpet pull-off test [15] at two locations on the mould finished surfaces of the three slabs immediately after the permeation test. All the six results were averaged and reported. After the pull-off test, one Φ75-mm core was taken from each of the slab and the water absorption test was carried out by following BS 1881: Part 122: 1983 [16]. The porosity of the concretes was then calculated based on the volume of the voids occupied by the absorbed water.

3. Results and Discussion

3.1 Properties of fresh concrete

Fig. 2 shows the free water content for different mixes. It can be seen that when the FBA sand and Lytag were used to replace natural sand and basalt, respectively, the water demand of the concrete decreased. This is attributable to the spherical/round particle shape of both FBA sand and Lytag [4, 17], which, compared to the angular particles of sand and basalt, have a “ball-bearing effect” and thus reduce the water demand of the fresh concrete. When 30% of the OPC was replaced with FA in both series, there was also a water reduction compared to the mix 2. This is again attributable to the “ball-bearing effect” of the FA particles. Therefore, it can be seen from the above results that when FA, FBA and Lytag were used to manufacture lightweight concrete, the water demand of the concrete decreased.

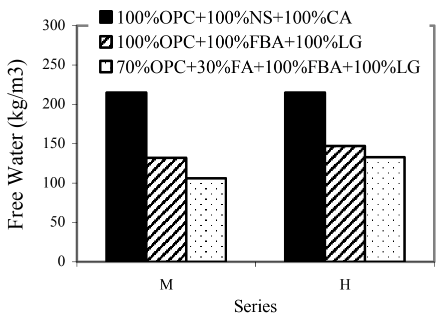


Fig. 2: Free water content of NWC and LWC

3.2 Density

Table 4 reports the density of hardened concrete at saturated-surface dried (SSD) condition measured at 28 days. It can be seen that when natural sand and basalt were replaced with FBA sand and Lytag respectively, there was a significant reduction in the density of hardened concrete for both series. This suggests that the low density of both FBA sand and Lytag is beneficial to produce LWC. When FA was used in mix 3 to replace 30% of the OPC, the density was further reduced. This, again, is due to the lower density of FA compared to that of OPC. Thus, it can be concluded that the low density of FA, FBA and Lytag is a benefit for manufacturing lightweight structural concretes. In the current study, the SSD density in the range of 1560-1960 kg/m^3 was achieved.

Table 4: Density (kg/m^3) of hardened concrete at 28 days (SSD)

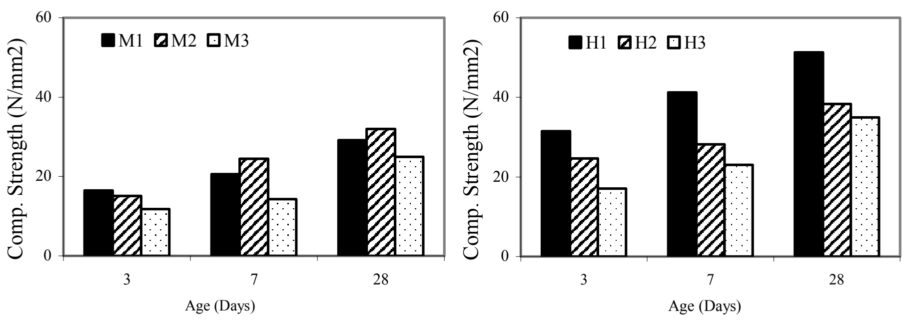
M1	M2	M3	H1	H2	H3
1977	1725	1559	2471	1952	1819

3.3 Compressive strength

Fig. 3 presents the compressive strength of both series at 3, 7, and 28 days. Fig. 4 illustrates the relationship between the 28-day compressive strength and the SSD density. In Fig. 5, the contribution of different mix to the compressive strength is compared in terms of the specific strength, i.e., ratio of strength to relative density.

From Fig. 3 it can be seen that when the FBA sand and Lytag were used to replace natural sand and basalt respectively, different effects can be observed for series M and H. In series H, the compressive strength decreased from H1 to H3 at all the ages. However, in series M, this trend was visible only for the 3-day results. At the age of 7 and 28 days, there was an increase in strength when the NS and CA were replaced with FBA and Lytag, respectively.

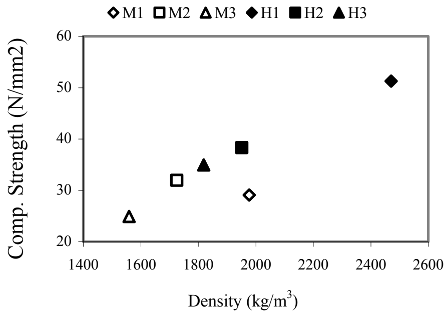
As indicated in Fig. 4, except for one data point corresponding to mix M1, there is a linear relationship between the density and the compressive strength, i.e. the compressive strength is directly proportional to the SSD density of hardened concrete. This indicates that the lightweight was achieved at the cost of reduction in the compressive strength. Nevertheless, it is still possible to manufacture LWC with SSD density in the range of 1560-1960 kg/m^3 and 28-day compressive strength in the range of 20-40 N/mm^2.



(a) Series M

(b) Series H

Fig. 3: Compressive strength of NWC and LWC



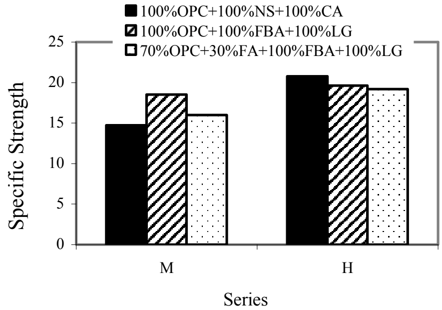


Fig. 4: Compressive strength vs. density Fig. 5: Specific strength of NWC & LWC

Fig. 5 indicates that the specific strength for M2 and M3 are higher than M1, which suggests that for the same weight of concrete, LWC provided marginally higher compressive strength than NWC. For series H, the specific strength for H2 and H3 are lower than H1. However, the difference was small. Therefore, it can be concluded that FA, FBA and Lytag can be favorably used to manufacture medium strength LWC. In the case of high strength concrete, these replacements would result in decrease in compressive strength of the concrete.

3.4 Pull-off surface tensile strength

Fig. 6 presents the results of the pull-off test. It can be seen that, for Series M, the surface tensile strength of M2 and M3 are higher than that of M1, and that of M2 is equal to that of M3. However, for Series H, the pull-off tensile strength of H2 and H3 are lower than that of H1, and the value for H3 is also lower than that for H2. Thus, in terms of the pull-off surface tensile strength, FA, FBA and Lytag have a beneficial effect on medium strength LWC, but a slightly adverse effect on high-strength LWC.

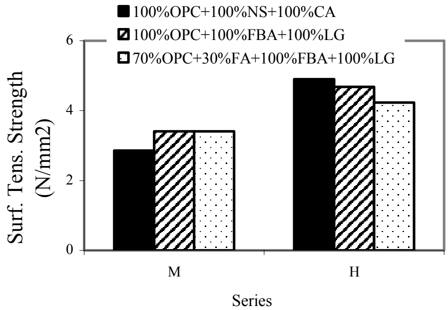


Fig. 6: Surface tensile strength of NWC and LWC

3.5 Permeability

The near surface permeation property was evaluated by using the "Autoclam Permeability System." Figs. 7 and 8 show the air permeability and sorptivity results, respectively.

It can be seen that when FBA sand and Lytag were used to replace natural sand and basalt to manufacture LWC, the air permeability dramatically increased. From Fig. 2, it can be seen that, due to the water reduction effect of FBA and Lytag, the free water of mix 2 for both series is lower than mix 1. Since the binder content was the same for all the mixes in each series, the decreased free water content would result in a decreased free water-binder ratio, which should have decreased the air permeability [18]. In addition, although the particles of Lytag are quite porous [17], they have no effects on the air permeability of LWC [19]. Thus, the increased air permeability should be attributable to the porous particles of the FBA sand [5]. However, the air permeability indices of Mix 3 for both series are lower than mix 2, but still higher than mix 1. The decrease of the air permeability indices of mix 3 can be considered to be due to the physical filling effect and pozzolanic reaction of FA, leading to the densification of the pore structure. This reveals that the increased air permeability caused by the porous FBA particles can partly be compensated by the FA. However, since the slabs were only 28 days old, the pozzolanic reaction has not fully developed. Thus, a long-term study is required in order to investigate any possible further beneficial effect of FA on the LWC.

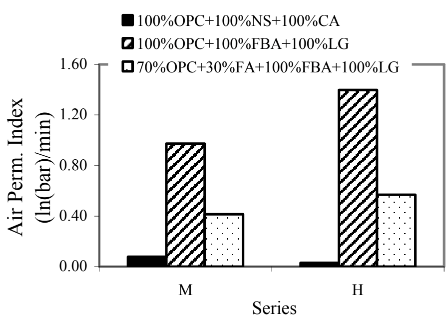


Fig. 7: Air permeability of NWC & LWC

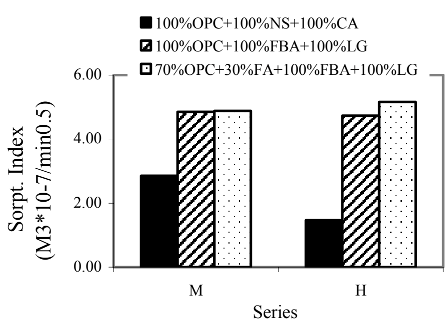


Fig. 8: Sorptivity of NWC & LWC

The sorptivity result in Fig. 8 indicates that when natural sand and basalt were replaced with the FBA sand and Lytag, the sorptivity indices for both series were higher than the corresponding control (mix 1). This is mainly attributable to the porous FBA and Lytag particles. However, when FA was used in mix 3 to replace 30% of the OPC, the sorptivity did not decrease as it did in air permeability. Thus, the FA has no beneficial effect on reducing the sorptivity of LWC at 28 days. On the contrary, the sorptivity increased. Again a long-term study is required to investigate any further beneficial effect.

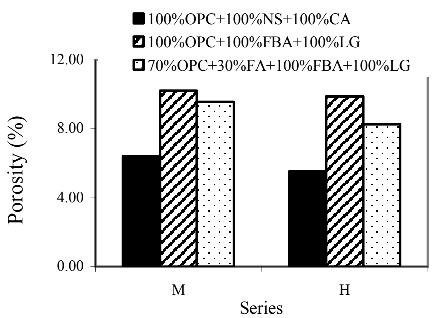


Fig. 9: Porosity of NWC & LWC

3.6 Porosity

The porosity result is reported in Fig. 9. The trend was similar to that of air permeability in Fig. 7, i.e., when natural sand and basalt were replaced by the FBA sand and Lytag respectively, the porosity of LWC increased. However, when FA was used in mix 3 to replace cement, the porosity was lower than mix 2, but still higher than mix 1 for both series. The result further confirms that whereas FBA sand and Lytag increase the porosity of LWC, the FA would partly compensate the detrimental effect caused by FBA sand and Lytag on the porosity and air permeability.

4. Conclusions

- By using FA, FBA and Lytag, it is possible to manufacture lightweight concrete with density in the range of 1560-1960 kg/m^3.
- In terms of contribution to the compressive strength by per unit weight of concrete, FA, FBA, and Lytag can be beneficially used to manufacture medium strength concrete.
- LWC incorporating FBA and Lytag resulted in an increase in the permeability; by replacing 30% of OPC with FA, the permeability of LWC could be improved.
- In order to manufacture durable LWC, measures should be taken to further improve the permeation property.

Acknowledgments

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References

1. Chandra, S. and Berntsson, L. *Lightweight aggregate concrete: science, technology and applications*. Noyes Publications.
2. Berra, M. and Ferrara, G. "Normal weight and total-lightweight high-strength concretes: A comparative experimental study," SP-121, 1990, pp.701-733.
3. Kayali, O.A. and Haque, M.N. "A new generation of structural lightweight concrete," *ACI*, SP-171, 1997, pp. 569-588.
4. Bai, Y. and Basheer, P.A.M. "Influence of Furnace Bottom Ash on properties of concrete," *Proceedings of the Institution of Civil Engineers, Structure and Buildings* 156, February 2003, Issue 1, pp. 85-92.
5. Bai, Y. and Basheer, P.A.M. "Properties of concrete containing Furnace Bottom Ash as a sand replacement material," *Proceedings of structural faults and repair* (CD-ROM), London, July 1-3, 2003.
6. British Standards Institution. "Specification for Portland Cements," BSI, London, 1991, BS 12.
7. British Standards Institution. "Specification for Aggregates from Natural Sources for Concrete," BSI, London, 1992, BS 882.
8. British Standards Institution. "Method of Mixing and Sampling Fresh Concrete in the Laboratory," BSI, London, 1986, BS1881: Part 125.
9. "Lytag: an introduction to Lytag concrete," September, 1996.
10. British Standards Institution. "Method for Determination of Air Content of Fresh Concrete," BSI, London, 1983, BS1881: Part 106.
11. British Standards Institution. "Method for Determination of Slump," BSI, London, 1983, BS 1881: Part 102.
12. British Standards Institution. "Method for Determination of Compressive Strength of Concrete Cubes," BSI, London, 1983, BS 1881: Part 116.
13. British Standards Institution, "Methods for determination of density of hardened concrete," BSI, London, 1983, BS 1881: Part 114.
14. Basheer, P.A.M., Long, A.E. and Montgomery, F.R. "The Autoclam: A new test for permeability," *Concrete*, July/August, 1994, pp. 27-29.
15. Long, A.E. and Murray, A.M. "Pull-off test for in-situ concrete strength," *Concrete*, Dec. 1981, pp. 23-24.
16. British Standards Institution. "Method for determination of water absorption," BSI, London, 1983, BS 1881: Part 122.
17. Swamy, R.N. and Lambert, G.H. "Microstructure of Lytag aggregate," *The International Journal of Cement Composites and Lightweight Concrete* (3), November 4, 1984.

18. Long, A.E., Basheer, P.A.M. and Montgomery, F.R. "In-site permeability testing: A basis for service life prediction," Proceeding of the Third CANMET/ACI International Symposium, Aukland, New Zealand, ACI SP-171, pp. 651-670.
19. Bamforth, P.B. "The properties of high strength lightweight concrete," *Concrete* 21(4), April 1987, pp. 8-9.

STUDY OF FEASIBILITY AND MECHANICAL PROPERTIES FOR PRODUCING HIGH-FLOWING CONCRETE WITH RECYCLED COARSE AGGREGATES

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Abstract

This study uses crushed waste concrete with compressive strength ranged from 210 to 350 kgf/cm^2, as recycled aggregates to produce high-flowing concrete. Proper amount of fly ash (25%, 30%) and superplasticizer is added. The water-to-cementitious material ratio (w/cm) was 0.50, 0.55, and 0.60. The engineering properties including compressive strength, splitting tensile strength and bond strength were tested. Meanwhile, the results were compared with those from specimens made of natural-aggregate with same mix proportions.

The physical properties of recycled aggregates obtained from crushed waste concrete of this experiment meet CNS1240 (equivalent to ASTM C33) specifications and requirements. The engineering properties of concretes made from natural and recycled aggregates showed only slight differences. The utilization of recycled aggregates for high flowing concrete is confirmed and is an environment friendly material.

1. Introduction

1.1. Definition of high flowing concrete

High-flowing concrete is defined as concrete with high workability and enough cohesiveness without causing segregation and bleeding. For local needs the strength are set between 280 and 350 kgf/cm^2, cement efficiency ≥1.1 kgf/cm^2 per kg, amount of cement less than 300 kg/m^3, initial slump 220±20 mm, slump flow 500±100 mm, 45-minute slump larger than 200 mm, slump flow above 400 mm, w/c = 0.42, and pozzolan material = 30% [1].

1.2. Basic property of recycled aggregate (RA)

1) Aggregate shape and surface structure
RAs obtained from crushed waste concrete have more angles. The surface is highly porous and rough. Its length-to-width ratio is between that of gravel stones and crushed stones, and its shape is similar to that of gravel stone which meets the shape of aggregates [2].

2) Density and absorption rate of aggregates
According to the research of Hansen and Narud [3], if the weight of per unit of waste concrete ranges from 2380 to 2410 kg/m^3 (the specific weight of natural aggregate is from 2.50 to 2.61), SSD specific weight of recycled aggregate ranges from 2.34 to 2.49 (its aggregate diameter is from 16 to 32 mm) and is not affected by the source of waste concrete.
The absorption rate (AR) of recycled aggregate is higher than that of natural one. The research of Hansen and Narud [3] points out that the AR of recycled aggregate is 8.7% for diameter from 4 to 8 mm, 3.7% for diameter from 16 to 32 mm. The AR of natural aggregate is only from 0.8% to 3.7%. It is obvious that the AR of recycled aggregate is higher. It is generally suggested to wet the RA before it is used.

1.3. Property of high flowing concrete made with RA (CRA)

1) Amount of water and workability
When the aggregate is under the condition of saturated surface dry (SSD), the consistency of CRA is very similar to that of high flowing concrete made with natural aggregates (CNA), but its rate of slump and slump flow loss is higher. According to Mukai [4], to produce CRA (recycled aggregate plus natural sand) and CNA of same slump, the amount of water is increased by 10 kg/m^3 or 5% for CRA as compared to same mix proportion of CNA.

2) Water to cementitious materials ratio (w/c) and amount of cement
From literature, it is found that the relationship between compressive strength and w/c of concrete is approximately linear for both CRA and CNA. However, the strength of CRA is not as high as that of CNA. At same w/c, to produce CRA with the same workability as CNA, the amount of water is increased by 5%. The cement must be increased by 5% to keep w/c constant [2, 3].

3) Mix proportioning design
Mix proportioning design of CRA is generally similar to that of normal one, and ACI mix proportioning design method is suitable.

4) Compressive strength and strength development
According to literature [2], it is found that the strength of CRA is lower than that of CNA by 10%. If the w/c of old concrete is less than w/c of newly made CRA, the strength of the new CRA will be able to match or even exceed the strength of CNA with the same mix proportion.

5) According to Tsong, Yen [5], the variability of bond strength of CRA is higher and the strength is less than that of CNA at the same mix proportion.

2. Experimental Design

2.1. Testing materials

1) Water
   This experiment chooses tap water as mixing water of concrete.
2) Cement
   Type I portland cement, with fineness 3400 cm^2/g and specific weight 3.15.
3) Fly ash
   The fly ash for this experiment was from Linko Plant of Taiwan Power Company and with fineness 3050 cm^2/g, specific weight with 2.3 and ignition loss 4.2%.
4) Recycled aggregate
   The recycled aggregates are from concrete with compressive strength from 210 to 350 kgf/cm^2. The waste concrete was crushed by the crushers of a modern aggregate processing plant. The maximum diameter of recycled aggregate is 19 mm. The specific weight, AR, and FM are listed in Table 1, and the results of sieve analysis are shown in Fig. 1, which meet the specification of CNS 1240. Meanwhile, before mixing, the fines smaller than 75-μm sieve in recycled aggregates should be washed out to less than 1% per CNS 1240. The waste concrete of this experiment does not include other materials of constructions like paints, glasses, plastics, and bricks.
5) Natural aggregate
   The maximum diameter of natural aggregate of this experiment is 19 mm. Its property analysis is in Table 1, and sieve analysis is illustrated as Fig. 1, which meet the specification of CNS 1240.
6) Fine aggregate
   The fine aggregate of this experiment is natural river sand; its property analysis is shown in Table 1. The sieve analysis is illustrated as Fig. 1, which meets the specification of CNS 1240.
7) Reinforcing bar
   SD42 reinforcing bar with yielding stress of 5438 kgf/cm^2 is used. The elongation is 17.5% (>12%), which meets the specification of CNS 560 (equivalent to ASTM A615).
8) Superplasticizer
   Superplasticizer (SP) of G Type with sulphonated naphthalene formaldehyde condensates (SNF) as main constituents is used. The superplasticizer has a solid content 41.40% and specific weight 1.21, which meets the specification of ASTM C494.

Table 1: Physical properties of coarse and fine aggregates

Type / Property	Recycled coarse aggregate	Natural coarse aggregate	Natural fine aggregate
SSD specific weight	2.41	2.63	2.66
OD specific weight	2.29	2.61	2.63
AR (%)	5.26	0.80	1.09
FM	6.38	6.56	2.91

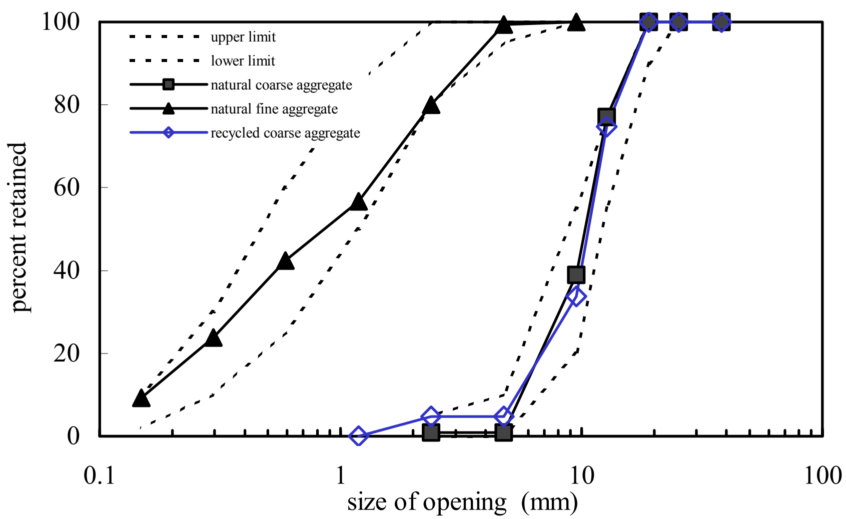

Fig. 1: Grading curve for aggregates

2.2. Mix proportioning design

This research is mainly to explore the differences between recycled-aggregate made high flowing concrete and natural-aggregate made high flowing concrete. The mix proportioning design uses ACI absolute volume method. The variables include water to cementitious ratio (w/c=0.50, 0.55, 0.60), superplasticizer (SP = 1.3%, 1.4%, 1.5%), fly ash (25%, 30%), and the value of S/A (0.40, 0.45, 0.50, 0.55), as shown in Table 2.

2.3. Tests

1) Workability

Slump and slump flow of all mix proportions were tested; the slump test is based on CNS1176 (equivalent to ASTM C143) [6] and slump flow test is based on JASS 5 T-503.

2) Curing and testing
   Specimens were made and cured according to relevant standards until the age of 28 days. Compressive strength and splitting tensile strength were then tested to find the best mix proportion for middle-and-low-strength concrete.
3) Test of bond strength
   According to CNS 11152 (equivalent to ASTM C234), each mix proportion respectively produces three cubes with sizes of 15×15×15 cm and 15×15×30 cm. Reinforcing bars were placed concrete were cast as shown in Fig. 2. When the specimens are between 7 and 14 days of age the 15×15×30-cm prisms were broken into half in flexure to form two 15×15×15 cubes.

Table 2: Mix proportion of concrete

No.	Mix proportioning no.	w/c	S/A (%)	Amount of water (kg)	SP (kg)	Cement (kg)	Fly ash (kg)	Coarse aggregate (kg)		Fine aggregate (kg)
								Natural	Recycled	
1	R50F25SP14	0.5	50	184.7	5.32	285	95	0	804	887
2	N50F25SP14			184.7	5.32	285	95	877	0	887
3	R50F30SP15			184.3	5.70	266	114	0	801	884
4	N50F30SP15			184.3	5.70	266	114	874	0	884
5	R55F25SP13	0.55	50	204.0	4.94	285	95	0	781	862
6	N55F25SP13			204.0	4.94	285	95	852	0	862
7	R55F30SP13			204.0	4.94	266	114	0	778	858
8	N55F30SP13			204.0	4.94	266	114	849	0	858
9	R55F30SP13(S40)		40	204.0	4.94	266	114	0	934	687
10	R55F30SP13(S45)		45	204.0	4.94	266	114	0	856	773
11	R55F30SP13(S55)		55	204.0	4.94	266	114	0	700	945
12	R60F25SP13	0.60	50	205.5	4.55	262.5	87.5	0	793	875
13	N60F25SP13			205.5	4.55	262.5	87.5	865	0	875
14	R60F30SP13			205.5	4.55	245	105	0	790	872
15	N60F30SP13			205.5	4.55	245	105	862	0	872
16	R60F30SP13(S40)		40	205.5	4.55	245	105	0	948	697
17	R60F30SP13(S45)		45	205.5	4.55	245	105	0	869	784
18	R60F30SP13(S55)		55	205.5	4.55	245	105	0	711	959

Note: R = recycled aggregate concrete; N= normal concrete; F = fly ash; SP = superplasticizer; S = S/A.

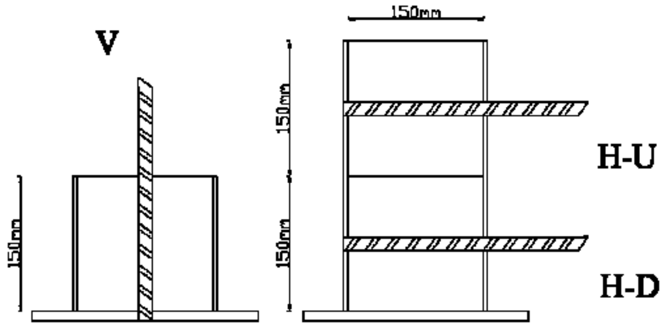

Fig. 2: Reinforcing bar position of bond strength test

3. Testing Result and Discussion

3.1. Coarse aggregate of waste concrete

The surface of the recycled aggregates is highly porous and rough, and is covered with cement mortar, whose volume makes up 34.94% of the recycled aggregates, which corresponds to other research results [3]. The SSD specific weight of recycled coarse aggregate is less than that of natural by 8.4%; its AR is much higher than natural one (as Table 1).

3.2. Workability of fresh concrete

The tested results of slump and slump flow of each fresh concrete is listed in Table 3.

1) Recycled-aggregate or natural-aggregate high flowing concrete generally meets high flowing concrete requirements at the same mix proportion, the slump loss at 45 minute of CRA is about 2.04% to 8.7% higher than that of CNA. The loss of 45-minute slump flow of CRA is about 0.7% to 10.0% higher than that of CNA. It is inferred that this phenomenon results from the re-hydration of old mortar on the surface of recycled aggregates, which consumes water and is also because of high AR of RA.
2) For both recycled-aggregate high flowing concrete or natural-aggregate one, the concrete with 25% replacement rate of fly ash showed a higher loss of slump and slump flow than that with 30% replacement rate.
3) For specimens with w/c of 0.55 or 0.60 and the S/A of 40% and 45%, the initial slump is lower and the concrete segregates. It is because that the fine aggregates are not sufficient and coarse aggregate contents are too high. The loss of slump and slump flow with 50% S/A is lower than that with 55% S/A. The loss of slump and slump flow is also lower for w/c = 0.55 specimens than that of w/c = 0.60.

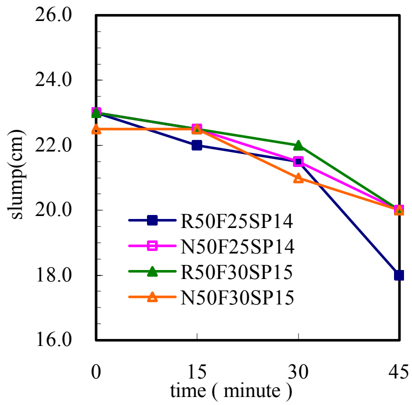

Fig. 3: Development of slump (w/c=0.50)

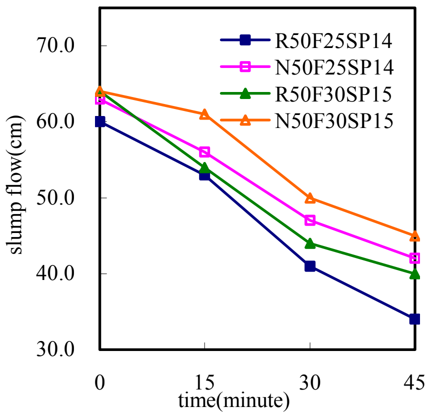

Fig. 4: Development of slump flow (w/c=0.50)

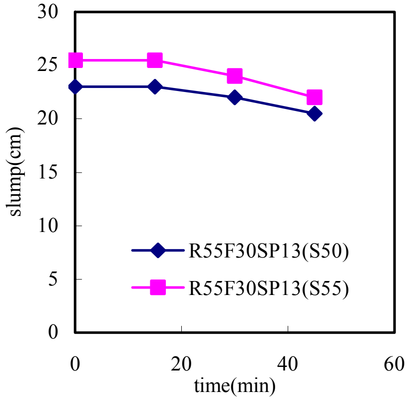

Fig. 5: Development of slump loss of recycled concrete with w/c=0.55, s/a=50%, 55%

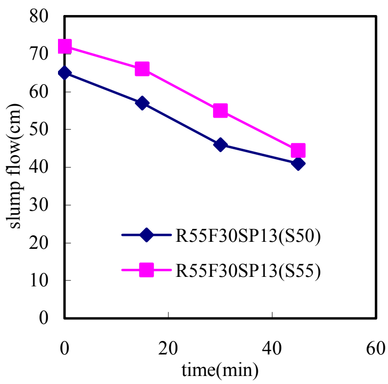

Fig. 6: Development of slump flow loss of recycled concrete with w/c=0.55, s/a=50%, 55%

Table 3: Comparison of slump and slump flow

No.	Mix proportioning no.	Slump (cm)					Slump flow (cm)				
		0 min.	15 min.	30 min.	45 min.	45-min loss rate	0 min.	15 min.	30 min.	45 min.	45-min loss rate
1	R50F25SP14	23.0	22.0	21.5	18.0	21.74 %	60.0	53.0	41.0	34.0	43.33 %
2	N50F25SP14	23.0	22.5	21.5	20.0	13.04 %	63.0	56.0	47.0	42.0	33.33 %
3	R50F30SP15	23.0	22.5	22.0	20.0	13.04 %	64.0	54.0	44.0	40.0	37.50 %
4	N50F30SP15	22.5	22.5	21.0	20.0	11.11 %	64.0	61.0	50.0	45.0	29.69 %
5	R55F25SP13	23.5	22.5	22.0	21.0	10.64 %	69.0	59.0	50.0	42.0	39.13 %
6	N55F25SP13	22.0	22.0	20.5	20.5	06.82 %	69.0	63.0	54.0	44.0	36.23 %
7	R55F30SP13	23.0	23.0	22.0	20.5	10.87 %	65.0	57.0	46.0	41.0	36.92 %
8	N55F30SP13	21.5	21.5	21.5	20.5	4.65 %	63.5	57.0	47.5	40.5	36.22 %
9	R55F30SP13(S40)	16.0	Segregation								
10	R55F30SP13(S45)	17.5	Segregation								
11	R55F30SP13(S55)	25.5	25.5	24.0	22.0	15.56%	72.0	66.0	55.0	44.5	38.19%
12	R60F25SP13	26.0	24.0	22.5	20.5	21.15 %	70.0	59.0	52.0	41.5	40.71 %
13	N60F25SP13	24.5	23.0	20.5	20.0	18.37 %	71.5	60.5	52.0	44.0	38.46 %
14	R60F30SP13	24.5	24.0	22.5	21.5	12.24 %	69.0	64.5	52.0	42.5	38.41 %
15	N60F30SP13	24.5	24.0	23.5	22.0	10.20 %	70.0	63.0	57.0	49.0	30.00 %
16	R60F30SP13(S40)	23.5	Segregation								
17	R60F30SP13(S45)	19.5	Segregation								
18	R60F30SP13(S55)	24.5	24.0	20.5	19.0	22.45%	62.0	55.5	43.0	37.5	39.52%

3.3. Compressive strength

Compressive strength of this study is shown in Table 4. The following results can be obtained.

1) For both CRA and CNA, it is helpful for workability of concrete when the amount of replacement of fly ash is high (as 30% in this research). But it has a negative influence on the strength of concrete. This is similar to other research results [7].
2) Compressive strength of recycled-aggregate high flowing concrete with 25% of the amount of replacement of fly ash is generally higher than that of CNA, which is illustrated as Figs. 7–9. However, its late strength develops slowly, and even slower than that of natural-aggregate high flowing concrete (as R50F25, R55F25). Besides, this phenomenon is more obvious when w/c is lower. It is inferred that this phenomenon results from the re-hydration of cement in the mortar that covered the recycled aggregates.

   In addition, recycled aggregate is rougher, which gives a better aggregate-mortar bond strength. However, the specific weight of the recycled aggregate covered by mortar is less, and is more porous and weaker as compared with natural aggregate. Therefore, the strength at late age of CRA is less than that of CNA. That is the reason why that some compressive strength of CRA is less than that of CNA and is more pronounced when w/c is lower.

3) Compressive strength of CRA with 30% of replacement rate of fly ash is generally lower than that of CNA at the same mix proportion with increased w/c. This agrees well with previous research results, i.e., the higher the replacement rate of FA, the less the strength gained.
4) The effect of S/A is shown in Fig.10. It is found that for CRA, the strength from S/A = 0.55 specimens is higher than the S/A=0.50 companion specimens. That is, R55F30SP13(S55) > R55F30SP13, and R60F30SP13(S55) > R60F30SP13.
5) The investigation on the effect of w/c concludes that at the same fly ash replacement rate the smaller the w/c, the higher the 28-day strength. This is true for CRA or CNA.
6) The following regressive equations are obtained for predicting 28-day strength with S/A=0.5:

(1)Amount of fly ash 25%

$0.5 \le w/c \le 0.6$

Normal concrete: $f'_c = 67\times(w/c)^{-2.8266}$ R^2=0.9496 (kgf/cm^2)

Recycled concrete: $f'_c = 101\times(w/c)^{-2.36}$ R^2=0.9975 (kgf/cm^2)

(2) Amount of fly ash 30%

$0.5 \le w/c \le 0.6$

Normal concrete: $f'_c = 73.7\times(w/c)^{-2.5284}$ R^2=0.9795 (kgf/cm^2)

Recycled concrete: $f'_c = 19.1\times(w/c)^{-4.5785}$ R^2=0.9860 (kgf/cm^2)

It can be observed that the change on the coefficients is smaller for CNA and larger for CRA, which also illustrated the high variability of recycled aggregate.

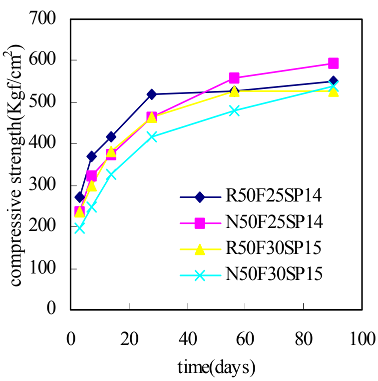

Fig. 7: Development of compressive strength (w/c=0.50)

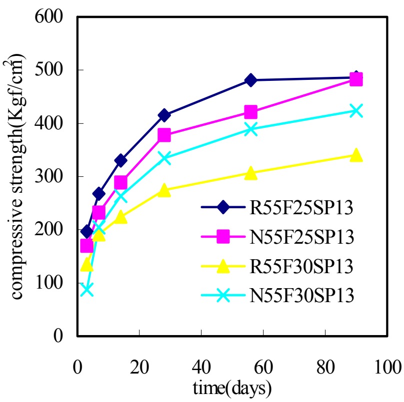

Fig. 8: Development of compressive strength (w/c=0.55)

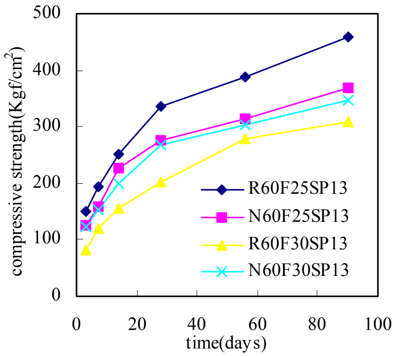

Fig. 9: Development of compressive strength (w/c=0.60)

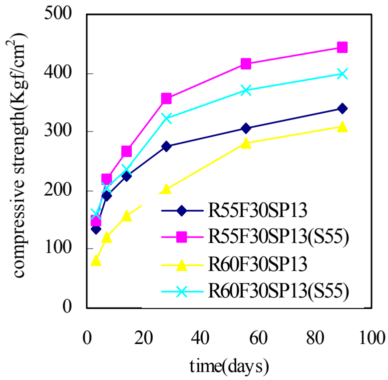

Fig. 10: Development of compressive strength of recycled concrete with different S/A and w/c

3.4. Splitting tensile strength

Test results of splitting tensile strength of high flowing concrete are illustrated in Table 4.

1) From Figs. 11 and 12, it can be observed that at the same FA replacement rate, the lower the w/c, the higher the splitting tensile strength. This is true for both CRA and CNA. At the same w/c, the splitting tensile strength of 25% replacement rate of fly ash is higher than that of 30%. This finding is similar to compressive strength, and shows that splitting tensile strength depends mainly on compressive strength.
2) The ratio of splitting tensile strength (f_{ct}) to compressive strength (f_c') of CRA is 7.44%-12.72%, and the ratio of splitting tensile strength to compressive strength of CNA is 8.25%-11.13%. This shows that the differences arises from different type of aggregate is not obvious.
3) From the last column of Table 4 and Fig..13, it can be observed that the splitting tensile strength, after being normalized by $(f_c')^{0.5}$, the $f_{ct}/(f_c')^{0.5}$ generally agree well with ACI suggested values, from $1.6(f_c')^{0.5}$ to $2.0(f_c')^{0.5}$ (for kgf/cm^2 units, and from 6 $(f_c')^{0.5}$ to $7.4(f_c')^{0.5}$ by U.S. customary units).

   A regression analysis suggests the following:

   Natural-aggregate high flowing concrete:

   $$f_{ct} = 1.715(f_c')^{0.5} \qquad R^2=0.77 \quad (\text{kgf/cm}^2)$$

   Recycled-aggregate high flowing concrete:

   $$f_{ct} = 1.75(f_c')^{0.5} \qquad R^2=0.66 \quad (\text{kgf/cm}^2)$$

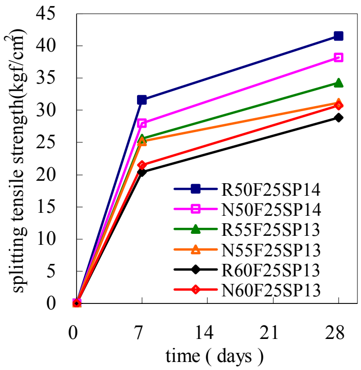

Fig. 11: Development of splitting tensile strength (25% replacement rate of fly ash)

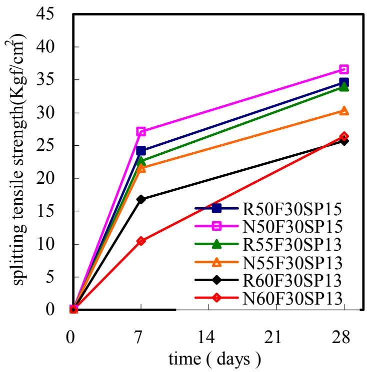

Fig. 12: Development of splitting tensile strength (30% replacement rate of fly ash)

Table 4: Strength development curve model of compressive strength and splitting tensile strength

No.	Mix proportioning no.	Compressive strength (kgf/cm^2)						28-day splitting tensile strength (f_{ct} , kgf/cm^2)	$\frac{f_{ct}}{f_c'}\times 100$	$\frac{f_{ct}}{\sqrt{f_c'}}$
		3d	7d	14d	28d	56d	90d			
1	R50F25SP14	272	368	415	518	527	551	42	8.02 %	1.83
2	N50F25SP14	236	323	372	463	560	592	38	8.25 %	1.77
3	R50F30SP15	234	299	381	465	528	528	35	7.44 %	1.60
4	N50F30SP15	197	247	327	417	480	537	37	8.76 %	1.79
5	R55F25SP13	197	268	330	415	481	486	34	8.27 %	1.68
6	N55F25SP13	170	232	289	378	421	483	31	8.25 %	1.60
7	R55F30SP13	135	192	225	275	307	341	34	12.35 %	2.05
8	N55F30SP13	88	205	264	335	389	424	30	9.05 %	1.66
11	R55F30SP13(S55)	149	220	268	357	415	445	–	–	–
12	R60F25SP13	149	194	251	337	388	458	29	8.56 %	1.57
13	N60F25SP13	125	158	226	276	313	370	31	11.13 %	1.85
14	R60F30SP13	81	120	157	202	280	308	26	12.72 %	1.81
15	N60F30SP13	124	153	200	268	304	348	26	9.87 %	1.62
18	R60F30SP13(S55)	160	204	235	322	370	399	–	–	–

3.5. Bond strength

The results of bond tests are shown in Table 5.

Table 5: Relationship of bond strength and compressive strength

No.	Mix proportioning no.	Position	Bond force (kgf)	Bond strength (kgf/cm^2) (a)	$\sqrt{f_c'}$ (b)	$\frac{a}{b}$
3	R50F30SP15	V	11425	127	21.57	5.9
		H-D	8864	99		4.6
		H-U	5556	62		2.9
4	N50F30SP15	V	17589	195	20.43	9.5
		H-D	11327	126		6.2
		H-U	10848	121		5.9
5	R55F25SP13	V	13371	149	20.37	7.3
		H-D	12553	140		6.9
		H-U	11312	126		6.2
6	N55F25SP13	V	13918	155	19.43	8.0
		H-D	10370	115		5.9
		H-U	10300	114		5.9
7	R55F30SP13	V	9262	103	16.58	6.2
		H-D	8943	99		6.0
		H-U	7589	84		5.1
8	N55F30SP13	V	15117	168	18.30	9.2
		H-D	12496	139		7.6
		H-U	10340	115		6.3
14	R60F30SP13	V	10489	117	14.22	8.2
		H-D	9012	100		7.0
		H-U	6764	76		5.3
15	N60F30SP13	V	9606	107	16.36	6.5
		H-D	7704	86		5.3
		H-U	5818	65		4.0

1) The variability of bond strength of CRA is higher. As shown in Fig. 13, most results of bond strength of CRA are slightly less than that of CNA. (Except when w/c is 0.6, the bond strength of these two materials is similar.)
2) For w/c = 0.5 CRA, the 25% FA replacement rate concrete, shows a 30% higher bond strength than those of 30% replacement ones, which agrees with compressive and tensile strength test results.
3) According to the experiment, the bond strength from various bar positions are V>H-D>H-U, which agrees with previous research [8]. This is true for both CRA and CNA. The main reason is that air and water tends to be more easily accumulated under horizontally placed reinforcing bars than that of vertically

placed reinforcing bars. The top bar may accumulate more water than the bottom bar due to bleeding.

4) To effect of aggregate is not observed in bond test.

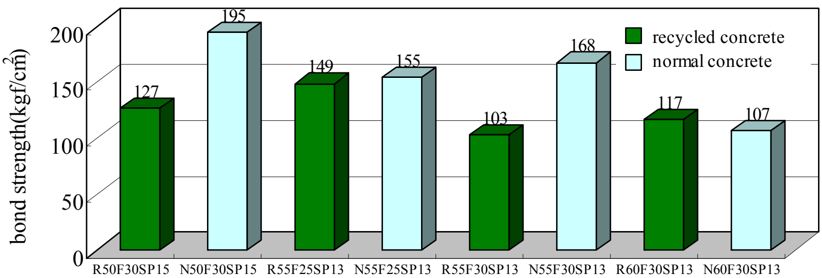

Fig. 13: Bond strength of recycled and natural aggregates (reinforcing bar placed vertically, V)

4. Conclusions

- Recycled-aggregates obtained from crushing deserted concrete have more edges and corners. The surface is highly porous and rough. Therefore, it has a lower specific weight and a higher AR than that of natural-aggregates. Although its shape and other qualities are not as good as natural ones, it still meets the requirement for concrete aggregates.
- It is feasible to produce high flowing concrete by using recycled-aggregates; however, the compressive strength of deserted concrete should be at least 210 kgf/cm^2. Besides, the mix design and production of CRA are the same with those of CNA.
- The loss of slump and slump flow of CRA is relatively 2.04%-8.7% higher right after mixing, and 0.7%-10.0% higher than that of CNA with same proportion after 45 minutes.
- It is helpful for workability to use fly ash (25%, 30%). But FA has a negative influence on the strength of concrete.
- The 28-day compressive strengths of CRA with 25% replacement rate of fly ash are generally higher than those of CNA. However, the strength development for FA added concrete is slowing down at late age (90 days). This is more pronounced for higher w/c specimens.
- Larger amount of replacement of fly ash causes a lower compressive strength of CRA.
- Splitting tensile strength increases with the increase of compressive strength and agree well with ACI suggestions. The normalized splitting strengths (by $(f_c^{'})^{0.5}$) are in the range of $1.6(f_c^{'})^{0.5}$ to $2.0(f_c^{'})^{0.5}$ (in kgf/cm^2).

- The variation of bond strength of CRA is larger than CNA. In addition, the bond strength of CRA is slightly less than that of CNA.
- The bond strength from the specimens as to the relative position is V>H-D>H-U. This is observed for both CRA and CNA and is in consistent with other researches.

5. Conversion Factors

1 kgf/cm^2 = 14.22 psi
= 0.098 MPa

References

1. Chen, Chen-Chuan. "The Current and Future of HPC." *Proceedings of the HPC Practice Conference*, Taipei, 1998, 1-17.
2. Buck, A.D. "Recycled Concrete as A Source of Aggregate." *ACI Journal*, No. 74-22, 1977, pp. 212-219.
3. Hansen, T.C., and H. Narud. "Strength of Recycled Concrete Made from Crushed Concrete Coarse Aggregate." *Concrete International* 5(1), 1983, pp. 79-83.
4. Mukai, T., M. Kikuchi, H. Koizumi. "Fundamental Study on Bond Properties between Recycled Aggregate Concrete and Reinforcing Bar." 32nd Review, Cement Association of Japan, 1978.
5. Yen, Huang, and Chen. *Reuse of Deserted Concrete*. Report, ABRI, MOE, 1997.
6. *HPC Flowability Standard: Japan Current Practice and Concrete Constructions Automation Study*. CPAMI, MOE, 1988, pp. 125-149.
7. Russell, H.G., S.H. Gebler, and D. Whiting. "High Strength Concrete Weighing the Benefits." *Civil Engineering* 1989.
8. Geoffrey, B.W., and J.F.P Bruce. "Bond Strength of Reinforcement Affected by Concrete Sedimentation." *ACI Journal* 63, 1965, pp. 251-264.

FOR SUSTAINABLE DEVELOPMENT: TO PRODUCE CEMENT BY ANOTHER CONCEPT

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Abstract

From the discussion of some accidences of concrete preparation taking place on site and the current situation of cement production in China, an argument is introduced that production of cement by another concept is beneficial to improvement of properties of cement and concrete and sustainable development of cement industry. Some operation processes of concrete can be moved into factory. It can optimize much accurately the composition and properties of cementitious materials used for preparation of concrete. Three issues must be considered for the production principle of new cement: (1) Hydration characteristics of new kind of cement, (2) particle size distribution of new kind of cement, and (3) compatibility of chemical admixtures and hydraulic constituents in new kind of cement. Some new properties proofing methods and standards must be developed to enhance the utilization of this new cement.

1. Introduction

High volume fly ash concrete developed by Malhotra and his colleagues (1, 2) is coming be well known in China. A typical example is the application of high performance concrete in the project of Shenzhen subway tunnel (3). The underground soil of Shenzhen contains moderately aggressive medium such as SO_4^{2-} and Cl. The conventional concrete cannot satisfy the designed requirement of durability for the structure of Shenzhen subway. High volume mineral admixture concrete was suggested by Tsinghua University, firstly. A full-scale section mock up was constructed in 1999 to investigate practical possibility, mechanical properties and durability of this new type of concrete in aggressive coastal environment with hot and moist weather. The designed compressive strength class is C30. The mix proportion of this concrete is: ordinary portland cement OF PO-42.5 (containing less than 15% of mineral admixture) 180 kg/m^3, fly ash 180 kg/m^3, ground granulated blast-furnace slag 80 kg/m^3, W/B 0.42. This concrete showed excellent workability, mechanical properties and durability. A barrier wall was built with this concrete for a vehicle terminal of Shenzhen subway in 2002.

Everything is in two aspects. Superiority and deficiency exist simultaneously. High performance concrete with good properties has complex binder composition. Multi-constituent would make troubles for managing of production, purchasing and batching of raw materials as well as controlling of quality. Once in a building site, a worker was mistaken to add fly ash as cement into mixer. As a result, of course, the columns cast with the falsely proportioned concrete had no strength and mould be pulled down. Therefore, fly ash does not be used any longer in the project of this company, even though the managers know the advantages of fly ash. About 3 years ago, another similar accident also happened, but that mistaken was between fly ash and superplasticizer. It resulted in a part of concrete no setting after 5 days.

These accidents force people to think a question. Why don’t we produce a type of cement containing all cementitious materials and chemical admixtures used for concrete to simplify the manufacture process of concrete in site? The fluctuation of concrete quality can be decreased by the way of using high-quality raw materials produced through a strictly controlled process in factory. We should change our traditionally angle of view on the relationship of cement and concrete. It can be considered that to produce cement according to requirement of concrete practice and to examine quality of cement according to regulation of concrete use is urgent affairs.

2. The Current Relationship of Cement and Concrete in China

More than 0.7 billion ton of cement was produced in China in 2002. Among those, more than 50% is ordinary portland cement (containing less than 15% mineral admixture), about 40% is slag portland cement (containing normally 20%-40% ground granulated blast-furnace slag); the others include fly ash portland cement, composite portland cement and special cements. The slag content in Chinese slag portland cement is rarely more than 40% although 70% of substituting ratio is allowed by national standard. The production of fly ash portland cement is even rare in China. It is always used for masonry as a low class of product.

Relational ISO standard has been accepted in China since 2001 to verify the quality of cement. Strength of cements blended with high volume of mineral admixture shows lower especially in early ages than that of ordinary portland cement because a uniform water-cement ratio of 0.5 is used for testing strength of all kinds of cements. Concrete producers do not welcome blended cements with high volume of mineral admixtures due to their low strength, especially in early age. They prefer to add fly ash into concrete in situ to improve workability and economy of concrete. They only ask for cements with quickly hardening and high strength to satisfy the strict demand of high constructing speed, but disregard other properties of cement. Therefore, cement producers do their best to enhance cement strength. The main technologies for increasing strength, especially in early age, of cement are rising of content of C_3S and C_3A in clinker and increasing of special surface of cement. Both producers of cement and concrete do not understand the opposite side each other, and do not know really what the actual requirement of concrete structure is. Both them do not know what would happen while such cement were used in concrete. There is a high risk to crack with the concrete. Compatibility between cement and superplastisizer might be another problem. Workability and durability of the concrete could be impaired.

3. The Conventional Concepts Need to be Changed

Strength is considered as the most dominant index for the qualification of cement for a long time. Therefore, cements involving high volume of mineral admixture are classified in the range of low quality. Actually the quality index of products should be homogeneity and uniformity. Strength of cement examined by the standard method is only an index to reflect the stabilization of producing process in a factory and to compare the relative quality difference of cement among different factories. It does not present the properties of cement when it is used to prepare concrete. Judging the cement quality rightly must concern not only strength but also other characteristics of cement. When we inspect the properties of cement based on the mechanical properties, workability and durability of concrete simultaneously, strength and fineness of cement need not be so high and more mineral admixture can be involved into cement. Thus, more raw materials with lower quality can be used, more mineral admixture can be involved in cement, less energy is resumed and less greenhouse gas is exhausted during the cement manufactory. It benefits the discharge of ecological load for our world.

Cement producers concern little about the preparation of concrete, otherwise, concrete engineers understand little about the cement chemistry in the last century. Then there is not serious trouble because the concrete mixture was simply consisted from cement, aggregate and water; and its strength class was not high. Nowadays the new types and the new constituents of concrete continuously emerge along with the progress of science and technologies. Modern concrete is much more complex than that before a few decades. At present-day, concretes with different strength classes can be made using the same kind of cement, whereas, concretes with same strength class can be made using cements with different strength classes. Sometimes more than 10 kinds of material are included in a concrete mixture. It is very difficult for the engineers in site or in ready-mixing station to know the characteristics of all materials and to determine an appropriate proportion of concrete mix. Thus, there is an increasing demand to supply ready-mixing station a ready cementitious material to simplify the mixing procedure and quality-controlling system of modern concrete. Some pioneering attempts have been done in Canada, Russia, and China (4-7).

4. Producing New Types of Cement by Another Concept

First of all we must answer two questions. One is which principle is based to produce new types of cement. Another is how the properties of cement are examined.

4.1. The principle based to produce new types of cement

Looking back the history of cement and concrete, it is found that concrete was developed based on the properties of cement that was previously invented. It is already observed that some hydration productions and paste structure of traditional portland cement is not beneficial to durability of concrete structure. Demand of concrete must be fully considered in the producing process of new kind of cement. It is not too simple to mix all raw materials and grind the mixture together. Three issues must be considered.

1) Hydration characteristics of new kind of cement: Optimization of SO_3

The composition and production of new type of cement must conform the principle of sustainable development. The new cement should be constituted with less clinker but more supplemental cementitious materials discharged from other industry as waste. Its hydration characteristics are different from the traditional portland cement. For example, gypsum plays a role not only as the setting regulator, but also an activator to enhance the potential hydration activity of supplemental cementitious materials involved in new cement and would control shrinkage of concrete by suitable dosage . Because the SO_3 content is inadequate in concrete adding high volume mineral admixture in situ, when the new kind of cement will be produced in factory, SO_3 content in cement must be optimized to fulfill the above-mentioned tasks.

2) Particle size distribution of new kind of cement: Optimization of constitute and Ground process

Besides the composition, particle size distribution is another impotent factor influencing the properties of cement. Conventional blended cement produced in China is ground mainly by means of collective pulverization of all constituents. The hardness of constituents blended in cement is greatly different from each other. Thus, a perfect particle size distribution of cement is not easy to obtain with the process of collective milling. For example, when a blended cement constituted of clinker and granular blast-furnace slag is ground collectively to special surface of 350 m^2/kg, the fineness of ground granular blast furnace slag is only about 220m^2/kg due to its higher hardness, while clinker will be over-ground in this case. One of results from this situation is that clinker will hydrate too quickly, contrarily slag functions like an inert material. It results in bleeding of fresh concrete and low strength development of hardened concrete. Therefore, conventional blended cement is not considered as a top-quality product. The advanced production of blended cement is that clinker and mineral admixtures are ground separately. The process can be optimized to obtain the perfect particle size distribution with lest energy consume based on the grindability of each constituent of blended cement. Besides, if fly ash and granular blast-furnace slag were blended together with clinker, fly ash and slag could be grinding aids each other.

3) Compatibility of chemical admixtures and hydraulic constituents in new kind of cement: Process for adding the chemical admixtures

The new type of cement may contain the same uniform chemical admixtures to modify the efficiency of production and the properties of cement. Same chemical admixtures added into concrete when it is prepared in ready-mixing station can be added into the cement now. This procedure simplifies much the production and quality controlling system of concrete in situ. One of the problems facing concrete engineers in recent years is that more and more chemical admixtures are used to produce modern concrete. Same of them is not always compatible with modern cement. It results in poor workability of fresh concrete. The causation of compatibility of chemical admixtures and hydraulic constituents is complex and difficult to control by an inexperienced engineer in situ. Quality and quantity of chemical admixture can be finely determined through a lot of experiments and theoretical analysis when they are added into cement in factory. The optimal compatibility can be confirmed during this production process.

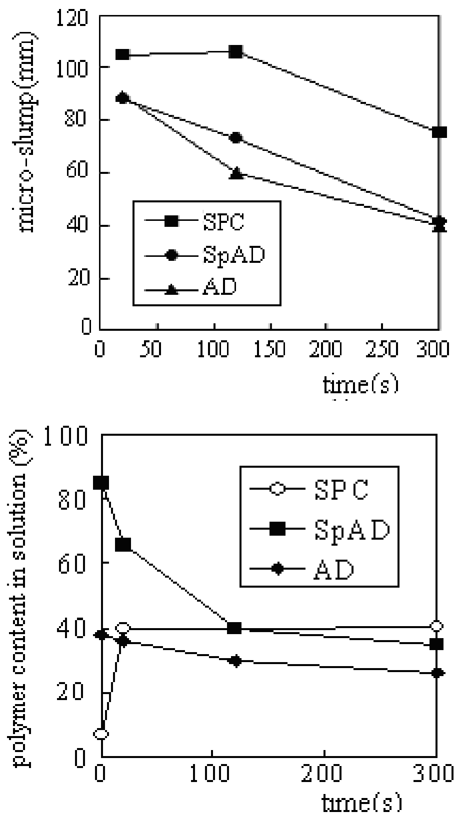

Fig. 1: Efficiency of chemical admixtures when adding process varies

It was reported by Rossetti et al. (8) that efficiency of chemical admixtures is different by various adding process as shown in Fig. 1. SPC is a cement sample with superplastisizer added during producing of cement, SpAD is the sample with superplastisizer added into cement product, and AD is the sample with superplastisizer added into mix water during the preparation of concrete. Water reducing efficiency of sample SPC is better than that of both SpAD and AD.

4.2. The methods and standards to verify the properties of new kind of cement: To select w/c according to regulation of concrete practice

With optimized added way and dosage of superplastisizer, compounding of constitutes involving mineral admixture and clinker, water demand for normal consistence of cement paste can be 15%-20% depended on raw materials used, which differs greatly from traditional cement. If the ISO strength verifying method is used to determine the strength of new cement, the mortar is too soft to be cast. Water demand for molding of new cement should be determined according to the normal consistence of mortar. It reflects the real using situation of cementitious materials in concrete. The method and standard to proof the properties of a material need not be constant with ones to control the production process of the material. For example, dry mortar is also a kind of cementitious materials, but its properties are proofed with the methods differing obviously the ISO testing methods of cement.

5. Example

Table 1: Properties of new kind of cement

Water demand (%)	Setting time (h:m)		Hydration heat (kJ/kg)		Flexural strength		Compressive strength	
	Initial	Final	3d	7d	3d	28d	3d	28d
17.6	4:59	7:00	144	180	5.2	10.4	33.7	67.6

The above mentioned new cement has been studied and cooperating with Concrete Co. of City Construction Ltd., Beijing, a product of pilot-plant test has been used to prepared concrete of C30 and C40 for constructing a inner wall and cover board of first step underground garage of Meilin apartment building in Beijing.

After optimizing, that cement consists of 40% of fly ash, 10% of slag, and 6% of gypsum besides 50% of portland cement clinker. Properties of that cement are shown in Table 1. The principal properties of concrete made by that cement is shown in Table 2. It has been proved by experiments and practice that the technical path mentioned above is feasible.

Table 2: The principal properties of concrete made by new kind of cement

Concrete	Slump (mm)	Slump loss After 1h (mm)	Setting time (h:m)		Compr. strength on 28d (MPa)	Shrinkage on 28d (%)	Carbonated depth (mm)
			initial	final			
C40	220	15	13:41	15:21	52	0.017	6
C30	215	10	12:12	14:23	38		

6. Conclusions

- For sustainable development, production of cement should be considered to fulfill regulation of concrete structure practice, so that the traditional concept on that strength must be changed to be beneficial to durability of concrete structure under various environmental conditions.
- High volume mineral admixture concrete is an effective way for sustainable development of concrete. Production of cement should be seasoned with this requirement. For simplifying the mixing process of concrete in situ to eliminate the occasional operating mistakes, Some operations of concrete production would be moved into cement plant to optimize much accurately the composition and properties of cementitious materials used for preparation of concrete. In this way, the composition and properties of cementitious materials used for preparation of concrete can be optimized much accurately.
- Examination of cement for quality control of product should be also considered according to regulation of concrete practice. Some new properties proofing methods and standards must be developed to enhance the utilization of this new cement.

References

1. N. Bouzoubaa, V.M. Malhotra. Performance of lab-produced HVFA blended cements in concrete. *Concrete International* 4, 2001, 29-33.
2. N. Bouzoubaa, M.H. Zhang, A. Bilodeau, V.M. Malhotra. Laboratory-produced high-volume fly ash blended cements: physical properties and compressive strength of mortars. *Cement and Concrete Research* 28(11), 1998, 1555-1569.
3. Yan Peiyu, Lu Xinying, Lian Huizhen, and Li Yulin. Preparation of high performance concrete for the subway construction in Shenzhen, China. *Proceedings of the 6th International Symposium on Utilization of High Strength/High Performance Concrete*, ed: G. Koenig, F. Dehn, T. Faust, Leipzig, Germany, 16-20 June 2002, pp. 813-820.
4. N. Bouzoubaa, M.H. Zhang, and V.M. Malhotra. Superplasticized Portland cement: production and compressive strength of mortars and concrete. *Cement and Concrete Research* 28(12), 1998, 1783-1796.
5. S.A. Podmasova, S.T. Balev, Y.S. Volkov. New low water demand binders for high strength concrete. *Proceedings of International Conference on High Strength Concrete*, Norway, 1993.
6. Lian Huizhen, and Wu Zhongwei. Sustainable development of concrete and high performance cementitious material. *Concrete* 6, 1998, 8-12 (in Chinese).
7. Lian Huizhen, Ruan Qingge, and Li Yulin. The properties and examination of FK high performance cement—Experimental study of high performance binders (II). *Concrete* 1, 1999, 20-24 (in Chinese).
8. V. Alunno Rossetti, F. Curclo, and Cussino. Production performance and utilization of a special superplasticized cement. *Proceedings of 9th International Conference on the Chemistry of Cement*, New Delhi, 1992.

PROPERTIES OF GREEN LIGHTWEIGHT AGGREGATE CONCRETE

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Abstract

With increasing concern over the excessive exploitation of natural aggregates, synthetic lightweight aggregate produced from environmental waste is a viable new source of structural aggregate material. The uses of structural grade lightweight concrete reduce considerably the self-load of a structure and permit larger precast units to be handled. In this paper, the mechanical properties of a structural grade lightweight aggregate made with fly ash and clay will be presented. The findings indicated that water absorption of the green aggregate is large but the crushing strength of the resulting concrete can be high. The 28-day cube compressive strength of the resulting lightweight aggregate concrete with density of 1590 kg/m^3 and respective strength of 34 MPa. Experience of utilizing the green lightweight aggregate concrete in prefabrication of concrete elements is also discussed.

1. Introduction

Most of normal weight aggregate of normal weight concrete is natural stone such as limestone and granite. With the amount of concrete used keeps increasing, natural environment and resources are excessively exploited. Synthetic lightweight aggregate produced from environmental waste, like fly ash, is a viable new source of structural aggregate material. The use of lightweight concrete permits greater design flexibility and substantial cost savings, reducing dead load, improved cyclic loading structural response, longer spans, better fire ratings, thinner sections, smaller size structural members, less reinforcing steel, and lower foundation costs [1-3]. Weight of lightweight concrete is typically 25% to 35% lighter but its strengths is comparable to normal weight concrete.

This paper discusses the mechanical properties of a newly developed structural lightweight aggregate which is made from expanded clay. The aggregate is reinforced with a PFA rich surface coating applied at a later stage of firing. The experience of utilizing this green lightweight aggregate concrete in the prefabrication of structural element is also presented.

2. Experiments and Results

2.1. Characteristics of the aggregate

The quality of the green aggregate [in terms of crushing strength] was specified by a crushing strength test based on GB2842-81 (China Standard). The strength as measured by compressing the aggregate in a steel cylinder through a prescribed distance of 20 mm is 3.8 MPa. Results of the sieve analysis and water absorption of the aggregate at different time are given in Table 1.

Table 1: Properties of the aggregate

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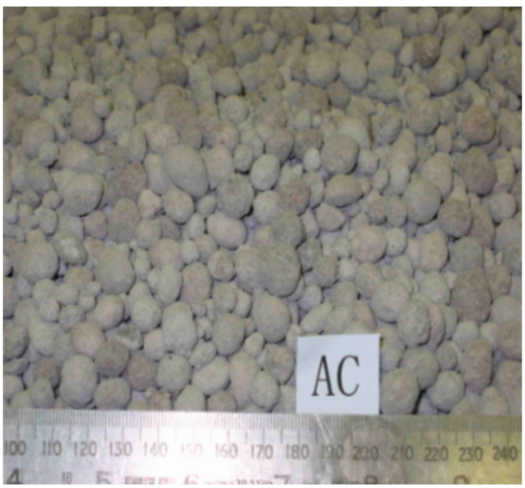
<tr><td colspan="3" rowspan="10">
</td><td>Bulk Density</td><td>840 kg/m^3</td></tr>
<tr><td>Apparent Density (pre-wet 1 hour)</td><td>1525 kg/m^3</td></tr>
<tr><td>Crushing Strength</td><td>3.7 MPa</td></tr>
<tr><td colspan="2">Sieve Ratio (mass %)</td></tr>
<tr><td>>14mm</td><td>0</td></tr>
<tr><td>14mm~10mm</td><td>23.2</td></tr>
<tr><td>10mm~5mm</td><td>60.2</td></tr>
<tr><td>5mm~2.36mm</td><td>15.1</td></tr>
<tr><td>2.36mm~1.18mm</td><td>1.3</td></tr>
<tr><td><1.18mm</td><td>0.2</td></tr>
<tr><td>Time (min.)</td><td>5</td><td>10</td><td>30</td><td>60</td></tr>
<tr><td>Water absorption rate (%)</td><td>9</td><td>11.2</td><td>12</td><td>13</td></tr>
</table>

Fig. 1 examines the topography of the aggregate specimen using an optical microscope with 200X magnification. We can see that there is a thick shell rich in PFA at the outside surface of the aggregate. The compact external shell of the aggregate contributes to the higher strength resistance than the traditional lightweight aggregate without coating. Moreover, it is critical in controlling the water absorption of aggregate during concrete mixing, reducing the slump loss of concrete with time [4].

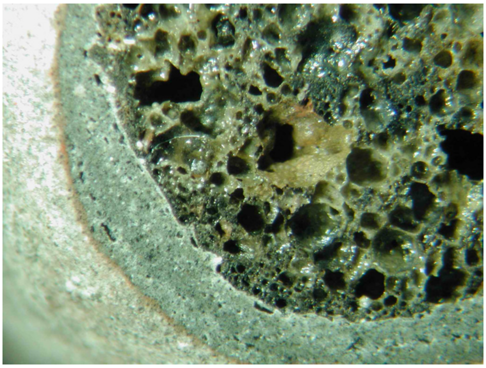


Fig. 1: Section of the lightweight aggregate

3. Prefabrication using Lightweight Aggregate Concrete

The structural lightweight aggregate was used to develop precast concrete elements for green construction. The mix proportion used is given in Table 2.

Table 2: Mix proportion of the green lightweight concrete (kg/m^3)

Cement	Water	Sand	AC agg. (pre-wetted)	Admixture
420	175	715	630	1000 ml

Fig. 2 displays that a good workable fresh concrete for concrete casting. The slump of lightweight concrete measured 30 minutes after batching was 50 mm.

Fig. 2: Highly workable fresh concrete

Fig. 3 shows the protocol of finished lightweight concrete precast façade.

Fig. 3: Protocol of finished lightweight concrete precast façade

Comparison of the design requirements with the concrete quality of the prefabricated façade are given in Table 3 below. It is seen that the gross weight of the lightweight concrete façade achieved only 70% of the density of normal weight concrete with the same compressive strength. Fig. 4 also indicated the bonding between reinforcing steel and lightweight concrete is good.

Table 3: Comparison of design requirement with actual concrete produce

	Specification	Façade quality
Unit weight	2275 kg (normal concrete)	1590 kg
1-day strength	15 MPa	14.5 MPa
28 days	30 MPa	34 MPa
Slump	75 mm	50 mm
Density	2400 kg/m^3	1750 kg/m^3

Fig. 4: Bonding between the steel bars and the lightweight concrete

The following advantages are concluded for using lightweight concrete in prefabrication in building:

- Reduce the dead weight of a façade from 5 tons to about 3.5 tons
- Reduce craneage load, allow handling, lifting flexibility with lighter weight
- Good thermal and fire resistance, sound insulation than the traditional granite rock
- Allow design and construction flexibility for larger prefabrication modules
- Allow maintenance flexibility with replaceable modules
- Factory production of module enhances quality of product
- Enhance speed of construction, shorten overall construction period
- Enhance green building construction, minimize wet trade on site
- Improve damping resistance of building
- Utilization of PFA in aggregate production resolves the waste disposal problems of ash and reduce the production cost of concrete

4. Conclusions

The successful application of structural lightweight aggregate demonstrated that lightweight used for precast structural elements can be used in building construction to increase the speed of construction, enhance green construction environment such as reducing the wet trade on site and keep dust level at construction site to the minimum.

Acknowledgments

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References

1. Short and W. Kimniburgh. *Lightweight Concrete*, 3rd ed., Applied Science Publishers, London, 1978.
2. *FIP Manual of Lightweight Aggregate Concrete*, 2nd ed., Surry University Press, Glasgow and London, 1983.
3. Satish Chandra and Leif Berntsson. *Lightweight Aggregate Concrete*, Noyes Publications, New York, USA, 2002.
4. Lo,Y., Cui, H.Z., and Li, Z.G. "Influence of Aggregate Prewetting and Fly Ash on Mechanical Properties of Lightweight Concrete." *Journal of Waste Management*. (in press).

THE HIGH-TECH RESEARCH PROCESS OF INDUSTRIAL SOLID WASTE IN CHINA

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Abstract

In this paper, the present status of the industrial waste, development foundation, and research progress of high technology are discussed based on the author's experience on the development of industrial waste. The important academic and utility values are presented.

1. Introduction

With the expansion of production scale in modern society, the contradiction between the human beings' needs and the environment becomes more and more acute. This leads to the huge burden in energy, natural resources and environmental pollution. All of these have threatened mankind's subsistence and development.

Material is the physical base and the premise of society development and it is the milestone of mankind advance, too. It creates the material civilization and improves the living condition, but it also accelerates energy consuming and environmental pollution. So the ecological degree of the material's whole life periodicity is an indication that can evaluate the environmental quality.

2. Industrial Solid Waste—Renewable Resource

Based on the national medium-term and long-term technology development outline, the renewable resource is defined as a kind of resource emerged in the process of society production, circulation and consumption, lost their original use value, being stored in many forms, but the useful value can be extracted through different processing methods.

According to the present status of the industrial solid waste in China, mineral tailings, fly ash and coal gangue are the three main industrial solid wastes. The chemical compositions (shown in Table 1) were SiO_2, Al_2O_3, Fe_2O_3 and some impurities.

Table 1: Chemical composition of mineral tailings, fly ash, and coal gangue

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Other	Ignition loss
Iron tailing	73.27	4.07	11.60	3.04	4.22	2.1	2.18
Fly ash	50.6	27.2	7.0	2.8	1.2	2.1	8.2
Coal gangue	53.16	15.53	7.43	4.14	0.97	/	16.30

Notes: The mineral tailings data come from AnShan in LiaoNing province. The coal gangue data come from XinWen in ShanDong province. The fly ash data are the national average.

According to the phase diagrams, these industrial wastes belong to SiO_2-Al_2O_3-X system. If the appropriate components are added, a series of materials will be developed, such as SiO_2-Al_2O_3-CaO system, and SiO_2-Al_2O_3-MgO system.

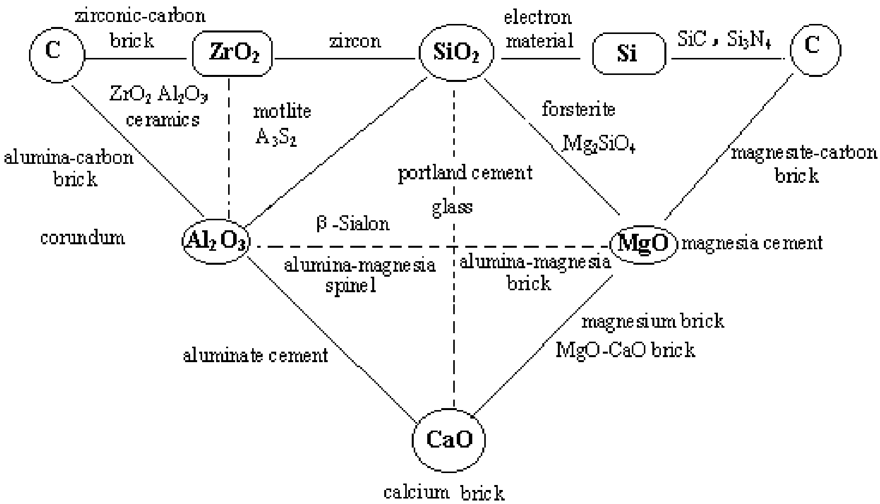

Fig. 1: Derivative diagram of SiO_2-Al_2O_3-X phase diagram

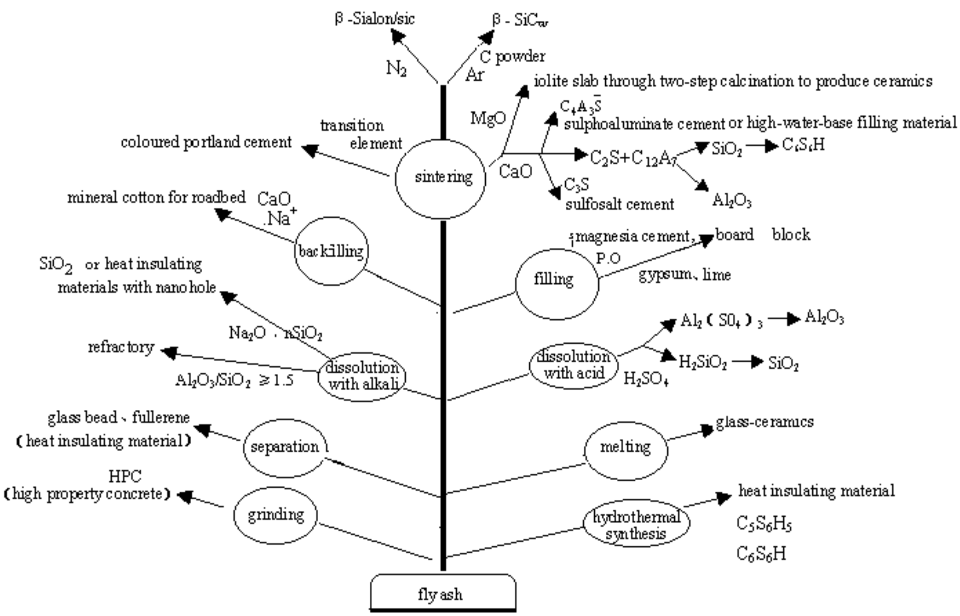

Fig. 2: Fly ash development tree derivation

Fig. 1 is derived from SiO_2-Al_2O_3-X phase diagram. It is obvious that a series of high-tech products can be developed. It involves glass, ceramics, cement, refractory, wall materials, heat insulating materials, function material, etc. Fig. 2 is the tree derivation of fly ash development. And the tailing has a similar development trend to fly ash. From Fig.2, we can see that the materials, developed by using fly ash, involve almost all the building materials.

3. The High-Tech Research Process

3.1. Micro-crystal glass [1]

Micro-crystal glass has the advantages of mechanical performance, corrosion resistant ability, resistance to abrasion, decorative property, which are also the good attributes of glass and ceramic. Building micro-crystal glass, made by industrial waste, has varies impurity and are often used as building materials.

According to the mineral compositions of these industrial wastes, SiO_2-Al_2O_3-MgO, SiO_2-Al_2O_3-ZnO or SiO_2-Al_2O_3-LiO_2 system can be chosen to composite the basic glass, and the proper nucleating agent should be chosen, such as TiO_2, ZnO, LiO_2, CaF_2, NaF, etc. In general, there are three production modes, i.e., sintering process, rolling process and floating process.

At present, there are 14 factories product glass-ceramics with raw materials as copper tailings, kaolin clay and sand of weathering in China.

3.2. Metakaolin cement [2]

Metakaolin Cement, named by Professor Wang Lijiu, has a major mineral composition of metakaolin. Others also named it as soil polymer or Pyrament (alkali agitated pozzolana cement trass gel material). Using the kaolin ($Al_2O_3.2SiO_2.2H_2O$-AS_2H_2) as the raw material, it forms anhydrous aluminosilicate after dehydration at the right temperature (600-900°), i.e, metakaolin ($Al_2O_3.2SiO_2$-AS_2), one kind of artificial volcanic ash material with high reactivity. After being stimulated by alkali or sulphate, these binding materials can form the hydration products with the composition and structure, which are similar to the hydration products of portland cement. Metakaolin can also react with calcium hydroxide (CH) and water. Adding it into cement can greatly improve certain properties of the cement.

The study of mechanics property indicates the MK's contribution to concrete strength. Similar to zeolite powder, mixing MK into the concrete or test mortars will make steady growth of later time strength, and the MK's contribution to concrete strength will catch up with or even exceed zeolite powder. Wild et al. believed that this is due to three causes: filling effect (the most directly one), accelerating the cement hydration (happening in the first 24 hours), and the volcanic ash gelatinization (When the content of MK varies from 5%-30%, the effect can last for 7 to 14 days at most.) .The experiment of DING Tao et al. indicates that mixing the MK into the portland cement solely would improve the compressive strength for 10 MPa[3]. Qian Xiaoqian and Li Zongjin found that mixing 10%-15% MK into the concrete would improve its properties: tensile strength, compressive strength, bending strength and even impact toughness to certain extent [4].

Because adding MK will greatly affect and improve the pore structure, it has been reported that, with the addition of MK, the capillary porosity volume will decrease, while just the porosity whose diameter is 0.05-10 um can increase the penetrability. So it can increase the concrete's resistance to the erosive solution and ion diffusion, the freezing resistance will be improved, as well. Gruber's studies showed that the high reactive metakaolin (HRM) can improve the concrete durability conspicuously. Mixing 8% and 12% HRM into concrete, the chlorine ion diffusion coefficient is obviously lower than that of the reference block. The study of Khatib and Wild indicated that the sample with 15% MK could show better resistance to sulfate [5]. Walter's research showed that the concrete sample with MK can effectively restrain the alkali-aggregate reaction. The concrete with 10%-15% MK almost has no cracking and surface damage [6]. Kostuch found that the expansion as the result of alkali-aggregate reaction had disappeared in concrete that has 15% MK added.

In U.S.A, a high strength and quick setting cement which is stimulated by alkali has been developed in 1987, i.e., Pyrament. By using this kind of cement, the compressive strength of the concrete can reach 18 MPa in 4 hours and 82.8 MPa in a month [7]. In Finland, "F binding materials" was produced by using the alkali activator ($NaOH+Na_2CO_3$) and lignosulfonic acid [8]. In Japan, the metakaolin is also used for the preparation of binding materials.

3.3. Compound partition plate

In China, the using of vitrified bond bricks has a history of over 2,000 years. But according to the statistics, throughout the country, 80-100 units of fields have been destroyed to product bricks and such power-wasting manufacture makes the total coal used in chamotte production and heating amounts to 1,500,000,000 tons per annum. It is stipulated in Chinese State Department [1999] No. 72 File: "Since Jun 1, 2000, to Jun 30, 2003, solid chamottes are forbidden to use in 160 large and medium coastal cities." But the problem of the chamottes' substitutes has not been solved.

As usual, it is facile to use concrete hollow blocks as chamotte substitute, but it has many defects: the large shear strength and dry shrinkage cause walling cracks; the 3-cm wall thickness causes erosion and leakage of rain; at the same time, it's not easy to achieve insulating, either internal or external; and also, the tailor-made "paving cement apparatus" in construction makes the masonry complex. So the concrete hollow blocks are not popular till now.

Fly ash wall is made of 70% fly ash, 18% pearlite flour, and 12% gelatinization materials. It can be made into 3000×600×90 mm internal or external wall plates, and plates with 7Φ50 reinforcing steel of the same size. Its qualities are well conformity with Chinese Construction Industry Trade Standards: bend load 0.45 kN/m^2, single-point load > 0.8 kN, coefficient of heat conductivity 0.38 w/(m·k), sound insulation 39 db (one layer), 45 db (double layer).

3.4. Joint product method of coal-fired power and cement production

Coal plays an important roll in our nation's development, but it also causes heavy pollution during its production and using. In China, over 80% of coal is used to burn directly, and 1/3 of the production is used in coal-fired power. So the research and development of high efficiency clean burning have a very important reality mean to our nation.

On the other side, our nation's cement annual yield amounts to 6,000,000,000 tons, amounting to 1/3 of the world's gross output value. The cement production costs a lot of crude materials, including clay and lime rock, and the two are both non-renewable resources. The widely use of clay destroyed our land resources seriously; the mining of lime rock destroyed the terrains, landforms and vegetation, and during the production CO_2 is let out. Our electric industry lets out billions of tons of fly ash every year, in 2000, the discharge quantity adds up to 1,600,000,000 tons.

The chemical constitution of coal power's burned remains is about the same to clay's, so it is significance to combine the power generation with cement production. During the generation, adding in crude materials such as calcareous, and letting them react with burned remains can get clinkers, that is to say, the power generation can be directly abrasives into powder as cement.

Adding fertilizer can increase the burning efficiency of coal power to pledge normal production. Its combustion action is that: lower the burning temperature; improve the combustibility; reduce pollution. The application of mineralizer is to lower the synthetic temperature of clinkers, and make the minerals react at lower temperature.

This method has many advantages:

- It solved the problem of acid rain, and SO_X can react with lime into cement additive $CaSO_4$.
- It can make full use of the remaining energy of generation, saving crude materials.

- It reduces the pollution of fly ash, since the remains can be made into cement directly, heaps can be called off to save land, and avoid the damage of land resources.

The chemical constitution of output cement is C_2S ($2Ca{\cdot}SiO_2$), it reduces the discharge quality of CO_2 and the greenhouse effect. Since cement production and power generation both pollute the environment, making them into one can reduce the pollution greatly.

Combining two processes into one, avoids replication of constructing generation station and cement factory, as result, the investment was reduced and the input-output ratio was increased. This process simplifies the cement production technique, and abrasives the crude materials before power generation. The two processes take place at the same time, saving time.

3.5. Construction formwork technique [9]

Concrete is the most popular construction material in the world. But the settlement and removal of forms in construction waste a lot of manpower, materials and funds; at the same time, the heat preservation of concrete still can't be achieved. From 1960s to 1970s, some skills, such as large type formworks and slip forms were tried in use, but were not popular since the high costs and complex technique. Light bricks were used as substitute of chamotte, but still no widely used because of its poor durability and shrink resistance.

These years, our nation's walling production and construction technique adheres to the principle of low cost, energy-saving, environment protecting, less pollution and easy construction, to develop new walling materials, but still hasn't any breakthrough until now.

Construction formwork is a brand-new concrete construction technique, which provides construction of bearing walls and heat preservation. The key technique is construction formwork, which made up of snakeskin meshes, stiffening rib, zigzag loop and benzene plate, as Fig. 3 shows.

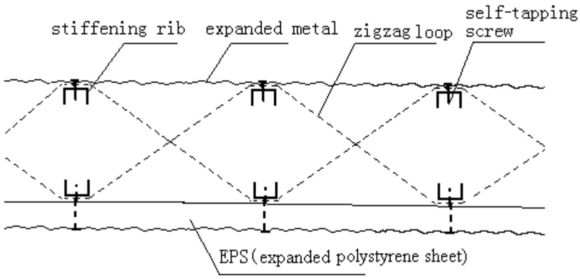

Fig. 3: Conformation of formwork

The formworks are manufactured in factories and packed on-the-spot, pouring in concrete can get formwork concrete. The technique constructs easy, densified by itself without vibration, and has little noise pollution, constructs fast, safe and civilized. The structure has good earthquake resistance and can be filled with many industry wastes such as fly ash, gangue, and tailing. The Construction Formwork Concrete Structure Technique Regulation DB21/1210-2001 chiefly written by Professor Wang, has been put into use since April 1, 2001.

Since its defects that rust-eaten of zigzag loops, durability of the whole structure, the irrationality of formwork structure which will affect the joint construction and the hardness of steel distribution inside meshes, the structure only suits for constructions under multistory. Professor Wang has invented new generation of formworks, especially suits for under multistory, constructs more easily, more safety.

3.6. Super namometer-hole heat insulator [10, 11]

The super heat-insulating material is the heat insulator which coefficient of heat conductivity is lower than that of non-convection air in certain condition. Because the free paths of the main constitutions –oxygen and nitrogen –are both about 70 nm,only when most of hole size is less than 50 nm can avoid internal convection. In addition, the largest material bulk density should be less than 171 kg/m^3.

By now, all the nm-hole heat insulators all use SO_2 aerogel as the carrier of nm-hole TEOS is widely used as the main crude material of SiO_2 aerogel. Because of the high cost of TEOS, it's important to find its substitute. Since the pureness of construction insulating materials is not very critical, certain industry wastes can be used as TEOS's substitute.

The process flow is making wastes into water-glass, because its particle phase is some Si-O net structure site in metastable state, and the size range belongs to colloid particle size range. Water-glass will turn into hydrogel by adding in sodium fluosilicate, then let gas instead water in the position during desiccation can get nm-hole aerogel. This gel must be modified because of its low strength and ductility. Usually, fiber is added in order to strengthen it.

4. Summary and Conclusions

The first part of this paper shows the situation of industry wastes in brief. The second part is the theoretical basis of industry wastes research and development. The last part introduces the developments of high-technical research of industry wastes, most of them are latest achievements and patents of the author himself, and also represent present level of our nation's utilization research of industry wastes.

References

1. Wang Lijiu, and Cheng Shifan. "Test Investigation of Industrialization of Fly Ash Building Micro-crystal Glass." *New Building Material* 4, 1994.
2. Wang lijiu, Li Ming, and Wang Baomin. "Present State and Perspectives of Metakaolin Cement." *Annual Report of 2002* 8, 2000.
3. Ding Zhu, Li Zhongjin, and Wu Keru. *Transaction of Building Material* 6, 2001, 105-109.
4. Qian Xiaoqian, and Li Zongjin. *Concrete and Cement Production* 1, 2001, 16-18.
5. Khatib, J.M., and Wild, S. *Cement Concrete Research* 28(1), 1998, 83-92.
6. Walter G.V., and Jones T.R. "Effect of Metakaolin on Alkali-Silica Reactions in

Concrete Manufactured with Reactive Aggregates." *Proceedings of the Second International Conference on the Durability of Concrete*, Vol. II, ed. V. M. Malhotra, Montreal, 1991, 941-947.

7. Ding Zhu, Zhang Decheng, and Wang Xiangdong. *Silicate Journal* 4, 1997, 57-61.
8. Wang Lijiu, and Zhao Xianghui. "Progress in Research on Ecological Cement." *Housing Materials & Application* 4, 2002, 19-21.
9. Wang Lijiu, and Liu Xianfu. "DP Construction Formwork." *Housing Materials & Application* 4, 1999.
10. Ni Wen and Liu Fengmei. "Principle and Preparation of Nanophase Pore Super Heat-insulating Materials." *New Building Materials* 1, 2002.
11. Wang Lijiu and Shi Fei. "Investigation of Developing Nanophase Pore Super Heat-insulating Materials by Industrial Waste." *Annual Investigation Report.* Building Material Institute, Dalian University of Technology, 8, 2002.

ENVIRONMENT-PROTECTING UNBAKED CEMENT AND ITS HYDRATE MECHANISM

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Abstract

This experiment was carried out to make cement with a strength of 42.5 MPa using blast-furnace water-hardened slag and two active agents. The authors probed the hydrate mechanism of the cement based on the measurements of pH value and heat of hydration and XRD patterns. They also observed hydrate production through an electron scanner. This research found that the cement hydrate process includes several stages, such as an inducement prophase, inducement phase, accelerating phase, the second inducement phase and the second accelerating phase. The main hydrate products were C-S-H gelatin, C_3AH_{13}, AFt, AFm, albite, and micro plagioclase.

1. Introduction

China increases its cement production each year. It is estimated that cement production will be 800-850 million tons by the year 2010, equaling nearly half of the world total cement output. One ton of cement needs about 0.8 ton of portland cement clinker, which requires one ton of CO_2. From 1995 to 2010, the cement industry in China will add 7.5 billion tons of CO_2 to the earth's atmospheric layer, about half of the world discharge amount. With this amount of CO_2 production, we can see how the Chinese cement industry influences the environment. We must find a way to strictly limit the output of portland cement clinker in the future. One of the goals of this research is to research and develop a environment-protecting binding material.

Low activity water-hardened slag and heavy slag have not been used efficiently. The current method for discharging and stacking the slag pollutes the environment. So compounding non-clinker or little-clinker environment-protecting unbaked cement by stimulating the activity of slag it would be a significant innovation.

The purpose of this research is to compound 42.5 environment-protecting unbaked cement with the water-hardened slag, the primary raw material, and the compound activated agent by simple grinding-mix technology (i.e., omitting calcinations process) and to explore the hydrate mechanism of the environment-protecting unbaked cement.

2. Raw Materials and the Main Properties of the Environment-protecting Unbaked Cement

Water-hardened slag from the Hancheng iron factory was used for this research and its chemical composition is listed in Table 1. The basicity coefficient and mass coefficient were found by calculating the chemical component by 0.930 and 1.795, respectively. The slag is acidic. The fineness of the selected slag was 0.08 mm, and the sieve residue was 2%.

Table 1: Chemical component for water-hardened slag

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	Alkalescence coefficient	Quality coefficient
Ratio (%)	32.40	15.24	2.41	40.26	4.76	0.98	0.930	1.795

X-ray diffraction of the slag is shown in Fig. 1. Analysis shows that 65% of the slag is noncrystalline, with significant amounts of active SiO_2 and active Al_2O_3 present. In addition, there is about 35% gehlenite $2CaO \cdot Al_2O_3 \cdot SiO_2$ and 4% hemative in water-hardened slag, so it is a type of low-activity slag.

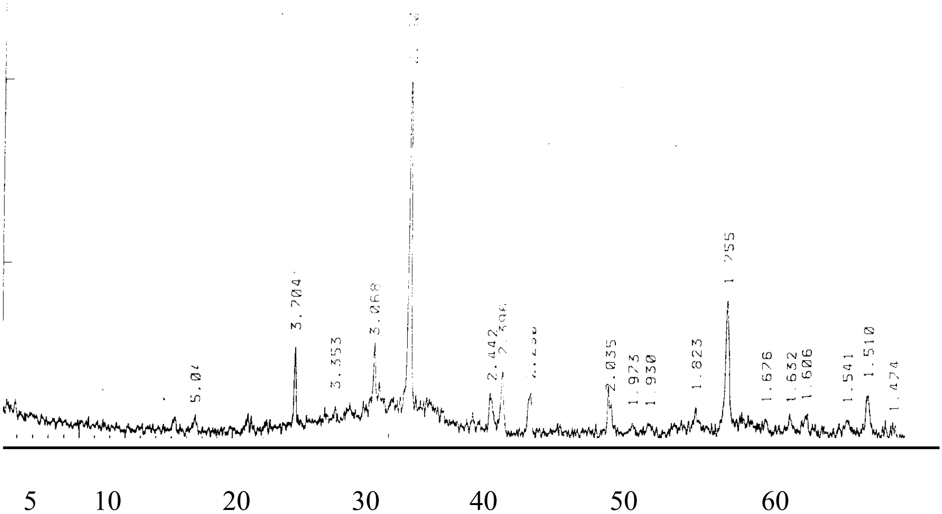

Fig. 1: XRD patterns of water-hardened slag

According to experiments, the authors chose active booster B and C. Different components of fines are mixed for 8 minutes in a ball crusher. The mortar strength test for environment-protecting unbaked cement is detailed in specification ISO679. The standard quality for sand and water used as cementing material are 450g, 1350g, and 225 g. The result of the experiment is shown in Table 2. We can see that the optimum proportion of active booster B is 3.5% and active booster C 2.5%, the compressive strength of 3d and 28d is 26.6 and 44.9 MPa, respectively; the bending strength of 3d and 28d is 5.1 and 6.6 MPa. The cement conforms the national strength grade standard (GB1344-1999) for portland cement.

Table 2: Paste strength under different mix proportion

Serial number	Water-hardened slag (g)	Component B (g)	Component C (g)	Compression stress (MPa)		Folding stress (MPa)	
				3d	28d	3d	28d
1	433.1	9.8	7.1	8.4	20.1	2.9	4.4
2	429.6	11.8	8.6	17.1	28.7	4.0	4.8
3	426.4	13.7	9.9	22.0	35.7	4.9	6.1
4	422.7	15.9	11.4	26.6	44.9	5.1	6.6

The other technological properties measured by Chinese national standard GB/T1346-1989 indicate that water consumption for standard consistency is 152 ml, higher than water consumption for ordinary portland cement. Initial set time is 78 minutes and final set time is 135 minutes, both a little longer than ordinary Portland cement set times. Volume stability passes the pat test. Overall, properties of this cement conform completely to the demands of Chinese national standards.

3. Hydrate Reaction and Mechanism Analysis of Environment-protecting Unbaked Cement

The activity level of water-hardened slag depends on its chemical composition and internal structure (noncrystalline content). The slag demonstrates a rapid-cool effect when mucked out. It forms a loosely netted glass structure with many apertures. It can be described by the Zachariasen three-dimensional distorted netted structure.

Water-hardened slag is hydrated when the sharp reaction of active agent and OH^{-1} ions is initiated by the agent when OH^{-1} enters the aperture of the netted glass structure. The hydration mechanism of cement can be analyzed by determining the change in

OH^{-1} density (pH value) in the cement-water system and the hydrate heat-releasing speed.

The x-ray diffraction experiment indicates that the main hydrates of the 28-day-old cement include C-S-H Aft C_3AH_3 Afm albite and microplagioclase, etc. As seen in Fig. 2, the main hydrates are C-S-H and AFt. In addition, the cement-water system pH value and the cement heat of hydration are determined by studying the cement hydrate and water (1:50) solution, which indicates the curve of the pH value change as seen in Figure 3. The heat of hydration for the cement is determined using the method formulated by the Chinese national standard board. When environment-protecting unbaked cement is mixed with water, the excitation medicament acts rapidly in water and releases ions such as OH^-, Na^+, and SO_4^{2-}. The pH value of the system increases rapidly and the hydration reaction occurs at the same time. The OH^- ions in the solution get into the reticular formation gap of the water-hardened slag's vitreous body, acts with the activity silica-alumina positive ions, scatters, and dissolves the slag's reticular formation, dissolving out Ca^{2+} and forming C-S-H, Aft, C_3AH_3, albite, and micro plagioclase.

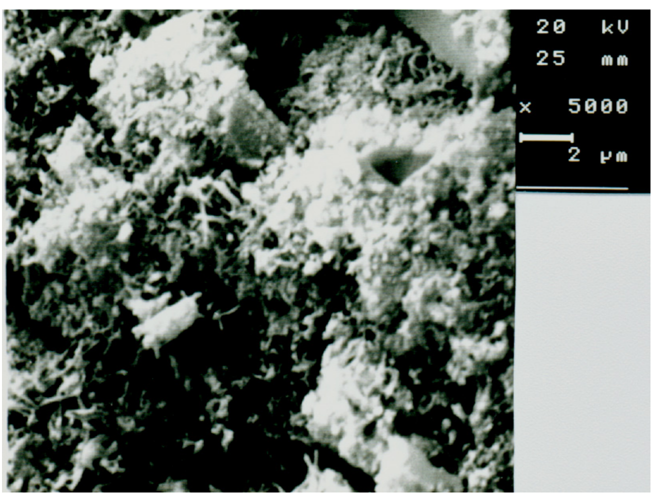

Fig. 2: Scanning electrical-mirror photo of 28-day age

Meanwhile, the Ca^{2+} ions in solution increase, causing over-saturation of the C-S-H and hydration calcium aluminate, making the hydrate condense and increase. In slag, $2CaO{\bullet}Al_2O_3{\bullet}SiO_2$ reacts with the SO_4^{2-} Ca^{2+} Na^+ ions and forms AFt and C-S-H (part of Ca^{2+} is substituted by Na^+).

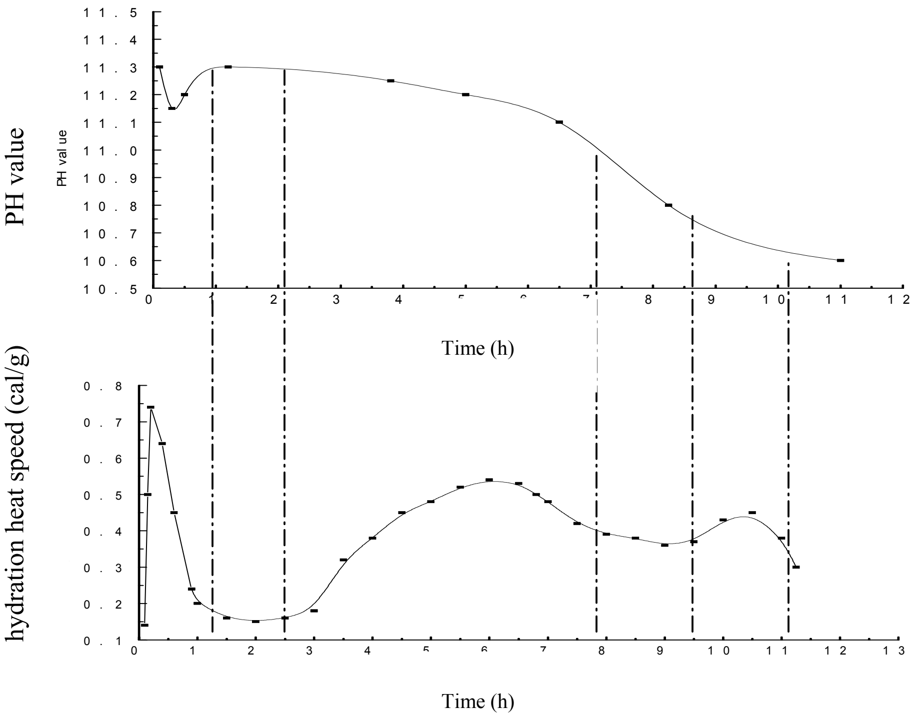

Fig. 3: PH value and hydrating heat speed curve of cement

When the hydration reaction reaches a certain point, Ca^{2+} and SO_4^{2-} ions are not enough because of excessive consumption. At this point, AFt forms sulphuric hydration calcium aluminate sulfate (AFm). The final products are C_3AH_{13} AFt AFm albite and C-S-H (in which a part of Ca^{2+} is substituted by Na^+).

It can be seen from the reaction mechanism of the cement that the solution and reaction of B and C creates AFt deposits when the cement is mixed with water. It separates the slag from solution and controls the hydration process. At the beginning of the hydration reaction, the pH value of the solution increases rapidly, the hydration of cement is very fast, and the hydration process moves into the pre-induction period. As seen in Fig. 3, as the pH value increases to 11.3 or so, the slag reacts quickly with Ca^{2+} OH^{-} SO_4^{2-} Na^{+} ions of the medium and forms a hydrate of AFt C-S-H (a part of Ca^{2+} is substituted by Na^{+}). At this point, the pH value of the solution drops to 11.1 and the cement's hydration rate increases rapidly. The main product of this phase is AFt. After 20 minutes, AFt and C-S-H adhered to the slag grain surface as it increases, impeding the diffusion of OH^{-} Ca^{2+} SO_4^{2-} ions in the slag reticular formation, postponing the hydration velocity of the cement. This process lasted about an hour until the hydration reached the induction period.

As the speed of hydration in the induction period decreases, the pH value of the solution continued to be high. Extensive hydration makes AFt and C-S-H on the surface of slag grain become thick and crystal stress is produced. Crystal stress is increases with increased thickness. When the crystal stress reaches a certain threshold, AFt and C-S-H burst locally, exposing the fresh surface of slag grain that is not hydrated. The slag's fresh surface forms the hydrate of AFt at the reaction of OH^{-} Ca^{2+} SO_4^{2-} Na^{+} etc, helping the exploded surface recover. The hydrated surface of the slag grain produces the process of "warp-crack," and meanwhile the hydrate scatters to the surrounding slag grain gradually and fills up the space occupied by the solution between slag grains. The pre-induction and induction periods consume a great number of SO_4^{2-} ions as the density of SO_4^{2-} ions in solution drops. Then the system hydration accelerates. We can see from Fig. 3 that the pH value of the solution starts to drop for 2.5 hours before beginning the hydration acceleration period.

The observed hydration of the acceleration period is mainly the reaction between Ca^{2+} OH^{-} Na^{+} ions and active SiO_2 Al_2O_3. The main hydrate is C-S-H and C_3AH_{13} albite and micro plagioclase. The hydration velocity of cement in this stage accelerates as the pH value of the solution gradually decreases. After the acceleration period, the slag hydration is violent and the velocity of hydrate heat-release is fast, resulting in a heat-release velocity peak of about 6 hours. Heat-release velocity has been very slow, about 7.5 hours, and the curve of heat-release velocity tends to be smooth, ending with the hydrate acceleration period before the stable period.

The stable period of the hydrate continues for 9.5 hours. At this point, the second hydrate period begins, and the lack of SO_4^{2-} in the system leads to a reaction between hydrate AFt and Al_2O_3 in the slag and forms AFm, releasing a large amount of hydration heat in the process. As the hydrate heat-release velocity increases, the second hydrate heat-release peak appears at about 10.5 hours. The second hydrate acceleration period ends after about 1 hour. When the cement hydration gets into the second stable period, there is not an obvious hydrate heat-release velocity peak and the hydrate velocity of slag is slow. This process continues until the end of cement hydration.

During this process, the paste of environment-protecting unbaked cement completes the process of interlace conjunction and loses its working plasticity, forming a rigid-brittle material.

4. Conclusions

As low activity water-hardened slag is processed to increase the activity level, using up to 94% slag, the researchers found that is possible to make environment-protecting unbaked cement could that meets the standard 42.5 slag cement in strength condensing time and cubic stability.

X-ray diffraction and scanning electrical-mirror experiments indicate that the main hydrate of this cement is C-S-H amorphous gel C_3 AH_{13} AFt Afm, albite, and microplagioclase. According to the change in pH values and the determination of heat hydrate, an analysis of the hydrate process of this cement, includes the pre-induction period, induction period, acceleration period, stable period, the second acceleration period, and the second stable period.

References

1. Wu, Zhong-wei. "Green High Performance Concrete and Science-Technology Creation." *Journal of Building Materials* 1(1), 1998, pp. 1-6.
2. Gesell, S.N. *Advances in Cement Technology*. India: Pergamon Press Ltd., 1983.

RESEARCH ON MgO-$MgCl_2$-H_2O SYSTEM CERAMSITE EXEMPTED FROM SINTERING

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Abstract

A new type of light aggregate from sintering is investigated. The aggregate has low apparent density, high strength, and high durability. This research introduces the MgO-$MgCl_2$-H_2O system to light aggregate production. The other point is that the closing technology will make a sealing course covering around the ceramsite to separate itself from those corrosive mediums effectively, so much as water.

Test results indicate that the strength of this ceramsite is at least one degree higher than those with the same degree of apparent density. The microstructure of the ceramsite sealing course has been testified by SEM testing. It shows remarkable economic and social benefits for using magnesite, halogen, and fly ash to develop new type light aggregate exempted from sintering.

1. Introduction

Since the 1990s, the research on light aggregate has been carried out in many fields. Light aggregate can be classified into sintered light aggregate exempted from sintering according to its production technology. When it comes to raw materials, light aggregate includes shale ceramsite, fly ash ceramsite, pumice ceramsite, glass ceramsite, diatomite ceramsite, etc. The MgO-$MgCl_2$-H_2O system ceramsite exempted from sintering discussed in this paper is different from normal man-made light aggregate. Its strength is at least one degree higher than the strength of those with the same degree of apparent density. High performance ceramsite cured in natural state is made from magnesite, $MgCl_2$, fly ash, and so forth. It is a kind of light aggregate, which can be produced through a series of manufacturing processes such as grinding, mixture making, foaming, ball-up, and natural curing. During foaming, gas is generated, which makes the ceramsite porous, light, and with a low density. It shows remarkable economic and social benefits by using magnesite, halogen, and fly ash to develop new type light aggregate exempted from sintering.

2. Experiment

2.1. Raw materials

2.1.1. Magnesite

The raw material in this test was made in Haicheng city, Liaoning Province. It was manufactured into magnesite after being calcined in the temperature of 600°C. The chemical composition of the raw material is displayed in Table 1. The raw material was calcined for 2 hours in silicon carbide rod electric-furnace with the temperature 850°C, and then it was cooled down to room temperature.

Table 1: Chemical composition of sample (in mass percentage)

MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	Loss
88.92	1.97	0.66	0.40	1.34	6.30

2.1.2. $MgCl_2$

In this test, the molecular expression of the raw material is $MgCL_2{\cdot}6H_2O$. Industrial material will be used when produced in industry.

2.1.3. Fly ash

The fly ash used in this test was produced in Tieling. Its chemical composition is listed in Table 2.

Table 2: Chemical composition of fly ash (in mass percentage)

SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Loss
53.19	6.16	28.52	1.91	1.47	8.75
47.84	6.69	25.23	1.24	1.55	17.45

2.1.4. Foaming

In this test, we use the foaming developed by our teaching and research section. Its chemical ingredients are organic oxidant and amid-based compounds.

2.2. Preparation of the pig-iron of the ceramsite
The magnesite and the magnesium chloride were mixed with the molar ratio of 4 to 6, and then fly ash and the foaming were added. As a result, the magnesian cement was obtained. The volume of the test sample was 200×400×600 mm^3 (0.144 m^3), while the volume was 2 m^3 when the pig iron of the ceramsite was produced in industry.

After the initial setting of magnesian cement, the cement was distilled into the plate so it could turn into balls. Then a layer of acrylic acid waterproof paint was sprayed, which can lower the water absorbing capacity of the test sample remarkably. Before putting it to use, the balls must be cured in natural condition for a few days. The production process of the magnesian ceramsite is illustrated in Fig. 1.

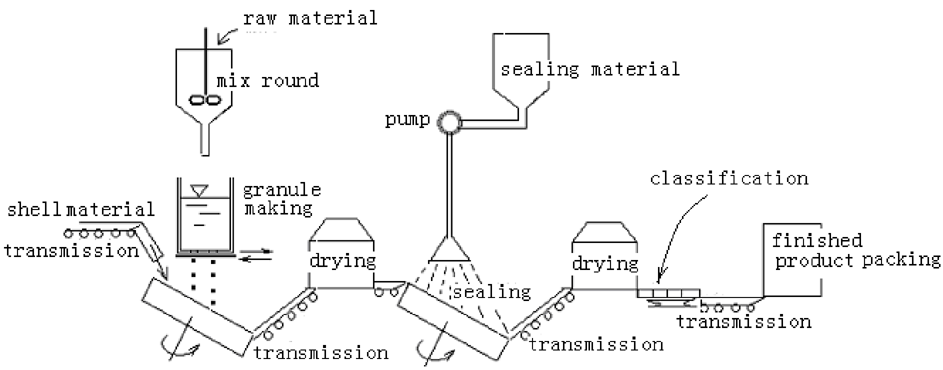


Fig. 1: Production process of the magnesian ceramsite

3. Discussion and Results

3.1. Property test
The property test in this paper was carried out in accordance primarily with the new devised national standard, light aggregates, and methods of tests (GB17431-1998.)

3.1.1. Apparent density

The test sample, which volume was 4 liters, was screened with the size of sieve pore 5.00mm. Then the remnant was separated into two portions, and one of the portions was baked out. The mixture with weight from 300 to 500 g, which was composed of the two portions of the remnant, was weighed after being mixed uniformly. Then the mixture was put into a graduate and soaked in water for 2 hours. After this, the mixture was taken out and put into another graduate, with the volume of 1000 ml. Following this, 500 ml of water was poured into the graduate. The test sample, which was floating on the surface, was pressed into water with a known volume circular metal slab, and the water level was measured.

The apparent density of the ceramsite can be calculated according to the following equation:

$$\gamma_k = \frac{g \times 1000}{V - V_1 - 500}$$

In this equation, γ_k is the unit weight of the ceramsite, g is the weight of the test sample in milliliters, V_1 is the volume of the circular metal slab in milliliters, and V is the water level of the graduate after adding the sample with the metal slab.

3.1.2. Strength of ceramsite

The strength of ceramsite is determined by the following equation:

$$R_1 = \frac{P}{F}$$

In this equation, R_1 is the strength of the ceramsite, P is the stress value sustained by the circular metal slab at the depth 20 mm under the water, and F is the projected area (i.e. the area of ram model F, 10000 mm^2).

3.1.3. Water absorbing capacity

The water absorbing capacity of the ceramsite is determined by the following equation:

$$W_c = \frac{g_1 - g}{g} \times 100$$

In this equation, W_c is the water absorbing capacity of the ceramsite (Mass %), g_1 is the weight of the test sample soaked in water, and g is the weight of the test sample baked out.

3.1.4. Soften factor

The soften factor of the ceramsite is given as follows:

$$K = \frac{R_1'}{R_1}$$

In this equation, *K* is the soften factor of the ceramsite. R_1 is the compressive strength of the ceramsite, which was soaked in water for 1 hour, and R_1 is the compressive strength of the ceramsite kept in dry state.

3.1.5. Sturdiness

In this part, the sample test was weighted and then put into a network of triangle. A container with sodium sulfate liquid was prepared. After that, the test sample and the network, as a whole body, were soaked in the liquid. The volume of the liquid is at least 5 times the test sample, and the temperature of the test sample should be restricted to the range from 25°C to 35°C. Before laying the network of triangle into the container, the liquid should ascend and descend for 25 times in order to eject the bubble in the test sample. The distance between the bottom of the network of triangle and the bottom of the container should be kept at about 3cm. The distance between the networks should be no less than 3cm. The surface of the liquid should be higher by at least 3cm than the test sample counterpart.

Soaked in water for 24 hours, the network of triangle was taken out from the container and roasted in bake out furnace for 4 hours. So far, the whole cycle was completed. When the test sample was cooled down to the temperature 25°C to 35°C, the next cycle started. In the second cycle, the time during which the test sample was soaked in water changed to 4 hours. This was repeated 5 times.

The test sample was soaked for an hour in water with the temperature lower than 25°C. Afterwards, it was rinsed in water with the temperature 60°C. The volume of the water was at least 10 times the test sample. Soaked in water like this, the test sample was roasted to get a constant weight. After being cooled down to the room temperature, the test sample was screened with the aperture that was one degree lower than the size category fraction. Then the remnant was weighted.

The weight loss of the test sample is calculated as follows:

$$Q_j = \frac{g_1 - g_2}{g_1} \times 100$$

In this equation, Q_1 is the weight loss of the test sample (%), g_1 is the weight of the sample in dry state before the test, and g_2 is the weight of the sample in dry state after the test.

3.1.6. Particle diameter

The particle diameter of the test sample is in the range of 5 to 15mm, which has a good screen sizing.

3.2. Test results

The results of the test are listed in Table 3.

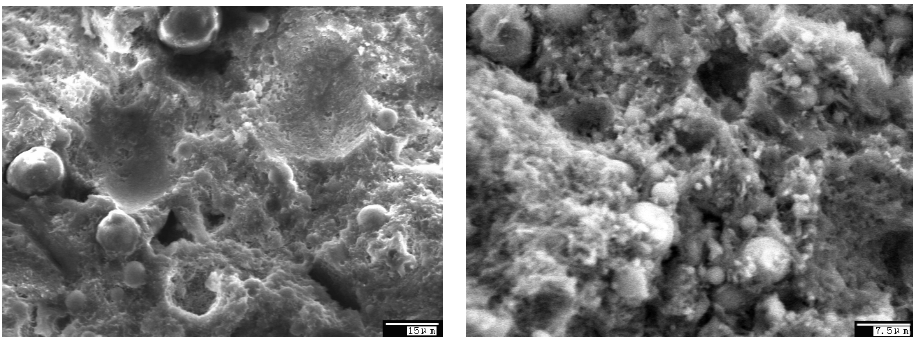
Table 3: Results of the property test of the ceramsite

	Apparent density (kg/m^3)		Strength (MPa)		Water absorbing capacity (%)		Soften Factor (%)	Sturd -iness	Particle diameter
	Natural state	Absolutely dry state	Natural state	Absolutely dry state	2h	24h			
Index	750	650-680	8.5-9.0	9.0-10.0	10	15	0.9	2.5	5-15

3.3. Results discussion

3.3.1. Hydration phase of oxychloride magnesium cement

Oxychloride magnesium cement has series of characteristics, such as fast hardening, high strength, light weight, and good adhesion, and the hydration phase primarily is $5M_g(OH)_2 \cdot M_gCL_2 \cdot 8H_2O$ (5-1-8 phase). The 5-1-8 phases have two fundamental structures: type I and type II. Type I is more stable than type II. The 5-1-8 phases, which are illustrated in Figs. 2 and 3, have a needle-like crystal and a compact structure. The needle-like crystal has a high strength.



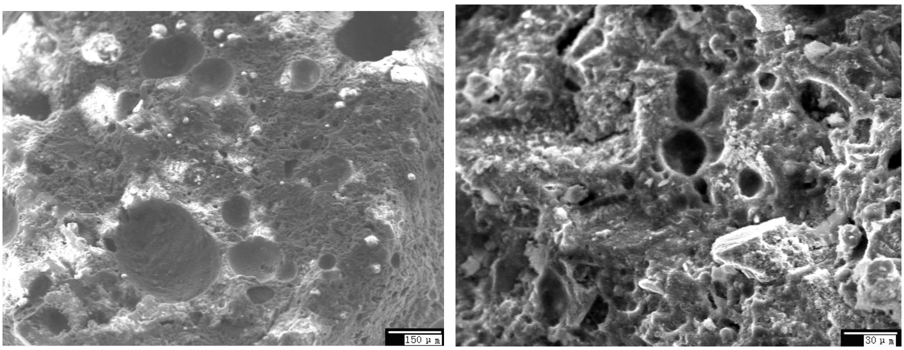
(a) 1000 times (b) 2000 times

Fig. 2: Microstructure in SEM of the magnesian ceramsite

3.3.2. Theory of expansion and sealing

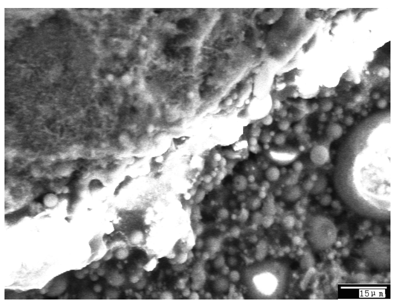
The expansion mechanism of the foaming is as follows: the organic oxidant and acid amides compounds produce many uniform small air bubbles, which expand the volume of the balls and make them porous. The diameter and content of the bubbles added, were connected not only with the content added, but also with the extend of mixing before forming, with temperature, and with time.

The purpose of the sealing the ceramsite was to prevent the permeability of oxychloride magnesium cement products with water. Using acrylic paint as waterproof layer, the chlorine ions in the ceramsite, which make the ball permeable, were kept in the waterproof layer. This prevented more water molecules from entering into the ceramsite body. At the same time, the phase changes of $M_g Cl_2 \cdot 6H_2O$ were favorable to energy saving through adjusting the temperature of the building around. From Fig. 4, we can see that there is a compact layer between the ceramsite body and the fly ash coating, i.e. sealing layer.



(a) 100 times (b) 500 times

Fig. 3: Microstructure in SEM of the magnesian ceramsite



1000 times

Fig. 4: Sealing layer structure of the magnesian ceramsite

4. Conclusions

- The magnesian ceramsite exempted from sintering is superior to other normal ceramsite exempted from sintering in lower density, high strength, and low permeability. It is a new man-made light aggregate with high performance, which apparent density is 650-680 kg/m^3. Its compressive strength comes out at 10.0 MPa, which is at least one degree higher than those with the same degree of the apparent density.
- Sealed by acryl waterproof layer, the magnesian ceramsite has a higher water-resistance. Moreover, its water absorbing capacity is reduced largely.
- The difficult point of shaping technique for the magnesian ceramsite is initial setting time control, which is related to temperature and mixing degree.
- It shows remarkable economic and social benefits for using magnesite, halogen, and fly ash to develop new type light aggregate exempted from sintering.

References

1. Yuan Runzhang. *Science of Cementious Materials*, 1989, 61-68.
2. Wang Lijiu. "Study on the fracturing mechanism in expansion of the hardened magnesium oxychloride cement." *Silicate Transaction* 23(4), 1995, 471-475.
3. Li Fuyan and Wang Lijiu. "Study of microstructure and properties of material on MgO-MgCl2-SiO2-Al2O3-H2O system." *Journal of Dalian University of Technology* 33(3), 1993, 328-332.
4. Cao Mingli. Experimental studies on the improvement about F-adjusting agent to magnesium cement, Master degree paper, Wuhan University of Technology, 1996.

RESEARCH ON SINTERED FLY ASH AGGREGATE OF HIGH STRENGTH AND LOW ABSORPTION OF WATER

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Abstract

Research on a sintered fly ash aggregate is presented. The aggregate was manufactured through material orthogonal test and quick chilled firing schedule test. It displayed high strength (7.8 MPa) and low water absorption (4.2%). Lightweight aggregate concrete made with this aggregate reached compressive strength more than CL60, slump over 20 cm, 60 minutes slump loss less than 2 cm, and expansibility higher than 50 cm. Such properties meet the modern concrete requirements for high strength and pump-ability. This new technology has important economic and social impacts on the use of industrial waste residue and on the environmental protection.

1. Introduction

Fly ash and auxiliary raw materials—clay, canbyite-melt sludge, coal, and paper-mill waste—were used to produce a sintered fly ash aggregate. The manufacturing process was as follows: (1) drying, grinding, and mixing of raw materials; (2) palletizing and desiccating, presintering, and sintering of raw meal pellets. During sintering, raw meal pellet softens, and expanded gas forms from the chemical reaction of Fe_2O_3 and C. The expansion mechanism of sintered lightweight aggregate is a dynamic balance process of expanded gas escaping from pellet and inhibiting effect of fitting viscosity liquid [1]. The interaction described above results in the expansion of sintered fly ash aggregate. Research on mix ratio optimum test and quick chilled firing schedule test was done. Test results have indicated the chosen technical measures are feasible.

2. Raw Materials and Test Methods

2.1. Raw materials

Nine supplementary materials were studied in this study: (1) deposition fly ash from Wuhan Qingshan Heating-and-Power Center, Hubei, China, whose 80μm retained percentage is 24%; (2) quality fly ash from Wuhan Yangluo Heating-and-power Center, Hubei, China, belonging to first grade according to GB 1596-91; (3) clay from Wuhan Yangluo, Hubei, China, whose index of plasticity is 3.8; (4) canbyite-melt sludge from Wuhan Steel Corporation, Hubei, China; (5) coal from Henan Pingding Mountain Coal Plant, Hunan, China, whose ash content is 18.10%, volatile content is 29.96%, and fixed carbon is 51.94%; (6) paper-mill waste from Wuhan Paper Corporation, Hubei, China; (7) 42.5R portland ordinary cement from Wuhan Huangshi Cement Plant, Hubei, China, whose specific surface is $310m^2/kg$; (8) sand from Wuhan Sand Plant, Hubei, China, whose fineness modulus is 2.8 and mud content is 1.0%; (9) water-reducing admixture from Wuhan Haoyuan Admixture Plant, Hubei, China. Chemical composition of deposition fly ash, quality fly ash, clay, canbyite-melt sludge, and cement are shown in the Table 1.

Auxiliary raw materials (clay, canbyite-melt sludge, coal, and paper-mill waste) were used in this test in addition to the principal raw material (deposition fly ash). The auxiliary materials were used to facilitate palletization, and expanded gas escaping from pellet and inhibiting effect of fitting viscosity liquid were matched during sintering.

Table 1: Chemical composition of raw materials (wt %)

Raw materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Loss
Deposition fly ash	53.85	26.50	4.06	3.20	1.30	1.12	1.18	8.69
Quality fly ash	50.00	32.85	4.21	4.91	1.58	1.42	1.35	3.22
Clay	70.59	13.49	5.94	1.11	1.10	0.47	0.50	6.80
Canbyite-melt sludge	3.60	4.79	22.05	31.60	3.41	3.02	3.22	28.31
Cement	21.47	5.81	4.04	59.64	3.24	–	–	2.44

2.2. Test methods

In this study, correlative properties of sintered fly ash lightweight were tested according to GB/T 17431.1-2-1998. Fineness of deposition fly ash, canbyite-melt sludge, and clay was tested using the 80μm sieve according to GB 1345-91. Lightweight aggregate concretes were tested according to JGJ51-90. Correlative properties of lightweight aggregate concretes had been studied by measuring expansibility, slump, and compressive strength at different age according to GBJ80-85 and BGJ107-87. Test was designed by means of material orthogonal test to find out the optimum mix proportions of raw materials [2].

2.3. Factors and levels

According to the ranges of effective chemical composition and fitting dilating pressure promoted by C.M. Riley, the different factors and levels of auxiliary materials were designed as shown in Table 2.

Table 2: Factors and levels

Factors	Clay (g)	Canbyite-melt sludge (g)	Coal (g)
1	60	10	2
2	50	6	1
3	40	2	0

2.4. Test arrangement

Test was arranged with orthogonal table $L_9(3^4)$. Clay, canbyite-melt sludge, and coal were filled in line A, line B, and line C. Absorption of water, cylinder strength, and bulk density were appraisal index. Table 3 shows test arrangement and test results.

Table 3: Test arrangement and test results

No.	A Clay	B Canbyite-melt sludge	C Coal	Absorption of water (%)	Cylinder strength (MPa)	Bulk density (Kg/m^3)
1	1	1	1	14.1	3.8	776
2	1	2	2	8.6	6.5	819
3	1	3	3	5.4	7.8	834
4	2	1	2	10.2	4.5	785
5	2	2	3	6.7	7.2	827
6	2	3	1	8.0	6.4	815
7	3	1	3	8.6	5.4	806
8	3	2	1	9.6	5.8	812
9	3	3	2	7.8	6.8	822

A 300 g deposition fly ash was used in each test. Test processing parameters were as follows:

(1) 80μm retained percentage: deposition fly ash was 24%, and clay and canbyite-melt sludge were 15%. The volume ratio of paper-mill waste and water was 1 : 4.

(2) Pellets were produced by extruding. Water ratio of pellets was 25%, and size fraction of pellets was 5-20 mm.

(3) Drying schedule of green-compact was temperature 140° and time 4 hours, and presintering schedule of green-compact was temperature 700° and time 25 minutes.

(4) Sintering schedule of green-compact was that pellets were sintered at temperature 1250 degrees for 15min, then at temperature from 1250 to 1200° for 20 minutes, and then discharged from high temperature furnace.

3. Results and Discussion

The extreme deviation of appraisal index of absorption of water, cylinder strength, and bulk density was filled in Table 4. Analyzing the extreme deviation and appraising the aggregative index number, we chose the optimum mix ratio $A_2B_3C_3$, so the final mix ratio was that deposition fly ash : clay : canbyite-melt sludge was 150 : 25 :1.

Table 4: Extreme deviation of three performances index

Extreme deviation	Absorption of water (%)			Cylinder strength (MPa)			Bulk density (Kg/m^3)		
	A	B	C	A	B	C	A	B	C
K_1	28.1	32.9	31.7	18.1	13.7	16.0	329	267	303
K_2	24.9	24.9	26.6	18.1	19.5	17.8	327	358	326
K_3	26.0	21.2	20.7	18.0	21.0	20.4	340	371	367
k_1	9.4	11.0	10.6	6.0	4.6	5.3	110.0	89.0	101.0
k_2	8.3	8.3	8.9	6.0	6.5	5.9	109.0	119.3	108.6
k_3	8.7	7.1	6.9	6.0	7.0	6.8	113.3	123.6	122.3
R	1.1	3.9	3.7	0	2.4	1.5	4.3	34.6	21.3
Optimum	A_2	B_3	C_3	A_2	B_3	C_3	A_2	B_1	C_1

Based on the raw materials optimum mix ratio and the same processing parameters, fly ash lightweight aggregates were manufactured and their performances index numbers were filled in Table 5.

Table 5: Performances results of sintered fly ash lightweight

Absorption of water (%)	Cylinder strength (Mpa)	Bulk density (Kg/m^3)	Size fraction (mm)
4.2	7.8	843	5-20

To evaluate the actual application effect of sintered fly ash lightweight, trials of lightweight aggregate concrete had been made [3]. Test mix ratio and performance results of lightweight aggregate concrete with this aggregate were filled in Table 6. Results indicated that it was easy to manufacture lightweight aggregate concrete of compressive strength more than CL60, slump higher than 20 cm, 60 minutes slump loss less than 2 cm, and expansibility higher than 50 cm with the manufactured aggregate, by adjusting W/B, fly ash dosage, S/A, and quantity of total binding material. Such properties meet the modern concrete requirements for high strength and pump-ability.

Table 6: Test mix ratio and performance results of lightweight aggregate concrete

No.	Quantity of materials (kg/m^3)					A (%)	Expansibility / slump (cm)		Compressive strength (MPa)	
	W	C	F	S	L		0min	60min	7d	28d
1	160	477	53	619	506	0.8	68/25	58/21	52.8	62.5
2	160	495	55	607	498	1.2	58/21	51/19	56.6	69.6

Note: W = water; C = cement; F = quality fly ash; S = sand; L = lightweight; A = admixture.

4. Conclusions

The following conclusions can be drawn based on the present study:

- Through material orthogonal test and quick chilled firing schedule test, sintered fly ash lightweight aggregate demonstrated high strength and low absorption of water.

- Lightweight aggregate concrete made with this aggregate may have compressive strength more than CL60, slump higher than 20 cm, 60 minutes slump loss less than 2 cm, and expansibility higher than 50 cm. Such properties meet the modern concrete requirements for high strength and pump-ability.

References

1. Yu-shun Guo et al. "Comparison of properties of high performance lightweight aggregate and normal lightweight aggregate." *Journal of Concrete* (China), 2000(6), 22-26.
2. Wang Qing, Wang Li-jiu, and Ai Hong-mei. "Research on soda residue and fly ash high strength ceramsite." *Journal of Concrete* (China), 2000(6), 27-29.
3. Ding Qing-jiu et al. "Pumping technology of high-strength lightweight aggregate on bridge construction." *Journal of Concrete* (China), 2002(1), 58-60.

DEVELOPMENT OF STUDIES AND APPLICATIONS OF ACTIVATION TECHNIQUES OF FLY ASH

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Abstract

As green building material, fly ash is advantageous to solving the question of environmental protection and energy conservation. In this paper, combined with the author's research production, the latest development of studies and applications of activation techniques of fly ash is summed up, which is being looked forward to being useful to researchers and engineers. The latest researches show that when weight of fly ash reaches 20%-80% of cement, 32.5 grade cement or C40 concrete with high properties can be prepared through using activating techniques such as adding some high-efficiency fly ash activating admixture in cement or fly ash concrete.

1. Introduction

1.1 Source of pulverized fuel ash

Pulverized fuel ash, the solid dust collected from boiler flue in power plants, is also called fly ash. In recent years its discharge per year has been nearly upon 200 million tons. Because it can obviously improve the structure and properties of cement grout for the "morphological effect," "micro-particle effect," and "active effect" it has, it has become the most frequently used mineral admixture in the cement concrete engineering and one of the prime ingredients in preparation of High Performance Concrete in China. Pulverized fuel ash generally comprises monox 45%-60%, aluminum oxide 20%-30%, ferric oxide 5%-10% [1] as well as some minor calcium oxide, magnesium oxide, sulfur oxide, etc., and its major ingredients are influenced by combustion conditions and types of coal. Aluminum oxide and monox usually exist in the state of vitreous body, and the configurations are mostly silicon-oxygen tetrahedron, aluminum-oxygen tetrahedron or aluminum-oxygen trihedron that have large degree of polymerization, high bond energy along with low activity and slow hydration rate.

1.2 Utilization of pulverized fuel ash

Comprehensive utilization of pulverized fuel ash has great value. First, through substituting partial cement, it can be used as gel materials, and thus could reduce the pollution caused by cement production and the burden of environment. For example, when producing one-ton cement, the amount of carbon dioxide discharged is about one ton, which pollutes air much. Second, mass utilization of pulverized fuel ash can save a large quantity of energy. Furthermore, it can also improve some engineering techniques such as the enhancement of the workability of fresh concrete, the improvement of the durability of concrete and the decrease of the hydration heat of cement in mass concrete construction, etc. In a word, taking advantage of pulverized fuel ash, which is a kind of green material or environment coordination material makes social benefit and economic benefit advance together, and conforms well to the strategy of continuable development. Hence, with further understanding and study in pulverized fuel ash, focus on how to enhance its activity so as to increase its amount in concrete has gradually been one of central problems.

1.3 Source of Activity in Pulverized fuel ash

If taking into account of the chemical component, the potential activity of pulverized fuel ash is determined by the content of activated aluminum oxide and activated monox. According to the prescript of ASTM C618 in the United States, total content of SiO_2, Al_2O_3, and Fe_2O_3 must be over 70%; The JISA 6201 in Japan requires that percentage of SiO_2 be greater than 45% which is 40% prescribed in IOCT 6269 put forth in the period of the Soviet Union [2]; In most power plants in China, content of SiO_2 plus Al_2O_3 is over 60%. While in consideration of phase structure, the potential activity is related to the content of vitreous body as well as that of amorphous aluminum oxide and monox. Moreover, as for the pulverized fuel ash with the same specifications or characteristics, the major factor is the degree of fineness. Usually, higher degree of fineness corresponds to larger specific area, higher surface energy and more acting faces, which illustrate higher activity. These factors mentioned above are important to improve activity of ash coal, and should be studied specifically.

2. Evaluation of Activity

Lime absorption value method and lime strength method are generally used to evaluate activity of pulverized fuel ash.

2.1 Activity index

According to “The Pulverized fuel ash Used in Concrete and Cement,” the criterion in China, activity of pulverized fuel ash is assessed by the compression strength ratio. Two shares of cement are prepared, one contains 30% pulverized fuel ash, and the other is ash-free. Then make mortars of the two cements with the same fluidity. The ratio of the compression strength of them calculated after 28 days is the value. It is prescribed that the value of grade□must be greater than 75% and that of grade be greater than 62% [3]. Activity is considered enough when the value is up to 0.85 [4].

2.2 Index Number K proposed by Г.Н.КииГиеа of USSR

$$\mathbf{K} = \frac{Al_2O_3 + CaO}{SiO_2}$$

Pulverized fuel ash can be classified into four categories according to different values of **K** [5].

In 1967, for the first time I.A. Smith in England put forward **k** [6], the gelatinization coefficient of pulverized fuel ash, which represents the amount of cement substituted by 1 kg pulverized fuel ash added in concrete as the cementing material. Its practicability is limited because many factors need to consider and thus influence its application.

2.3 The specific strength proposed by Pu Xincheng

Professor Pu Xincheng defined the "specific strength" to evaluate the contribution ratio of pulverized fuel ash activity to cement [7]. It is defined that the "specific strength of cement" is the contribution of 1% unit clinker to the strength of cement mortar in fly ash cement of certain proportion at different age, it equals the result when the compressive strength or the bending strength is divided by the amount of clinker needed with the proportion at each age. The ratio of the specific strength of cement (or concrete) with active mineral filler and cement without active mineral filler is defined as the "specific strength coefficient," and ratio of the specific strength of cement (or concrete) without active mineral filler and cement with active mineral filler is defined as the "strength contribution coefficient." The plot of volcanic ash effect on the basis of these parameters can reflect the volcanic ash effect of pulverized fuel ash accurately.

2.4 Activity ratio proposed by Lian Huizhen

Professor Lian Huizhen in Tsinghua University defined the activity ratio of pozzolanic material [8] Ka. It is the percentage of total quantity of SiO_2 and Al_2O_3 reacted in saturated limewater in the total quantity of SiO_2 and Al_2O_3 of initial materials. The experiment shows that Ka not only reflects the chemical reactivity properties of pozzolanic material, but also relates to many physical properties of the material such as other components, degree of fineness and content of crystal, etc. By this method the activity ratio can quickly evaluate the quality of pozzolanic material in 8 hours. Quick determination and evaluation of activity of pozzolanic material is the major advantage of this method.

2.5 Gel coefficient method proposed by Wang Lijiu

Professor Wang Lijiu in Dalian University of Technology defined the gel coefficient of pulverized fuel ash βwhich has better practicability [9]. It means that when adding some pulverized fuel ash whose mass is F in 1 m^3 of concrete, and at certain age, the contribution of the pulverized fuel ash to the concrete strength is βF times as that of cement.βreflects the performance of pulverized fuel ash to the strength effect of concrete. To speak of the physical meanings, it is accordant with gel efficient coefficient **k** of pulverized fuel ash. The mathematical model is given by the following:

$$\beta = A f^{x} c^{y} w^{z}$$

where f is the degree of fineness (the 45 μm square mesh sieve residue, %); c the loss on ignition (namely content of carbon, %); w the ratio of water demand; A, x, y, z are undetermined coefficients.

In accordance with the current experimental standards and international conventions, the strength ratio of pulverized fuel ash-cement mortar test piece and cement mortar test piece is the basis to determine the gel coefficient β. Experiment results are given as follows:

14d: $\beta = 2.93 f^{-0.37} c^{-0.68} w^{-2.05}$

28d: $\beta = 1.19 f^{-0.045} c^{-0.5} w^{-6.31}$

56d: $\beta = 1.85 f^{-0.07} c^{-0.25} w^{-4.8}$

The influence of the ratio of water demand on pulverized fuel ash quality is reflected indirectly through the two factors: the degree of fineness and the loss on ignition [10]. The experiment results show that the ratio of water demand influences the gel coefficient less. Its simplified model is as follows:

$$\beta = m(f \times c)^{n}$$

According to the experiment data:

14d: $\beta = 3.58(f \times c)^{-0.55}$

28d: $\beta = 3.68(f \times c)^{-0.53}$

56d: $\beta = 5.14(f \times c)^{-0.42}$

Generally, the age of 28 days is adopted to calculate the value of β.

Analysis of experiment results shows that the gel coefficient increases with the augment of the degree of fineness, and decreases with augment of the content of carbon. The gel coefficient of pulverized fuel ash β also increases with the augment of age. This could be explained well in the aspect of the action mechanism of pulverized fuel ash in concrete. The classification of pulverized fuel ash is based on the gel coefficient β.

3. Major Activation Techniques of Pulverized Fuel Ash and Applications

3.1 Activation of chemical substances and its application

Chemical substances are widely used to excite the potential activity of pulverized fuel ash.

3.1.1 Alkaline reagents

These substances mainly include $Ca(OH)_2$, NaOH, etc. $Ca(OH)_2$, which is precipitated through the processing of hydration, reacts with activated SiO_2 and activated Al_2O_3, then produces hydrated calcium silicate and hydrated calcium aluminate, etc. This kind of substances can break the Si-O, Al-O bands in the vitreous body of pulverized fuel ash, and accelerate the dissolution of Si^{4+} and Al^{3+}. When reacting with gypsum, they produce AFt.

$$SiO_2\text{ (active)} + x\,Ca(OH)_2 + aq \rightarrow xCaO{\bullet}SiO_2.aq$$

$$Al_2O_3\text{ (active)} + x\,Ca(OH)_2 + aq \rightarrow xCaO{\bullet}Al_2O_3.aq$$

These substances are usually combined with other kinds of substances in order to enhance the effect.

3.1.2 Alkali Salt

This kind of salt involves Na_2CO_3, $Na_2O{\bullet}nSiO_2$, etc.

$$Na_2SiO_3 + nH_2O \rightarrow 2NaOH + SiO_2{\bullet}(n\text{-}1)\,H_2O$$

The hydrate of Na_2SiO_3 could maintain the concentration of alkali in solution, and on the other side its product, silica gel, would change to gel with solid properties when the gel loses water gradually. In fact this gelatinization is the process of transformation from linear structure to reticular structure.

The active effect of Na_2CO_3 is not ideal; Liquid alkali (such as water glass) is a better active agent, while has several disadvantages: inconvenient; not easy to control setting time because of fast gelatinization, and must add retardant in it which will increase the price; about 1.5% of alkali would be carried into cement.

3.1.3 Sulfate

$CaSO_4$ and Na_2SO_4 belong to sulfate. In alkaline conditions, gypsum reacts with Al_2O_3 to produce hydrated aluminium calcium sulfate crystal (AFt):

$$Na_2SO_4 + CH + 2H_2O \rightarrow CaSO_4 \bullet 2H_2O + NaOH$$

$$Al_2O_3\text{ (active)} + 3Ca(OH)_2 + 3(CaSO_4 \bullet 2H_2O) + 23H_2O \rightarrow 3CaO{\bullet}Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$$

The above reactions continuously consume Al^{3+}, which accelerates the hydration of pulverized fuel ash, and makes the activity fully exploited.

It's rare to adopt individually the methods mentioned above. The active effect of Na_2SO_4 is not ideal either, and the amount of alkali carried into cement is about 1.0%–1.4% [11].

3.1.4 High molecular materials

By now reports in this field are few. According to the structural properties as well as the physical and chemical index, Liu Baozhu in Anhui University developed a new type of high molecular composite material—the so-called HB high-efficiency fly-ash activating admixture, which makes the activity fully exploited. The weight percentage of this material is only about 1.5%–2.0% of that of pulverized fuel ash. As a result of usage of this polymer activator, the overall economic effectiveness of China National Petroleum Corporation and Liaoning Jinxi Oil Refinery has increased about 40% [12]. The pulverized fuel ash content in concrete has been 30%-80%, and the concrete strength C20-C35; the pulverized fuel ash content in cement produced has reached 30%-40%, and its strength index meets the ISO PF32.5R cement standards.

3.1.5 Special ion activator

Professor Wang Lijiu in Dalian University of Technology developed a high-efficiency fly-ash activating admixture, and its mechanism is ion activation. The composite activator, which is a kind of powder with gray color, has the effect of activation as well as that of water reduction. Some effective component in it could mend obviously the poor behavior of carbon resistance and seep resistance caused by increasing the pulverized fuel ash in cement, and thus take the mechanical performance and the endurance performance of cement into consideration at the same time. There are three kinds of this admixture, common water-reduced type, water-reduction and slow-coagulation type, and high efficient water-reduced type. When its weight accounts for 7.8% of the total weight of cement and fly ash, the early strength and the final strength could increase apparently, and the overall economic effectiveness can increase 20%-35%. It was approved by the urban authenticate, and has been used widely in the large-scale buildings in the region of Liaoning and Beijing. The transformation project of Dalian Luanjin Uptown, the first building that makes use of “Dipy formwork concrete” in China, adopted the admixture and pulverized fuel ash concrete entirely. The typical mix proportion and properties of concrete are showed in Table 1. (Cement: PO32.5 cement produced by Dalian Seven Star Cement Plant; sand: river sand; fineness modulus 2.7; stone: broken stone of 5-31.5 mm; pulverized fuel ash produced by Dalian Beihaitou Power Plant; water: tap water).

Table 1: Mixture and properties of concrete

Strength scale	Mixture of concrete (kg/m^3)						Properties of concrete			
	C	F	S	G	W	DG-1	Slump (cm)	Compressive strength (Mpa)		
								7d	28d	56d
C15	103	336	634	1013	212	33.8	22	11.5	22.2	30.3
C20	171	239	664	1011	213	54.1	23	15.5	28.2	37.5
C35	292	175.5	625	1103	190.3	36.5	19	26.1	44.0	54.4

It is found in the table that if the designed age is 56 days, the grade of strength will rise 1-2 grades.

3.1.6 Composite activation

In most cases, the chemical substances mentioned above are optimizationally combined together through orthogonality experiments to complement each other. That the effect of composite admixture is much better than that of the individual activators is just the meaning of the direction of exploitation of activating admixture. Actually the DG-1 activating admixture is also a kind of composite admixture. Professor Wang Zhenglan in Anhui Architecture and Industry Institute found that if compound component containing alkali (component of calcium pick-up), sulfate and water reduced component together, the pulverized fuel ash activating admixture produced could increase the early and the final strength apparently. The experiment results are showed in Table 2 [13]. (Cement: PO42.5 portland cement produced by Anhui Chaohu Cement Plant; sand: river sand; stone: broken stone of 5-16mm; pulverized fuel ash: ash of grade, produced by Huaibei Power Plant; water: tap water).

Table 2: Mixture and properties of concrete

No.	Mixture of concrete (kg/m^3)						Compressive strength (Mpa)			
	W	C	F	S	G	DG-1	3d	7d	28d	56d
1	0.92	1.00	1.00	3.49	6.48	0	11.4	21.9	29.5	37.2
2	0.92	1.00	1.00	3.49	6.48	0.075	16.1	23.0	33.2	49.9
3	1.92	1.00	1.50	4.36	8.10	0	8.6	13.0	20.6	30.1
4	1.92	1.00	1.50	4.36	8.10	0.075	10.9	17.9	23.1	33.4

Table 3: Mixture and properties of concrete

Strength scale	Mixture of concrete (kg/m^3)								Properties of concrete		
	W	C	F	S	G	Lime	Gyp-sum	MTN GE	Imperm-eability	Frost resist-ance	Carboniz-ation coefficient
C20	116	68	272	680	1360	17	10.9	4.1	0.8MPa	D100	1.01

By using pulverized fuel ash composite activating admixture and steam curing, Hu Mingyu in Nanchang University solved the problem that early strength of concrete with high volume pulverized fuel ash is very low. He thought that the concrete with high volume pulverized fuel ash might be widely used in the construction engineering [14]. Xi Guohua in Nanchang University prepared C20 concrete, whose mixture proportion and properties are shown in Table 3. The results show that the high volume fly ash concrete has excellent mechanical properties and durability [15].

Professor Yang Liyuan in Zhengzhou University developed the JC admixture, which is adulterated to produce the pulverized fuel ash and slag cement. It is found that when the content of pulverized fuel ash and slag adulterated is greater than 60%, the strength of cement could reach to 32.5 MPa. The cost is very low, and it is less than that of other kinds of cement about $2 per ton. At the same time, the early strength is superior to common cement, and other properties are equal to common cement [16].

3.1.7 Other methods

The study of XieYoujun in Zhongnan University is based on the research of Red Mud, the solid waste discharged from aluminum oxide plant after the alkaline process of bauxite, to produce pulverized fuel ash activating admixture [17]. The results show that Red Mud can effectively excite the activity, and make the strength of cement mortar increase greatly. The optimum content of red mud adulterated is 3%-5%. Compared with reference test pieces, the compression strengths or bending strengths all increase 20%-40% at different ages. The strength of cement mortar with 40% pulverized fuel ash adulterated at 28 day is no less than that of pure cement mortar, and the strengths of cement mortar at 56 days and 90 days have exceeded that of pure cement mortar respectively. It is also found that the contribution of ending strength is greater than that of compression strength at 28 days.

3.2 Mechanical physical methods

Mechanical physical methods to improve the degree of fineness through method of pulverization and thus increase the surface area and surface energy greatly so as to enhance the volcanic ash reaction potency or activity. There are many reports about this subject. The action principle could be explained as follows:

- Pulverization breaks the vitreous body and increases their surface area, which makes activity higher. The pulverized fly ash not only has the effect of filling and micro-particle, but also changes from the guest to the host in hydration reaction and becomes important component. Calcium silicate and calcium aluminate generated can effectively block the capillary channels of cement mortar, which enhances the tightness of hardened cement paste.
- The pulverized fuel ash has larger surface energy as well as more effective “ball bearing” lubrication. Hence the performance of fresh cement concrete is improved, either with that of hardening concrete.
- Through pulverization, the substituting ratio is increased and the micro crack caused by the heat of hydration could be decreased also, which leads to the improvement of properties of cement and concrete.

Of course the degree of fineness cannot be increased indefinitely for the limited techniques as well as price.

3.3 Physicochemical methods

3.3.1 Low temperature calcinations

It is reported [18] that low temperature calcinations (800-1000^{o}C, 80-150 min.) of fly ash would change the chemical components and mineral structure when adding some limestone and mineralized agent. It was quenched after calcination, and then pulverized fuel ash of very high activity was obtained. When content amounts to 50%, the 32.5 grade cement could be made. But the high cost of the calcination equipment limits the extensive use of this method.

3.3.2 Heat activation

This method is operated as follows [19]: First, blend the pulverized lime and pulverized fuel ash in a certain proportion, and then put in the autoclave. After heat activation with appropriate time and temperature, process with dehydration and cooling. The optimum conditions of pulverized fuel ash with different properties could be found out from experiments. The pulverized fuel ash obtained with this method has very high activity, and similar to the low temperature calcinations method, when the content amounts to 50%, the 32.5 grade cement could be made.

The major disadvantages of this method are its large investment and complicated techniques because the autoclave is needed.

3.3.3 Hydrothermal processing method

Yin Suhong in South China University of Technology researches on a new method of activating pulverized fuel ash, the hydrothermal processing of $NaSiO_3$ and $CaCl_2$ (or $CaCl_2$) on the mixture of pulverized fuel ash and CH. The product is called the activated ash. The mechanism is explained as follows: The PH value of solution determines the reaction rate of volcanic ash. The fact that the NaOH hydrolyzed from a little $NaSiO_3$ makes the PH value increscent, and that NaOH could be reproduced in the reaction would increase the reaction rate of volcanic ash. Meanwhile the introduced Cl^-, with strong transferring and penetrating power, could accelerate the erosion to pulverized fuel ash vitreous body. The introduction of Ca^{2+} could increase the quantity of soluble calcium, accelerate the generation of gel product in the reaction of volcanic ash, and improve the early and final strength of pulverized fuel ash concrete [20].

3.4 Mechanical activation combined with chemical activation

Utilization of mechanical activation and chemical activation at the same time makes the strength of fly ash concrete improved quite much [21].

4. Conclusions and Proposals

- All the three methods, chemical activation, mechanical activation and physico-chemical activation have good effect, and have its own advantages and disadvantages. While considered in all aspects, pulverization activation and combination of these activation methods are better than the others.
- Pulverized fuel ash should be used widely for the prominent economic benefit, environmental benefit, and social benefit it has. Utilization of it is not very balanced in China. Generally, the conditions in the south and the east are better than that in the north and the west. In the construction of

Shanghai construction engineering and Changjiang Sanxia irrigation works projects, the demand of pulverized fuel ash exceeded the supply of it. But in some other regions, the pulverized fuel ash is of no use at all.

- Now in China the utilization of pulverized fuel ash in the scientific circle is not very scientific and normative. The utilization of it is a systemic and complicated project that is related to many aspects. Although there are some achievements, the total situation in China is not very good, and more importance should be attached to it.
- The study in the durability of high volume fly ash concrete is still inadequate. The durability of concrete is a significant problem in the concrete project. There are many research developments and achievements in this subject, but profundity and normalization are not enough.

References

1. Wang Lijiu. *Building Materials*, China Water and Electricity Publishing House, June 2000.
2. Feng Naiqian. *High Properties Concrete Technology*, China Atomic Energy Publishing House, June 2000.
3. China Standard: GB1596, Fly Ash Used in Cement and Concrete, China Building Industry Publishing House.
4. Wang Lijiu. *Building Materials*, China Water and Electricity Publishing House, June 2000.
5. Feng Naiqian. *High Properties Concrete Technology*, China Atomic Energy Publishing House, June 2000.
6. Shen Danshen. *Fly Ash Concrete*, China Railway Publishing House, 1989
7. Pu Xincheng. "Study on Volcanic Ash Effect of Activated Mineral Filler in Cement and Concrete with Specific Strength Index." *Concrete and Cement Product* 3, 1997, pp. 6-14.
8. Lian Huizhen. "Fast Evaluation Method of Activation of Volcanic Ash Materials." *Journal of Building Materials*, 2001/4/3, pp. 299–304.
9. Wang Lijiu. "Some Mathematical Problems on Concrete." The No. 3 National Researches Meeting of Modern Building Materials Technology, Beijing, July 2002.
10. Yang Baike. *The New Applied Technology of Concrete*. Jilin Science and Technology Publishing House, 1998, pp. 845.
11. Li yushou, and Wu Qisheng. "Sudy on Slag and Fly Ash Cement and Concrete Activated by Alkali." *Concrete and Cement Product,* May 2000, pp. 42.
12. http://www.unitrade.com.cn/jjxq/hqjj/kjdsy/0110192.htm.
13. Wang Zhenglan. "Study on Increasing Strength of Fly Ash Concrete by Using Activation Admixture." *Concrete*, February 2000, pp. 36.
14. Hu Mingyu. "Study on High Volume Fly ash Concrete." *Concrete*, Jan. 1998, pp. 29-33.

15. Xi Guohua. "Durability of Fly Ash Concrete." *Concrete*, Jan. 1998, pp. 34-36.
16. Yang Liyuan. "Study on High Volume Fly Ash Cement." *New Building Materials*, Nov. 1999, pp. 14-16.
17. Zhou Wenxian, and Xie youjun. "Study on Activation on Fly Ash of Red Mud." *Concrete*, Jan. 2002, pp. 37-40.
18. Fang Rongli. "Study of Methods of Enhancing Activity of Fly Ash." *Cement*, June 1999, pp. 9-10.
19. Fang Rongli. "Study of Methods of Enhancing Activity of Fly Ash." *Cement*, June 1999, pp. 9-10.
20. Yin Suhong. "Activation and Effects on Properties of Cement and Concrete of Fly Ash." Master's thesis, Hua Nan University of Technology, 1998.
21. Wang Aiqin. "Hydration Dynamics of Fly Ash Cement." *Journal of Silicate* 40, Feb. 1997, pp. 123-129.

RESEARCH ON USING WASTE SLUDGE OF SMELTING LEAD AND ZINC TO SINTER CEMENT CLINKER

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Abstract

The chemical property of waste sludge of smelting lead and zinc and the application of the sludge in sintering of cement clinker are studied. The experimental and practical production results show that the waste sludge of smelting lead and zinc can be successfully used for replacing 50% siliceous materials and 100% ferrous materials so as to sinter cement clinker. High quality cement clinkers are fired by wet process kiln system, and the performance of the cement satisfies the requirements of the Chinese national standard.

1. Introduction

For environmental protection, the limitation of waste production and the use of waste materials have aroused worldwide concerns and initiatives. The heavy metal zinc (Zn) and lead (Pb) industries occupy the forth and fifth position in the world's metal industries, respectively. According to the manufacturing processes of lead and zinc, the amount of sludge of smelting lead and zinc is almost equal to the product of lead and zinc. More and more sludge of smelting lead and zinc are being produced with the development of zinc and lead industries. It is estimated that now about 3 million tons of waste sludge for Zn and Pb heavy metal is generated every year in China. It will have certainly great scientific and technical significance and grand social and economical benefits to use the sludge of smelting lead and zinc rather than disposal of it as waste. Unfortunately, up to present the detailed relevant information can hardly be referenced [1, 2]. In this study, therefore, the chemical property of waste sludge of smelting lead and zinc and its application in the sintering of cement clinker are investigated.

2. Chemical Property of Sludge of Smelting Lead and Zinc

The sludge of smelting lead and zinc is the residue on smelting lead and zinc in which fine mineral of lead and zinc sulfides is smelted in the metallurgical furnace and watered out of the furnace. A typical chemical constitution of the fine minerals of lead and zinc sulfides is shown in Table 1.

Table 1: Typical chemical constitution of the fine minerals of Zn and Pb sulfides (%)

Kinds	Pb	Zn	Sn	S	Fe	Cd	Cu	Sb	As	SiO_2	CaO
Fine mineral Zn	1.58	47.98		30.82	10.38	0.25	0.42	0.03	0.27	3.21	1.09
Fine mineral Zn	0.97	55.00		31.15	5.85	0.14	0.04	0.01	0.02	3.17	0.99
Fine mineral Pb	62.52	4.43	0.04	16.88	8.70	0.04	0.58	0.17	0.34	2.79	0.72
Fine mineral Pb	71.50	4.55	0.08	15.80	5.20	0.06	0.17	0.05	0.02	2.50	0.89

Table 1 shows that there are kinds of color heavy metal in the fine minerals of lead and zinc sulfides such as Cd, Cu, and S. In the sintering process of the fine minerals of lead and zinc sulfides, the sulfides are changed to the oxides and then reduced by carbon. The chemical components for the typical waste sludge of smelting lead and zinc made up by oxidation-reduction method are showed in Table 2.

Table 2: Chemical components for typical waste sludge of smelting lead & zinc (%)

Smelting furnace	SiO_2	Fe_2O_3	CaO	MgO	Al_2O_3	S	C	Cu	Pb	Zn
Zinc blast furnace	20.90	26.80	19.50			3.40		0.45	0.51	6.50
Lead blast furnace	22.50	27.20	13.40			0.55		0.50	1.80	16.30
Smelting rotary kiln 1	28.17	39.97	6.05	5.20	17.27	3.25	20.38		0.014	0.003
Smelting rotary kiln 2	28.06	39.42	5.26	5.56	17.27	3.47	15.33		0.067	0.008

Table 2 shows that the chemical components of waste sludge of smelting lead and zinc in different smelting furnaces are not the same. They are mainly SiO_2, Fe_2O_3, CaO, MgO, Al_2O_3, S, and C, in addition to a small amount of Pb and Zn especially for the sludge from smelting rotary kiln 1 and 2. Therefore, they can be used not only as a substitute for siliceous materials and ferrous materials to sinter cement clinker, but also as the mineralizer and fuel.

3. Proportioning Optimization of Raw Materials and Meal

Due to the high SiO_2, Fe_2O_3, S, and C content of sludge of smelting lead and zinc in the smelting rotary kiln, the proportion and quality of calcareous, siliceous and ferrous raw materials and fuel should be controlled. The chemical components of raw materials and combined coal ash and main apparatus used in Fanghou cement plant are shown in Tables 3 and 5, respectively. The industry analysis of combined coal (which combination ratio is one-third of bituminous coal to two-thirds of anthracite coal) is showed in Table 4.

Table 3: Chemical components of raw materials and combined coal ash (%)

Name	Loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	S	$\sum$
Calcareous raw	39.31	7.26	1.29	0.90	48.69	1.29		97.45
Siliceous raw	10.35	64.69	15.42	6.63	0.81	0.62		98.52
Ferrous raw	14.13	11.33	7.47	61.82	2.48	1.44		98.67
Sludge of smelting		28.11	17.27	39.69	5.65	5.38	3.36	99.46
Combined coal ash		56.30	28.14	6.50	2.88	1.46		96.28

Table 4: Industry analysis of combined coal (%)

Name	W^f	A^f	V^f	C^f	Q^y_{DW} (kJ/kg)
Combined coal	1.19	28.04	13.80	56.97	23,052

Table 5: Main apparatus in Fanghou cement plant

Name	Specification and type	Amount	Ability of design (t/h)
Limestone crushing	Φ1.25 vertical crusher	2	50×2
Raw meal grounding	Φ2.4×13 tube mill	1	50
Sintering clinker	Φ2.5/3.0×90 wet process kiln	3	10×3
Coal grounding	Φ2.2×4.4	1	10
Cement grounding	Φ2.4×13 tube mill	1	30
Cement bagging	two-mount bag filler	1	30

The proportioning optimization of raw meal and experimental results show that the waste sludge of smelting lead and zinc is successfully used for replacing 50% siliceous materials and 100% ferrous materials to sinter cement clinker. Lime saturation factor (*LSF*) and alumina modulus (*AM*) are suitably decreased and silica modulus (*SM*) is increased, which may improve the quality of cement clinker. The comparison of the chemical components of raw meals before and after using the waste sludge of smelting lead and zinc is shown in Table 6.

Table 6: Comparison of chemical components of raw meal slurry before and after using sludge

	Chemical components of raw meal slurry (%)								Three ratios		
	Loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	S	∑	*LSF*	*SM*	*AM*
Before sludge	36.47	11.17	2.71	2.78	44.63	1.35		99.11	1.25	2.03	0.98
After sludge	35.83	11.72	2.60	2.75	44.21	1.33	0.25	98.69	1.19	2.19	0.95

4. Effect of Using Sludge of Smelting Lead and Zinc on Sintering Cement Clinker

(1) Influence of sludge of smelting lead and zinc on fluidity of raw meal slurry

Table 7 shows that when water of raw meal slurry is 33%, 34%, and 35%, using sludge of smelting lead and zinc, the fluidity of raw meal slurry can increase 2-3mm because of higher C of sludge of smelting lead and zinc.

Table 7: Effect of sludge of smelting lead and zinc on fluidity of raw meal slurry

	Proportion of raw materials			Sludge of smelting	Water of raw meal slurry	Fluidity (mm)
	Limestone	Clay	Ferric powder			
A	89	8	3	0	33	66
B	89	8	3	0	34	69
C	89	8	3	0	35	71
D	89	7	0	4	33	68
E	89	5	0	6	34	72
F	89	3	0	8	35	74

(2) Influence of sludge of smelting lead and zinc on sinterability of raw meal

According to GB9965-88 (experimental method for sinterability of raw meal), effect of using sludge of smelting lead and zinc on fluidity of raw meal is shown in Table 8. It can be observed from the table that sludge of smelting lead and zinc contains trace amounts of heavy metals and higher S and MgO, which improve the burnability of raw meal. The amount of 6% sludge of smelting lead and zinc is considered the best.

Table 8: Effect of sludge of smelting lead and zinc on firing behavior of raw meal slurry

	Pb (%)	Zn (%)	SO_3 (%)	MgO (%)	f_{CaO} (%)		
					1350°C	1400°C	1450°C
C	0	0	0	1.54	5.89	3.85	0.83
D	0.0016	0.0002	0.13	1.71	4.67	2.65	0.79
E	0.0025	0.0004	0.20	1.80	4.18	2.01	0.63
F	0.0033	0.0005	0.27	1.90	4.37	2.29	0.75

(3) Influence of sludge of smelting lead and zinc on quality of cement clinker

The comparison of the chemical components, three ratios, mineral constitution and physical properties of cement clinkers before and after using the waste sludge of smelting lead and zinc are shown in Tables 9 and 10.

Table 9: Comparison of the chemical components and three ratios of cement clinkers

	Chemical components of clinkers (%)								Three ratios			
	Loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	f_{CaO}	*LSF*	*LSF⁻*	*SM*	*AM*
Before using	0.64	20.34	5.92	4.58	65.03	2.08		1.38	0.94	0.92	1.94	1.29
After using	0.58	20.91	5.71	4.65	65.17	1.51	0.37	0.57	0.92	0.91	2.02	1.23

Table 10: Properties of clinkers

	Mineral constitution (%)				Compression strength (MPa)			Flexural strength (MPa)			Specific surface	Setting time (h:min)	
	C_3S	C_2S	C_3A	C_4AF	3d	7d	28d	3d	7d	28d	(m^2/kg)	Beg.	End
Before using	58.74	13.99	7.92	13.92	5.3	6.4	7.8	28.5	43.8	60.7	302	2:38	4:41
After using	57.69	16.38	7.24	14.15	5.8	7.1	8.4	31.7	46.2	62.6	303	2:58	4: 45

It can be seen in Tables 9 and 10 that after using the waste sludge of smelting lead and zinc, f_{cao} in the cement clinkers is decreased from 1.38% to 0.7%. The total amounts of silicate minerals (C_3S + C_2S) are further increased from 72% to 74%. At about the same of the specific surface, the strength of cement clinkers at 3, 7, and 28 days is promoted and the performance of cement satisfies the requirements of the Chinese national standard.

Conclusions

- The chemical components of waste sludge of smelting lead and zinc contain mainly SiO_2, Fe_2O_3, CaO, MgO, Al_2O_3, S, and C. The sludge can be used as a raw material for production of cement clinker.
- The proportioning optimization of raw meal and experimental results show that the waste sludge of smelting lead and zinc is successfully used for replacing 50% siliceous materials and 100% ferrous materials to sinter cement clinker.
- Using the waste sludge of smelting lead and zinc to fire cement clinkers can improve the fluidity of raw meal slurry and the burnability of raw meal and promote the strength and performance of the cement.

References

1. Q.R. Wu, H.G. Lai, and Y.J. Zhang. "Application of Wet Sludge of Smelting Lead and Zinc in Firing of Cement Clinkers." *Cement* 10, 2000, 16-17 (in Chinese).
2. Q.R. Wu et al. *Patent of China*. 00117236.0.

Part II

Concrete Durability and Sustainable System

DEVELOPMENT OF GREEN ENGINEERED CEMENTITIOUS COMPOSITES FOR SUSTAINABLE INFRASTRUCTURE SYSTEMS

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Abstract

Over the last decade, enormous strides have been made in creating engineered cementitious composites (ECC) with extreme tensile ductility, on the order of several hundred times that of normal concrete or fiber reinforced concrete (FRC). Current ECC investigations include load carrying structural members in new infrastructure systems, as well as for repair and retrofitting of existing structures. ECC design has been built on the paradigm of the relationships between material microstructures, processing, material properties, and performance. This paradigm has worked very well in creating various versions of ECC that can be processed by self-consolidated casting, spraying, and extrusion. This paper describes preliminary results of an initial attempt at creating green ECCs, ECCs that maintain the tensile ductility characteristics, but which also incorporate sustainability considerations in the design of these materials for infrastructure applications. Sustainable material design integrates microstructure tailoring with life cycle analysis based on social, environmental, and economic (SEE) indicators. The framework of green ECC development is described. Some preliminary experimental results of the effect of cement substitution and fiber substitution with industrial by-products on the mechanical properties are reported. It is demonstrated that the concept of green ECC for sustainable infrastructures is feasible, although an extensive amount of research remains ahead.

1. Introduction

Materials engineering in recent years has emphasized the inter-relationship between material microstructure, properties, processing and performance (National Research Council 1990). This materials engineering paradigm, while widely adopted and shown to be effective, nonetheless does not take into account sustainability concerns. At the moment, there is no systematic approach in materials design that recognizes the inter-connection between microstructure, properties, processing, performance, and sustainability. The objective of this research is to develop a new materials engineering methodology that explicitly embodies sustainability in the form of SEE indicators. In this paper, this methodology will be briefly introduced. Emphasis will be placed on an initial attempt at creating a green (environmentally preferable) version of an engineered cementitious composite (ECC), which maintains the high tensile ductility characteristics but also incorporates sustainability considerations in the design of these materials for infrastructure applications.

The volume of concrete used in global infrastructure represents huge flows of material between natural systems and human systems. Global use of concrete for construction projects exceeds 12 billion tons per year. To support this amount, cement production in the year 2001 totaled 1.65 billion metric tons (van Oss 2002). Rates, compositions, and spatial distributions of such important flows are major determinants of the degree to which societies are sustainable. While concrete infrastructure continues to grow worldwide, evidence suggests that the performance of current infrastructure systems is deficient in terms of the SEE dimensions of sustainability. Some of the challenging sustainability issues regarding infrastructure include the following:

Social: 32 *percent* of U.S. major roads are in poor and mediocre condition, while 28 percent of US bridges are structurally deficient or functionally obsolete. Roadway improvements would reduce accidents and save lives. Of the 41,821 U.S. traffic fatalities in 2000, 30% have been attributed to inadequate roadway conditions (TRIP 2002). Furthermore, construction causes significant traffic delays. Total urban traffic congestion costs the nation $78 billion in wasted fuel and lost time each year (TRIP 2001).
Environmental: Cement production, an energy intensive process, is responsible for 3% of global greenhouse gas emissions (WBCSD 2002), and significant amounts of NO_x, particulate matter (PM) and other pollutants such as SO_2. The production of 1 ton of cement clinker requires approximately 1.7 tons of non-fuel raw materials and results in the release of 1 ton of CO_2 (van Oss 2002).
Economic: Roads represent one infrastructure system with significant economic impacts. For example, driving on roads in need of repair or improvement costs motorists in the US an average of $222 per driver in extra vehicle operating costs each year, or $41.5 billion total (TRIP 2001). Also, delayed shipments of freight can lead to productivity losses directly impacting business and industry.

The unsustainability of current infrastructure systems, coupled with the anticipated rapid growth of new ones, lead to an obvious need for improvement. Recent research suggests the possibility of substituting concrete with advanced cementitious composites that have superior mechanical performance. Introducing huge volumes of a new material is likely to have profound impacts in each of the three dimensions of sustainability. These impacts occur throughout an infrastructure system’s life cycle, which encompasses resource extraction, materials processing, construction, use, maintenance and repair, and end-of-life management. We must understand the nature of these impacts and optimize the overall performance of the new material through intelligent design and application.

Reinforced concrete's limited durability is responsible for significant amounts of infrastructure repair. Its brittleness has caused numerous and catastrophic failures of buildings and bridges in recent earthquake events. Alternative technologies promise to improve the performance of concrete-related materials. One such technology involves the family of engineered cementitious composites (ECC). Given the demand for infrastructure systems worldwide, the potential application of ECC could be enormous.

ECC represents a unique group of short fiber reinforced cementitious composite materials with ultra high ductility. As a successful sample of materials engineering on the paradigm of the relationships between material microstructures, processing, material properties, and performance (Li 1992), the fiber, matrix and interface of ECC are carefully tailored under the guidance of micromechanical models that link the composite ductility to individual phase properties (Li 1998). ECC strain-hardens in tension, accompanied by sequential development of multiple cracking after first cracking. Tensile strain capacity exceeding 5% has been demonstrated on ECC materials reinforced with polyethylene (PE) and polyvinyl alcohol (PVA) fibers (Li 1998; Li et al. 2002.). Closely associated with the strain-hardening and multiple cracking behaviors is the small steady state crack width. Even at a strain of 4-5%, crack widths of ECC remain below 100 µm. Such small crack widths imply a significant improvement in structural durability (Li 2002). Through careful material design, the fiber volume fraction in ECC remains moderate, typically below 2.5%. As a result, unlike many other high performance FRC, ECC can be prepared in standard concrete mixers. With appropriate control of rheology properties, ECCs suitable for self-consolidating casting (Kong 2003), spraying (Kim 2003), and extrusion (Stang and Li 1999) have been developed.

ECC material is emerging from laboratory testing to field applications. With its flexible processing, ECC can be used in either new construction or as repair and retrofitting material. Potential infrastructure applications under investigation include building frames (Fischer and Li 2001), bridge piers (Yoon and Billington 2002), bridge deck repair (Gilani 2001), extruded pipes (Stang and Li 1999), and most recently roadway repairs.

In this paper, an integrated materials design framework for sustainable infrastructure systems is proposed. Two major ingredients of ECC, i.e., the cement and fiber, account for the major part of the environmental impact. As a preliminary attempt, the effects of cement substitution and fiber substitution with industrial by-products on the mechanical properties are experimentally investigated. These findings highlight the feasibility of creating a green ECC material for sustainable infrastructure applications.

2. Integrated Materials Design Framework for Sustainable Infrastructures

A number of wide ranging disciplines must be brought together for life cycle assessment of any complex system. For ECC infrastructure systems, these disciplines include civil engineering, materials engineering, industrial ecology, environmental health, geology, and environmental economics. Such a team, sponsored by the US National Science Foundation, has been assembled at the University of Michigan.

The creation of a well-defined, integrated materials design framework was essential to facilitate cooperation between the various disciplines. For this project, the framework was specifically tailored to infrastructure applications, however it may be readily adapted to development of sustainable materials for other industrial applications. The design framework, which is an iterative process comprised of two loops forming a continuous "figure eight" is pictured in Fig. 1.

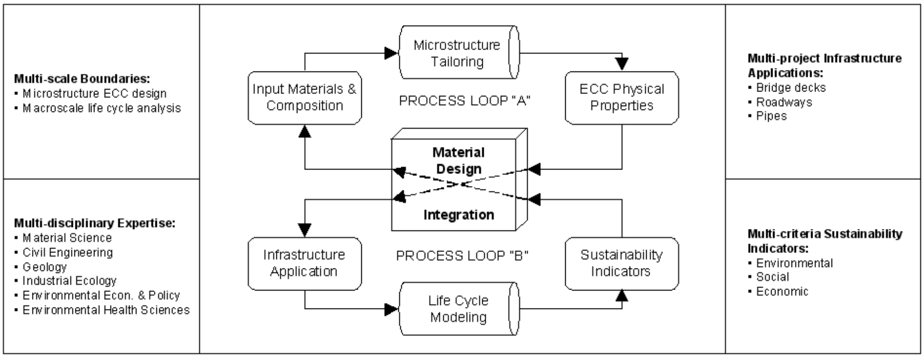

Fig. 1: Integrated materials design framework for sustainable infrastructures

Process loop A involves the microstructure tailoring of ECC. By adjusting the formulation of various input materials, the mechanical properties of the composite are controlled. Process loop B involves the evaluation of an entire infrastructure system using a complete life cycle model. Indicators of environmental, social, and economic sustainability are assessed on a macro-scale. The two loops provide feedback to one another through the central integration box. This box takes input from loop B to inform loop A on viable material compositions with favorable sustainability indicators and mechanical property demands of the particular infrastructure application. In turn loop A informs loop B of properties of ECC suitable for a particular infrastructure application, whose performance (e.g. durability/service life time) is taken into account in the life cycle model. Because of these feedback loops, both mechanical performance and sustainability indicators may be optimized simultaneously for the ECC material and the ECC infrastructure.

The infrastructure application chosen for initial implementation of this design framework is portions of a bridge deck in a simply supported steel-girder bridge. Currently, expansion joints between adjacent bridge spans are used to allow for thermal expansion and contraction of the bridge girders. However, these joints leak, allowing water and other corrosives to deteriorate the deck and girders, requiring replacement of the deck and/or the entire bridge superstructure. To eliminate the problematic joints, a link slab may be used to connect the two spans, creating a continuous deck over the steel girders. However, the link slab must be able to accommodate the high strain demand imposed by thermal length changes and drying shrinkage deformation in the deck along with any structural demand placed by highway traffic. The high strain capacity of ECC, mentioned earlier, make it an ideal material for the link slab application.

The use of the integrated design framework to develop a green ECC material for the link slab application appears promising. In addition to optimizing the ECC material directly using component substitutions and additional microstructure tailoring, the overall life cycle of the bridge system will be greatly impacted. According to the Michigan Department of Transportation, the expected service life of a typical bridge is forty years, while the expected service life of bridge waterproofing membrane is ten years (MDOT 2002). Bridge superstructures typically deteriorate most rapidly near joint regions due to leaking. Using ECC link slabs to prevent deterioration, the expected service life of a typical bridge will almost certainly be extended, but by how much is difficult to estimate. With the use of ECC link slabs, it is quite possible that the bridge will outlast its usefulness. In addition to extending the overall service life of the bridge, the maintenance frequency will almost certainly decrease. The combination of greener ECC materials along with the extended life cycle of the total infrastructure system suggests that the sustainability of highway bridges utilizing ECC link slabs will be far superior to the current concrete infrastructure system.

3. Guidelines for Designing Green ECC

The development of green ECC material is contained within process loop A of the integrated material design framework of Fig. 1. While loop A does not involve complete life cycle analysis, a significant number of sustainability considerations must be taken into account when designing a green version of ECC. To begin the design process, a small set of indicators, referred to as Material Sustainability Indicators (MSI) are chosen as preliminary indicators of overall sustainability. The MSI are selected to be dependent only upon ECC component materials, in order to initiate efficient material evaluation without complete life cycle analysis of the final application. In this study, the environmental indicators of total production energy, solid production waste, carbon dioxide generated during production, and chemically polluted water produced were chosen as the MSI. Values for these MSI are shown in Table 1 for both conventional concrete and a current ECC design (Li et al. 2002). The

MSI have been calculated based on data from MDOT, the Portland Cement Association, a local bridge contractor, Kentucky Transportation Center's KyUCP Model (KTC 2002), US EPA's MOBILE 6.2 program (US EPA 2002), and various material suppliers. A complete life cycle assessment is outside the scope of this paper.

Table 1: Properties and material sustainability indicators (MSI) for concrete and ECC

	Compressive strength (MPa)	Tensile strain capacity (%)	Total energy use (MJ/L)	Solid waste (Kg/L)	Carbon dioxide (g/L)
Concrete	35.0	0.02	2.68	0.152	407.0
ECC	65.0	5.0	8.08	0.373	974.8

As seen in Table 1, concrete and ECC show significant differences in both mechanical properties and MSI. While this version of ECC clearly outperforms concrete in mechanical performance, its production has greater environmental burdens than concrete due to the high cement content of standard ECC, and the inclusion of polymeric fibers. ECC material is only sustainable in terms of solid waste production due to the use of fly ash, an industrial waste from coal-fired power plants. This initial analysis suggests that a reduction in the cement content of ECC, along with reduced use of PVA fibers, may be possible methods of increasing the sustainability of ECC material with respect to concrete.

One natural solution is to replace fiber, cement and other components in the current ECC mix with industrial by-products, provided that the properties of the resulting green ECC would still meet the requirements for a particular application. At least 20 industrial waste materials have been identified as potential cement, virgin fiber, and aggregate substitutes in ECC. Among them, fly ash and bottom ash are of great interest due to their abundance and increasing negative impact on the environment related to their disposal.

Introduction of fly ash into the ECC matrix has an inevitable influence on the microstructure of matrix and interface, and in turn the micromechanical properties governing the fiber bridging behavior and cracking behavior. For PVA fiber reinforced ECC, experimental results from single fiber pullout tests and matrix fracture tests indicate that the interfacial bond strength and matrix fracture toughness decrease with an increase of fly ash content. The interfacial bond strength of PVA fiber in ECC is excessive due to its hydrophilic nature and must be artificially lowered (Li, et al 2002). The presence of fly ash may in fact lead to improved strain-hardening behavior.

The integrated material design framework emphasizes the tailoring of material properties for a specific application, e.g. link-slabs. Structural mechanics analysis reveals that the most important properties required for link-slabs are tensile strain capacity (ductility) and crack width control for durability purposes. The minimum ductility required to withstand temperature and drying shrinkage stress, as well as live loads, was computed to be 1.4% using a factor of safety of two. Furthermore, crack widths should be below 100 μm to minimize water/chloride penetration. These requirements are difficult, if not impossible, to attain for normal concrete, but are easily achievable with current ECC, which has ductility exceeding 3%. There is a rather large buffer in mechanical performance that can be "traded" for material greenness.

4. Experimental Program

This preliminary experimental program involves two sets of investigation, i.e. cement substitution with ashes and fiber substitution with recycled carpet fiber, in which the effect of the individual substitution on the mechanical properties of ECC is independently studied. For lack of space, only the research findings involving cement substitution is reported in this paper.

Mix proportions of five ECC mixes (ECC G0-G4) with high fly ash content are listed in Table 2, along with the reference concrete mix and a reference ECC mix (ECC R0). The cement used in this study is Ordinary Portland cement (OPC). Except for the concrete, which contains both coarse and fine aggregate, the aggregates in ECC mixes solely consists of fine silica sand with an average size of 110 μm. PVA REC15 fiber, specially developed for ECC materials (Li et al. 2002), is used in this study with a fixed volume fraction of 2%. Viscosity agent hydroxypropyl methylcellulose (HPMC) and superplasticizer (SP) are necessary in ECC mixes for achieving adequate workability.

Table 2: Mix proportions of concrete and ECC materials

	Cement (kg/m^3)	Fly ash (kg/m^3)	Aggregates (kg/m^3)	Fiber (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	HPMC (kg/m^3)
Concrete	390	–	1717	–	166	–	–
ECC R0	838	–	838	26 (PVA)	366	17	1.26
ECC G0	583	700 (Class F)	467	26 (PVA)	298	19	0.16
ECC G1	318	509 (Class F) 191 (fine fly ash)	701	26 (PVA)	289	19	0.16
ECC G2	318	701 (Class F)	701	26 (PVA)	289	19	0.16
ECC G3	318	191 (fine fly ash) 250 (Class F) 250 (bottom ash)	701	26 (PVA)	289	19	0.16
ECC G4	318	701 (bottom ash)	701	26 (PVA)	289	19	0.24

Two types of fly ash and one type of bottom ash are investigated. Fine fly ash is a special type Class C fly ash with high calcium content, and particle size (average 2 μm) much smaller than class F fly ash (average 13 μm) and bottom ash (average 50 μm).

The mechanical properties and MSI of mixes are shown in Table 3, where the compressive strength and tensile strain capacity are measured at 28 days. Direct uniaxial tensile test using coupon specimens was employed to characterize the tensile behavior.

5. Results and Discussion

As shown in Table 3, the introduction of a high content of ashes results in little change in composite ductility, while it significantly improves the MSI over current versions of ECC. Although fly ash has been widely used in structural concrete, the ratio of ash to cement (typically 10%-30%) is much lower than in these ECC mixes (ranging from 120% to 220%). Except for ECC G1, which shows a large variability in strain capacity, all other mixes with high ash content demonstrate a high strain capacity exceeding 4%.

Fig. 2 shows the compressive strength development of the green ECCs, where the strength gain rate was, as expected, slightly compromised due to the reduction of cement content. However, compared with conventional structural concrete, the green ECCs show similar early compressive strength and higher long-term strength. The type and the proportion of ash, due to different reactivity and particle sizes, have different influences on the compressive strength. Bottom ash, due to its low pozzolanity, leads to both lower early and long-term (up to the 100 days age for this set of tests) strength in the ECC. In the current calculations of MSI, these three types of ashes are not differentiated. However, their true recycle value is different. This difference will be reflected in future refinements of the model.

The distinguishing characteristics of ECC include its high tensile ductility and small steady state crack widths. Fig. 3 shows a tensile stress-strain curve and accompanying crack width development of ECC G2. The crack width stabilizes after 1% strain and remains below 80 μm until failure. Hereby, the mechanical properties of ECC G2, in terms of strength, ductility, and crack width well satisfy the performance requirements for the link-slab application. One obvious trend among the new greener versions of ECC is the larger amount of total energy used in material production. This high-energy demand is mostly due to the large amount of energy used in PVA fiber production. By using waste fiber substitution, the energy demand will be reduced, and the MSI will be further improved. These results will be reported in a separate paper.

Table 3: Mechanical properties and material sustainability indicators of green ECC

	Compressive strength (MPa)	Tensile strain capacity (%)	Total energy use (MJ/L)	Solid waste (Kg/L)	Carbon dioxide (g/L)
Concrete	35.0	0.02	2.68	0.152	407.0
ECC	65.0	5.0	8.08	0.373	974.8
ECC R0	42.0	4.9	8.79	0.280	957.8
ECC G0	68.0	4.5	7.16	-0.504	702.5
ECC G1	40.8	1.6	5.43	-0.585	440.7
ECC G2	38.6	4.0	5.43	-0.586	440.7
ECC G3	36.5	4.3	5.43	-0.576	440.7
ECC G4	29.1	4.3	5.43	-0.586	440.7

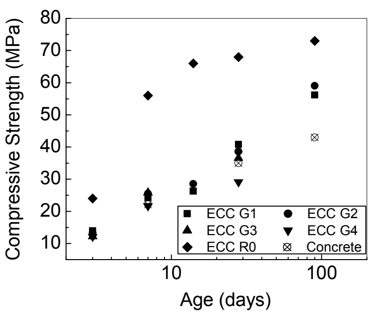

Fig. 2: Compressive strength development

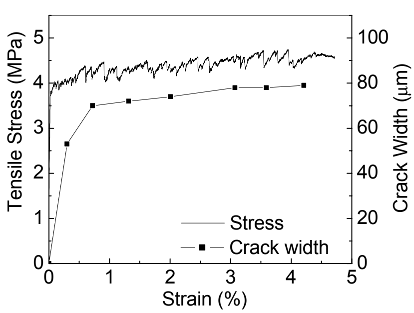

Fig. 3: Crack width vs. strain of green ECC

6. Conclusions

- Development of greener ECC based on consideration of material sustainability indicators (msi) is feasible.
- The generally deteriorated properties due to the use of low-quality substitutions can be offset by micromechanical tailoring of the ingredients.
- Mapping of the green ECC properties to required properties for specific infrastructure applications should lead to minimum performance reduction in the infrastructure, while greatly enhancing the sustainability indices.

Acknowledgments

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References

1. U.S. National Research Council. 1989. *Material Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials*. National Academy Press, Washington, DC, pp. 320.
2. van Oss, H.G., and A.C. Padovani. 2002. "Cement Manufacture and the Environment. Part I: Chemistry and Technology." *Journal of Industrial Ecology* 6(1) 89-105.
3. TRIP. 2002. Key Facts About America's Road and Bridge Conditions and Federal Funding. Accessed March 2002 from The Road Information Program (TRIP): http://www.tripnet.org/nationalfactsheet.htm.
4. TRIP. 2001. Stuck in Traffic: How Increasing Traffic Congestion is Putting the Brakes on Economic Growth from. Accessed March 2002 from The Road Information Program: http://www.tripnet.org/StuckinTrafficReportMay01.PDF.
5. WBCSD. 2002. Toward a Sustainable Cement Industry. Draft report for World Business Council on Sustainable Development. Battelle Memorial Institute. http://www.wbcsd.org/newscenter/reports/2002/cement.pdf.
6. Li, V.C., and H.C. Wu. 1992. "Conditions for Pseudo Strain-Hardening in Fiber Reinforced Brittle Matrix Composites." *Journal of Applied Mechanics Review* 45(8) 390-398.
7. Li, V.C. T. Kanda, and T. Hamada. 1998. "Material Design and Development of High-Ductility Composite Reinforced with Short Random Polyvinyl Alcohol Fiber." *Proceedings of the Japan Concrete Institute* 20(2) 229–234.
8. Li, V. C., C. Wu, S. Wang, A. Ogawa, and T. Saito. 2002. "Interface Tailoring for Strain-hardening PVA-ECC." *ACI Materials Journal* 99(5) 463-472.
9. Li, V.C. 2002. "Reflections on The Research And Development of Engineered Cementitious Composites (ECC)." *Proceedings*, DFRCC-2002, Takayama, Japan, 2002, pp. 1-22.
10. Kong, H.J., S. Bike, and V.C. Li. 2003. "Development of a Self-Compacting Engineered Cementitious Composite Employing Electrosteric Dispersion/Stabilization." *Journal of Cement and Concrete Composites* 25(3) 301-309.
11. Kim, Y.Y., G. Fischer, Y.M. Lim, and V.C. Li. 2003. "Mechanical Performance of Sprayed Engineered Cementitious Composite (ECC) Using Wet-mix Shotcreting Process for Repair." *ACI Journal of Materials*, accepted May 2003.
12. Stang, H., and V.C. Li. 1999. Extrusion of ECC-material. HPFRCC-3. Eds. H. Reinhardt and A. Naaman. Chapman & Hull. pp. 203-212.
13. Fischer, G., and V.C. Li. 2003. "Intrinsic Response Control of Moment Resisting Frames Utilizing Advanced Composite Materials and Structural Elements." *ACI Journal of Structures* 100(2) 166-176.
14. Yoon, J.K., and S.L. Billington. 2002. "Cyclic Response of Unbonded Post-Tensioned Precast Columns with Ductile Fiber-reinforced Concrete." Submitted for publication in *ASCE Journal of Bridge Engineering*, Aug. 2002.

15. Gilani, A. 2001. Link slabs for simply supported bridges: incorporating engineered cementitious composites. MDOT SPR-54181. Structural Research Unit, MDOT.
16. Michigan Department of Transportation (MDOT). 2002. Life Cycle Cost Analysis Assumption Sheet. Revised March, 2002.
17. Kentucky Transportation Center (KTC). 2002. The Cost of Construction Delays and Traffic Control for Life-Cycle Cost Analysis of Pavements. KTC-02-07/SPR197-99/SPR218-00-1F. http:www.ktc.uky.edu/Reports/KTC_02_07_SPR197_99_SPR 218_00_1F.pdf.
18. U.S. EPA. 2002. MOBILE 6.2. U.S. EPA. http://www.epa.gov/otaq/m6.htm.

LIFE-CYCLE ASSESSMENT OF REPAIR AND MAINTENANCE SYSTEMS FOR CONCRETE STRUCTURES

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Abstract

In many countries, there is a growing amount of deteriorating concrete infrastructures that not only affect the productivity of the society, but also has a great impact on resources, environment and human safety. The poor and uncontrolled durability with repairs and maintenance of all these concrete structures are consuming much energy and resources and are producing a heavy environmental burden and large quantities of waste. Therefore, the increasing amount of repairs and maintenance of concrete structures is not only a question of technical performance and economy, but also a question of impact to the environment.

In the present paper, the framework and methodology for quantifying the environmental burden of various repair materials and systems for maintenance of concrete structures are briefly outlined. This includes materials and energy consumption, waste generation and emission to the environment.

1. Background

Over recent years, there has been an increasing concern on how human activities affect the loss of biodiversity, the thinning of stratospheric ozone, climate changes and the consumption of natural resources. The term “sustainable development” (SD) was introduced in the final report of the Brundtland Commission (World Commission on Environment and Development, WCED) of 1987, where SD is defined as follows:

> Development that meets the needs of the present without comprising the ability of future generations to meet their own needs.

On the basis of weight, volume and money, the construction industry is the largest consumer of materials in our society. Thus, approximately 40% of all materials used are related to the construction industry [1]. From a production point at view, several of the construction materials have a great impact on both the local and global environment. This is particularly true for concrete as one of the most dominating construction materials. Therefore, an increased environmental consciousness in the form of a better utilization of concrete as a construction material and the creation of a better harmony and balance with our natural environment represent an increasing challenge to the construction industry, as expressed by the Lofoten Declaration of 1998 [2].

In addition to the large consumption of natural resources for concrete production, the production of portland cement is based on a very energy consuming and polluting industrial process. Thus, the production of each ton portland cement releases almost one ton of carbon dioxide in addition to a number of other polluting constituents to the atmosphere. The production of portland cement worldwide constitutes approximately 5% of the total global emission of CO_2. Therefore, proper design for durability and long-term performance of concrete structures is very important [3].

During recent years, deterioration of reinforced concrete structures has emerged as one of the most demanding challenges facing the construction industry [4]. Public agencies are already spending a significant proportion of available construction budgets for repair and maintenance of their existing structures.

In the years to come, repair and maintenance of concrete structures will be the subject to strict requirements both with regard to environmental impacts and economical constraints. It is very important to take environmental effects into consideration both during design and construction as well as in the management system for concrete structures.

The objective of the present paper is to focus on the framework and methodology for quantifying the ecological effects and impacts from various methods and systems for repairs and maintenance of concrete structures. Life-cycle assessment (LCA) includes assessment of materials and energy consumption, waste generation, emission to the environment and health risk.

2. Framework for Life-Cycle Assessment

The Institute of Ecosystem Studies define ecology as follows:

> The scientific study of the processes influencing the distribution and abundance of organisms, the interaction among organisms, and the interactions between organisms and the transformation and flux of energy and matter.

A practical way of interpreting LCA is to determine the impact on the environment, caused by all human activities throughout the whole life cycle of a structure. This is, however, a very difficult process since the relationship between the external environment and the category endpoint can be very complex. Normally, the LCA will stop at the step before the category endpoint showing only the impact categories, which is fairly easy to do, and then interpret the results from the various category indicators. The concept of category endpoints [5] is shown in Fig. 1. The methodological framework for the assessment of environmental impacts is given in the ISO-standards 14040-14043 [5-8].

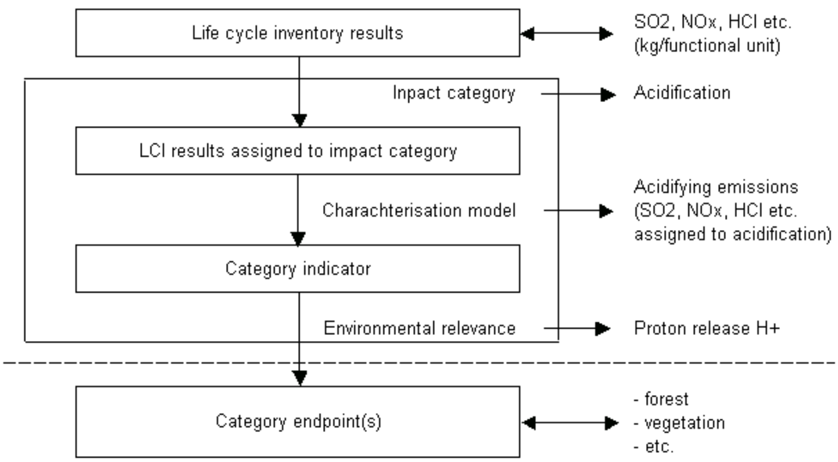

Fig. 1: Concept of category indicators

In order to apply the concept of category indicators on repairs and maintenance of concrete structures, all steps in the process have to be thoroughly evaluated. From the condition surveying of the concrete structure, the method and type of repair or maintenance action are first selected. These selections depend on the condition of the structure and the conditions of external environment as well as type of equipment and materials to be used in the process. The next step is to determine the functional unit, which is the reference unit used in the life-cycle study [7]. All emission, energy and flow of materials occurring during the process are related to this unit. The functional unit shall be measurable and depends on the goal and scope of the analysis. The goal of the life-cycle assessment shall unambiguously state the intended application and indicate to whom the results will be addressed. Thus, the functional unit for a protective coating may be defined as the unit surface (m^2) protected for a specified period of time.

The life-cycle inventory (LCI) phase will then consist of the following:

1. Quantifying the amount of all raw materials, chemicals and equipment that are necessary to fulfil the repair or maintenance function. This quantification gives the reference flow [8], for which all inputs and outputs are referred to and are closely connected to the functional unit.

2. Environmental data of consumed raw materials, chemicals and equipment from the suppliers (specific data) or from databases (generic data) or from a LCI carried out at supplier level. All materials used should have an environmental declaration with a "Cradle to port" type of scope. The environmental declaration shall include use of resources such as energy (renewable or non renewable), materials (renewable or non renewable), water and waste as well as emissions to air and water.

3. Quantifying and classifying the waste from the process such as recycling or disposal (hazardous or not hazardous).

The calculations to impact categories should be carried out according to Fig. 1. The impact categories will be: Global warming, ozone depletion, acidification, photo-oxidant creation and eutrophication. All calculated effects should be potential effects.

The classification is assignment of LCI results to impact categories. Classification and characterization should be carried out according to ISO 14042, using effect factors from IPCC * in the Montreal protocol [9]. Emission of a specific gas may be assigned to more than one category. An example is emission of $NO_{x,}$, which will be assigned to the categories of both eutrophication and acidification.

The final result may be displayed as impact categories or weighted to an environmental index, where the weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choice. This is an optional element in ISO 14042. Thus, factors from value-choices may be based on political targets according to the Kyoto-protocol or other similar preferences. Interpretation of the results based on ISO 14043 shall identify, qualify, evaluate and present the findings of significant issues.

3. Case Studies

3.1. General

In order to demonstrate how the above methodological framework for assessment of environmental impacts can be applied to various types of repair and maintenance systems for concrete structures, two examples of commonly used systems have been the subject for analysis [10], the results of which are briefly outlined in the following. The one system was a patch repair with shotcreting, where the damage was caused by a chloride-induced corrosion of embedded steel. The other system was a hydrophobic surface protection, which is commonly used as a preventive measure for protection of concrete against chloride penetration and moisture.

For both cases, some common assumptions for the calculation of the ecological impacts were made:

- Same transport distance forth and back (60 km)
- Materials and equipment were transported by truck.
- Fuel consumption (diesel) for the truck was 0.2 kg per ton-km
- Same functional unit (1 m^2 of repaired or protected concrete surface for a period of 10 years)

3.2. Patch repair

The analysis was based on the following assumptions:

- Surface area repaired: 30 m^2
- Rebound of shotcrete: 25%
- Power supply on construction site based on diesel engines

The various steps of the process considered:

- Removal of concrete cover to an average depth of 50 mm by high pressure hydro jetting (1000 bar)
- Cleaning of the reinforcing bars by sand blasting
- Protective coating of the reinforcement
- Application of the shotcrete layer
- Curing measures for the applied shotcrete

The consumption of energy and the ecological impacts of the patch repair are summarized in Table 1.

Table 1: Energy consumption and ecological impacts of the patch repair.

Process	Impact category				
	Use of energy (MJ/m^2)	Global warming (kg CO_2 eq/m^2)	Acidification (g SO_2 eq/m^2)	Eutrophication (g PO_4 eq/m^2)	Photo-oxidant formation (g Ethene eq/m^2)
Hydro jetting	677	84	75	1330	266
Cleaning of reinforcement	296	22	4	350	70
Protective coating on reinforcement	35	1,4	19	2,4	3
Application of shotcrete	59	4,4	19	70	14
Transportation	127	10	8	150	30
Sum	1194	122	125	1902	383

3.3. Hydrophobic surface protection

The analysis was based on the following assumptions:

- Hydrophobic agent: Iso-octyltriethoxy type of silane in combination with a mineral thickener.
- Surface area treated: 150 m^2

The various steps of the process considered:

- Preparation of the concrete surface by high pressure sand blasting (160 bar)
- Application of the hydrophobic agent by use of a high-pressure sprayer to a thickness of 0.25 mm. It was assumed that only 45% of the hydrophobic agent was applied to the concrete surface, which is equivalent to approximately 500 g/m^2, while the rest of the agent (approximately 600 g/$m^{2)}$ was emission to the air. The iso-octyltriethoxy type of silane is volatile and ethanol is released to the atmosphere.

The consumption of energy and the ecological impacts of the hydrophobic surface protection are summarized in Table 2.

Table 2: Energy consumption and ecological impacts of the hydrophobic surface protection

Process	Impact category				
	Use of energy (MJ/m^2)	Global warming (g CO_2 eq/m^2)	Acidification (g SO_2 eq/m^2)	Eutrophication (g PO_4 eq/m^2)	Photo-oxidant formation (g Ethene eq/m^2)
Production of hydrophobic agent	47	295	0.5	6	2
Surface preparation	17	13	0.4	7	1
Transportation and surface treatment	12	80	0.1	2	66
Long-term degradation		2171			1
Sum	76	2559	1	15	70

3.4. Comparison of the two cases

By comparing the two cases selected for analysis, it can be seen from Table 3 that the ecological impacts from the patch repair strongly exceeds that of the hydrophobic surface protection. The results demonstrate that the hydrophobic surface treatment can be repeated more than five times before the ecological impact in the form of photo-oxidant formation approaches that of the patch repair by shotcreting.

Table 3: Comparison between patch repair and hydrofobic treatment

Method	Impact category				
	Use of energy (MJ/m^2)	Global warming (kg CO_2 eq/m^2)	Acidification (g SO_2 eq/m^2)	Eutrophication (g SO_2 eq/m^2)	Photo-oxidant formation (g Ethene eq/m^2)
Hydrofobic treatment	76	2.6	1	15	70
Parch repair	1642	122	125	1902	383

4. Concluding Remarks

Assessment of impact on the environment caused by human activities throughout the life cycle of a structure may be very complex and difficult. Over recent years, however, a methodological framework for life-cycle assessments (has been established through a number of international standards and guidelines.

In order to carry out the present LCA, a number of assumptions had to be made. The results clearly demonstrate, however, that from an ecological point of view, it appears to be a very good strategy to carry out preventive maintenance of a concrete structure before a stage is reached where patch repairs may be necessary.

References

1. Ho, D.W.S., Mak, S.L. and Sagoe-Crentsil, K.K, "Clean Concrete Construction: An Australian Perspective", Proceedings, Concrete Technology for a Sustainable Development in the 21st Century, ed. by O. E. Gjørv and K. Sakai (E & FN Spon, London and New York, 2000) 236-245.
2. Concrete Technology for a Sustainable Development in the 21st Century", Proceedings of an international workshop in Lofoten, Norway, June, 1998, ed. by O. E. Gjørv and K. Sakai (E & FN Spon, London and New York, 2000) 386.
3. Gjørv, O.E., "Durability Design and Construction Quality." Submitted to Proceedings of the International Conference on Advances in Concrete and Structures 2003, Xuzhou, Jiangsu, China (2003).
4. Horrigmoe, G., "Future Needs in Concrete Repair Technology", Proceedings, Concrete Technology for a Sustainable Development in the 21st Century, ed. by O. E. Gjørv and K. Sakai (E & FN Spon London and New York, 2000) 332-340.
5. ISO 14042 Environmental management, Life cycle assessment, Life cycle impact assessment (2000).
6. ISO 14040 Environmental management, Life cycle assessment, Principles and framework (1998).
7. ISO 14041 Environmental management, Life cycle assessment, Goal and scope definition and inventory analysis (1999).
8. ISO 14043 Environmental management, Life cycle assessment, Life cycle interpretation (2000).
9. Centrum voor Milieukunde, Leiden, Holland, Environmental life cycle assessment of products (1999).
10. "Life Cycle Management of Concrete Infrastructures for Improved Sustainability, LIFECON", The European Union – Competitive and Sustainable Growth Programme, Project No. G1RD-CT-2000-00378, Document D5.2 (2003).

HOW SUSTAINABLE IS CONCRETE?

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Abstract

An analysis was carried out to determine whether concrete is a sustainable housing material. Sustainability generally means having no net negative impact on the environment, and this analysis compared the environmental impact of producing concrete and steel. To make this comparison, we first designed a simple reinforced concrete beam and a steel I-beam with the same moment capacity, and we then estimated the environmental impact of the production of these two beams using a commercial computer program designed for this purpose. The estimation showed that the concrete beam required much less energy and had a lower net environmental impact than the steel beam.

1. Introduction

Some time ago we wrote a proposal to study the use of cementitious materials in residential construction. In that proposal we argued that concrete is a sustainable material for housing. However, we knew very little then about how to compute the environmental impact of a construction material. The proposal was not funded, but it piqued our interest in how such a computation can be made. Since that time several computer programs for such computation have become commercially available, and we recently purchased such a program, ATHENA[1] to use in a course on sustainable housing for civil engineering students. The purpose of this paper is to describe the computation of environmental impact. As an illustration, we use ATHENA to compare the environmental impact of ordinary concrete with that of concrete containing fly ash, and to compare the environmental impact of concrete with the impact of steel. Through this computation we hope to answer the question posed in our earlier proposal – whether concrete causes less environmental damage than steel and therefore whether our claim that concrete is a sustainable material for housing was legitimate.

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[1] ATHENA™ is a registered trademark of the ATHENA Sustainable Materials Institute, Merrickville, Ontario, Canada.

2. Sustainability

As used in everyday speech, sustain means to support or to keep a process going,[2] and the goal of sustainability is that life on the planet can be sustained for the foreseeable future. There are three components of sustainability: environment, economy, and society. To meet its goal, sustainable development must provide that these three components remain healthy and balanced. Furthermore, it must do so simultaneously and throughout the entire planet, both now and in the future. At the moment, the environment is probably the most important component, and an engineer or architect uses sustainability to mean having no net negative impact on the environment. Thus the term sustainable has come to be synonymous with environmentally sound or friendly and "green."

The environmental component has our attention now because deterioration of our environment is driving the current worldwide focus on sustainable development. We could cite countless examples of environmental deterioration, and all are important. Probably the most troubling for the long-term health of the planet and for the goal of sustainability are the climate changes resulting from the thinning of the ozone layer and the progressive decline in biodiversity resulting from loss of habitat. Both of these changes are a direct result of human development.

The economic component is given less attention in the developed countries of the world, but is equally essential to the goal of sustainable development. There is poverty throughout the planet, and the global inequities in consumption of resources are staggering. Economic sustainability and environmental sustainability are closely linked. Much environmental degradation occurs when people are struggling to obtain the resources essential for life (food, water, shelter, etc.), and it is inevitable that the basic economic struggle may take precedence over environmental sustainability. Conversely, environmental deterioration exacerbates economic inequity, for example diseases associated with lack of clean water are a significant cause of poverty.

The social component is also given less attention at the moment but will hopefully be brought into balance in the ensuing decades. The goal of sustainable development clearly requires stable social structures. Only with broad social commitment implemented by governmental policies can we progress towards sustainable

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[2] This is the definition given in the Random House College Dictionary published in 1973, the edition on my (LS) bookshelf. Interestingly, this dictionary does not separately define sustainability. The latter term has found its way into common speech only more recently, with the more widespread interest in environmental impact during the last two decades of the 20th century.

development. War, probably inevitable in the absence of stable social structures, causes both economic disparity and environmental deterioration.[3]

Despite the critical importance of all three components (environmental, economic, and social) in sustainable development, this paper focuses only on the environmental impact of construction materials. Even that is a very broad issue. In the manufacture and use of construction materials, the critical elements of environmental impact are the utilization of resources, the embodied energy, and the generation of waste materials. These are the issues that engineers and architects must consider when planning and building a structure, and these are the issues we address here. That is not to say that economic and social issues are less important, merely that they are outside our purview.

3. Sustainability of Construction Materials

In order to estimate the environmental impact of a construction material, it is necessary to consider all stages in the life of the material (Fig. 1).

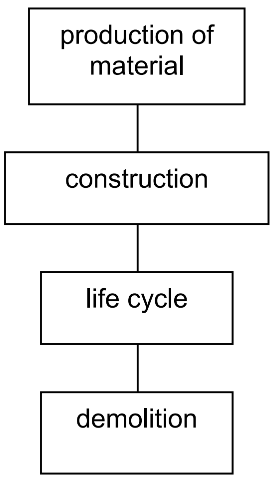

Fig. 1: Stages considered when estimating environmental impact

Each construction material is manufactured from some combination of raw materials, with some expenditure of energy, and with associated wastes. Therefore manufacture is an essential element in computing the environmental impact, and manufacture is probably the element most widely cited when considering the environmental impact of construction materials. Are the raw materials renewable? Are they scarce? Are they important to the global environment? How much energy is required in the manufacture? How much waste is produced during the manufacture? What impact do these wastes have on the environment? These questions are very important and

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[3] Because one of us (LS) grew up in the shadow of the major world wars of the last century, we recognize the horrendous negative impact of war on human development. We recognize as well that war is not prevented by stable social structures, but we hope, and history teaches us, that such social structures make war less likely.

this phase probably receives the most attention, both from the general public and from the government.

The construction process also involves some expenditure of energy and produces some waste. There are several important questions. How much of each manufactured material is used? Can materials be used that have less environmental impact? How much energy is used? How much waste is produced? What is the impact of the waste on the environment? Some of these questions can only be answered for a specific structure. Increasing attention is being given to the construction phase as part of global and regional efforts to make development more sustainable.

The lifetime of the structure has a direct impact on sustainability. When the structure deteriorates, it must be destructed and rebuilt. The lifetime is directly controlled by the durability of the construction materials. It is further influenced by the adaptability of the design to repair and renovation, and repair and renovation themselves have environmental impacts. Finally, the lifetime of a structure is influenced by cultural and market forces. When a structure no longer serves an important function (not necessarily the function for which it was constructed), it is likely to be destructed. And if it is not aesthetically pleasing, it may be destructed. So materials and design considerations directly affect the lifetime of a structure and the lifetime must be considered when computing environmental impact.

During its life, the structure uses considerable energy. Energy use during the life of a structure is a key element in computing its environmental impact and is also a factor widely recognized for its importance. Each material makes a contribution to the thermal insulation, thereby affecting energy use. Of course, energy use is strongly affected by the mechanical systems used to heat and cool the structure. Energy use is thus directly affected by both design and materials.

The final stage in the life of a structure is its demolition. How much of the structure can be reused? How much of the materials can be recycled? What is the environmental impact of the waste produced during the demolition? What materials must be disposed of? What is the environmental impact of the disposed materials? In the USA, there is little consideration of the demolition stage during design and construction. However, the impact of demolition must be considered when computing the environmental impact of a structure.

4. Sustainability of Concrete

Concrete is manufactured from aggregates (rock and sand), hydraulic cement, and water. It usually contains a small amount of some chemical admixture, and (at least in the USA) it often contains a mineral admixture replacing some portion of the cement. A typical concrete formulation contains a large amount of coarse and fine aggregate, a moderate amount of cement and water, and a small amount of admixture. Most of these constituents are themselves manufactured products, byproducts, or materials extracted by mining. In order to assess the environmental impact of concrete manufacture, it is necessary to consider the impact of each separate constituent.

The aggregates are usually obtained by mining. The coarse and fine aggregates are usually mined separately. Occasionally aggregate is obtained as a by-product of some other process (e.g., slag or recycled concrete). Aggregates may be crushed and may be washed. They are usually separated into various size fractions and reconstituted so as to satisfy the grading requirements. They may need to be dried. A modest amount of energy is involved in all these processes. The principal wastes are dust and water, neither of which is especially damaging to the environment. The dust may be used in some other process or may be disposed in a landfill.

The hydraulic cement may be straight portland cement or a mixture of portland cement and some proportion of a supplemental cementing material such as fly ash or slag. Portland cement is usually manufactured by heating a mixture of limestone and shale in a kiln to a high temperature (approximately 1500°C), then intergrinding the resulting clinker with gypsum to form a fine powder. Thus it is not surprising that the portland cement has a rather high embodied energy. The reaction between limestone and shale to produce clinker produces CO_2. Furthermore, the fuel used in the kiln and the electricity in the grinding mills themselves produces some amount of gaseous waste, principally CO_2 and CO. These gases are non toxic and are released to the atmosphere, where they contribute to global warming. Supplemental cementing materials, as noted above, may also be used as mineral admixtures in concrete. These are byproducts of other manufacturing processes and as such are taken to have minimal embodied energy.

The water in concrete is normally ordinary tap water with no further processing. Thus it has very little embodied energy and no waste. It is only an environmental issue in locations where the water is already not sufficient for basic needs.

Concrete is usually manufactured by combining and mixing these constituents in large batches in a ready-mixed concrete plant and hauling the mixture to the construction site in a truck. These processes (moving materials, mixing them, and hauling the concrete) require modest amounts of energy and produce small amounts of waste. Dust, unused concrete, and wash water contaminated with concrete are the principal waste, and the latter two wastes may be at least partially reclaimed and reused.

Concrete used in structural applications normally includes some amount of reinforcing steel, and in some applications this steel is prestressed. Prestressed concrete is often precast. Precast concrete is manufactured at a plant and heated to accelerate the early hydration reactions and allow rapid removal from formwork.

The environmental impact of using concrete at a construction site is basically similar to the impact of manufacturing concrete in a ready-mixed concrete plant. The concrete is moved to its desired location, consolidated into the formwork, and finished. After the concrete has set and gained some strength, the formwork is typically removed. These are all low-energy operations. Waste includes unused concrete, contaminated wash water, and used formwork. Formwork may be wood, which must be disposed in a landfill, but sometimes it is steel and can be reused.

The impact of concrete on sustainability during the lifetime of the structure is primarily a function of its role in energy transmittance (i.e., its insulating properties) and its role in energy storage. Concrete is not an especially good heat conductor, not as good as steel, for example. It is also not an especially good insulator, not as good as wood, for example. A very high porosity is necessary to provide good insulating properties, and concrete has less porosity than wood. On the other hand, concrete provides a large thermal mass so it can store energy and release it later.

At the end of its service life, a concrete structure must be demolished and disposed. The demolition process is done by brute force -- depending on the size of the structure, it may involve controlled blasting or some type of hammer. These processes use modest amounts of energy. Concrete is sometimes recycled, most commonly used as rock in a pavement sub base, but it is not commonly recycled in the USA. The waste produced by demolition of a concrete structure includes dust, powder, and fragments of concrete. These are typically land filled.

5. Computation of Environmental Impact

As noted previously, we used ATHENA™ to compute the environmental impact associated with concrete and other construction materials. Using an extensive database, this program makes quite straightforward computations to estimate the environmental impact of a building. Various aspects of the building design are input, including the specific construction materials. Any or all of the following are estimated: energy consumption, solid waste, air pollution, water pollution, global warming, or resource use.

The database used in ATHENA is critical to the validity of the computations. Reports that include the data and describe how the data were obtained are included as part of the program.

To answer the question raised in the introduction, whether concrete is a sustainable material, we compared the environmental impact of concrete with that of steel. We first estimated the energy produced during manufacture of concrete and steel. Because it is more realistic to compare energy for a structural element designed for a specific load, we then designed a simple structure to compare reinforced concrete and steel.

The ATHENA database, used in all our calculations, is from Canada, a country similar to the USA in cost and availability of materials but somewhat lower than the USA in average temperature. The cement energy calculation used data from cement plants on the west coast of Canada. The concrete computation was made both with ordinary concrete and with concrete containing fly ash, for which most of the energy is attributed to the production of power, not to the production of the material. The computation assumed normal Canadian industrial practice throughout. This included the fuel for cement and concrete manufacture and for vehicles used to transport materials. The steel results are sensitive to the type of furnace, and data were intermediate between a basic oxygen furnace and an electric arc furnace. Results are also sensitive to the use of scrap steel, and a reasonable (Canadian national average) value was used for scrap steel. The computation includes energy from sources such as coal, coke, electricity, and natural gas.

The mix proportions used for concrete, given in Table 1, were designed for 30 MPa compressive strength at 28 days.

Table 1: Concrete mix proportions

Constituent	Amount (kg/m^3 concrete)
Coarse aggregate	1092
Fine aggregate	722
Portland cement	350
Water	160

To compare the environmental impact of concrete and steel, we designed two beams with the same moment capacity, one using reinforced concrete and the other using steel. For concrete, we started with the dimensions and computed the moment. The beam (Fig. 2) is 0.30 m long, 0.15 m wide, and 0.29 m deep, with 2 bars of reinforcing steel, 30 mm in diameter and located 25 mm up from the bottom surface. The compressive strength of the concrete was assumed to be 30 MPa and the tensile strength of the reinforcing steel was assumed to be 415 MPa. We used the concrete mix in Table 1 but with 10% of the cement replaced by fly ash. The moment capacity of this concrete beam is 0.10 MN.m. The mass of concrete in this beam is 31.5 kg and the mass of reinforcing steel is 3.5 kg. For steel, we selected a steel I-beam of the same length to support the same moment (0.10 MN.m). This beam (Fig. 2) is 0.30 m long, 0.10 m wide, and 0.30 m deep. The tensile strength (i.e., yield stress) of the steel was assumed to be 250 MPa. The mass of steel in this beam is 10.0 kg.

6. Results

The energy consumed in the production of portland cement, shown in Table 2, was estimated to be 4.88 MJ/kg. The major energy, as expected, is consumed during pyroprocessing. A similar energy value, 5.5 GJ/kg (5.6 GJ/long ton), was reported for portland cement production in the USA in 1997; and this report noted that energy consumption in portland cement production in the USA has decreased 30% from 1970 to 1997 [1].

Table 2: Energy used in the production of portland cement

Production Step	Energy (MJ/kg cement)
Extraction of raw materials	0.044
Transportation of raw materials	0.089
Crushing and grinding of raw materials	0.386
Pyroprocessing	4.041
Grinding cement	0.188
Transportation of cement	0.133
Total	4.882

Using this value for portland cement and the mix proportions in Table 1, the energy in the production of concrete, shown in Table 3, was estimated to be 2.07 GJ/m^3 or 0.89 MJ/kg. Replacing 10% of the portland cement with fly ash reduced this to 1.94 GJ/m^3 or 0.83 MJ/kg. The major part of this energy, as expected, is associated with the portland cement.

Table 3: Energy used in the production of concrete

Constituent	Energy (MJ/kg concrete)
Coarse aggregate	0.028
Fine aggregate	0.028
Portland cement	0.735
Water	0.000
Manufacturing	0.102
Total	0.893

The total energy in the production of steel was estimated to be 23.70 GJ/kg. A reasonably similar energy value, 25.5 GJ/kg (25.9 GJ/long ton), was reported for iron and steel production in the USA in 1994 [2]. The value computed for steel is considerably higher than the value computed for concrete. We used the computed value for estimating the embodied energy in the beams, both for reinforcing steel in the concrete beam and for steel in the I-beam, although the latter would probably be hot-rolled and would therefore require some additional energy.

Using these computed energy values, the energy to produce the reinforced concrete beam shown in Fig. 2 was estimated to be 109 MJ and the energy to produce the steel I-beam shown in Fig. 2 was estimated to be 237 MJ. Thus the energy to produce a reinforced concrete beam was about half the energy to produce a similar steel I-beam.

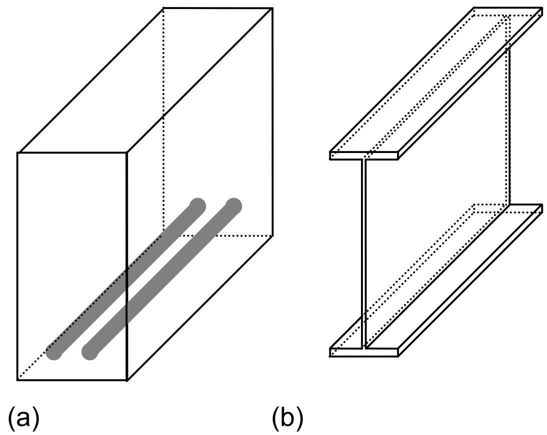

Fig. 2: Schematic of structures: (a) reinforced concrete beam and (b) steel I-beam

Other environmental parameters estimated for the two beams (reinforced concrete and steel) using ATHENA are listed in Table 4. The resource use for concrete was about double that for steel. Both produced high levels of carbon dioxide, but the amount for concrete was quite similar to the amount for steel. The water pollution index for concrete was about half that for steel. The air pollution values were similar. The solid waste values were similar. The energy consumption for concrete was about two-thirds that for steel. The energy values computed using ATHENA were different from the values we computed, in part because ATHENA included construction and demolition while we considered only the manufacture of the materials. Overall, the computation shows a smaller environmental impact for concrete than for steel.

Table 4: Environmental impacts of reinforced concrete and steel beams

Impact	Reinforced concrete	Steel
Resource use (kg)	48.85	18.69
Warming potential (kg equivalent CO_2)	9.97	8.95
Water pollution index	0.34	0.98
Air pollution index	2.01	2.46
Solid waste (kg)	1.87	1.80
Energy (MJ)	140.18	229.69

7. Discussion

Computing environmental impact is a very complex task. We chose a fairly simple problem here, comparing two structural materials. It is important to consider, as we did here, a specific structure, and we chose a fairly simple structure, a beam, so we could compare the amount of each material required for the same engineering function. It is certainly possible to estimate the environmental impact of a specific house that utilizes specific materials, but the computation becomes even more complex. In comparing the environmental impact of specific structural materials in a given structure, it is probably necessary to use a different structural design tailored for each specific material, as we did here.

The simple structure used here did not allow us to include any differences in insulating capacity of the two materials, although the program does provide that capability. Moreover, the program does not predict a life cycle to use in the calculation of environmental impact.

This computation showed that concrete has less environmental impact than steel when compared in structures designed for the same engineering function. It is much more difficult to answer the broader question of whether concrete housing is sustainable. That question requires that we weigh the environmental impact and economic cost of the structure against its social benefits. We have found no absolute criteria on which to evaluate sustainability. What we can conclude from this analysis is that concrete is more sustainable than steel in the same structure.

8. Conclusions

The environmental impact of a reinforced concrete beam and a steel I-beam designed for the same engineering function was estimated using a computer program designed for this purpose and commercially available. Based on this estimation, production of the concrete beam required much less energy and had a lower net environmental impact than production of the steel beam.

References

1. Martin, N., Worrell, E., and Price, L. *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Cement Industry*. Lawrence Berkeley National Laboratory, University of California, LBNL-44182, 1999; http://eetd.lbl.gov/ea/ies/iespubs/44182.pdf.

2. Worrell, E., Martin, N., and Price, L. *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Iron and Steel Sector*. Lawrence Berkeley National Laboratory, University of California, LBNL-41724, 1999; http://eetd.lbl.gov/ea/ies/iespubs/71724.pdf.

MEASURING THE LIFE-CYCLE ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF CONCRETE: THE BEES APPROACH

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Abstract

Society is increasingly concerned about the implications of manufactured products for the environment, public health, and future costs. How does a product affect global warming, smog, fossil fuel depletion, and human toxicity? How about its costs over time? Building for Environmental and Economic Sustainability (BEES) addresses these questions by measuring the life-cycle environmental and economic performance of construction products. Used by thousands of designers worldwide, BEES measures environmental performance using the life-cycle assessment approach specified in the ISO 14040 series of standards. All stages in the life of a product are analyzed: raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management. Twelve environmental impacts are assessed: global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, smog, ozone depletion, ecological toxicity, human health, criteria air pollutants, and water intake. Economic performance is measured using the American Society for Testing and Materials, International (ASTM) standard life-cycle cost method, which covers the costs of initial investment, replacement, operation, maintenance and repair, and disposal. Environmental performance and economic performance are combined into an overall performance measure using the ASTM standard for Multiattribute Decision Analysis. The paper will explain the BEES approach and illustrate its application to alternative concrete products with and without supplementary cementitious materials.

1. Introduction

Worldwide, about one ton of concrete is produced each year for every human being in the world (some 6 billion tons per year), making concrete one of the world's most popular construction materials. The construction market in Asia is the leading market in the world, with an estimated value of about 1.2 trillion U.S. dollars (USD). Japan and China continue to lead the region's construction industry. Europe's construction market is estimated at 1.1 trillion USD. The United States, with the world's healthiest market, and Canada, with a hot market of its own, put North America at about 1 trillion USD. Latin America, led by Brazil and Mexico, places South America next with a market of about 300 billion USD. The construction market in the Middle East is about 150 billion USD, followed by Africa with a market of about 60 billion USD. The world construction market is estimated to be about 4 trillion USD.

The amount of world trade dealing with concrete is estimated to be about 13 to 14 trillion USD. This includes various aspects dealing with the production and use of concrete. The magnitude of this number shows that the wave of economic globalization has an impact on the concrete industry, as concrete represents the basic building material for the development and maintenance of the civil infrastructure facilities that are an integral component of an economy. About 1% of the world population has jobs that directly relate to the concrete construction industry.

On the basis of the use of concrete per person per year, the world's biggest market for concrete is North America. In the United States, concrete is used in excess of 2.5 tons per person per year. Gross product of concrete and cement manufacturing revenue exceeds 35 billion USD annually. In addition to concrete and cement manufacturing, the industry includes aggregates and material suppliers, designers, contractors, and repair and maintenance companies. Over 2 million jobs relate to the U.S. concrete construction industry. It is estimated that the production and consumption of concrete will see a rise of about 1% per year for the next three to five years.

Sustainability is becoming an increasingly important issue for concrete construction. This paper presents an overview of the approach taken by the Building for Environmental and Economic Sustainability (BEES) program to address some of these concerns.

The U.S. National Institute of Standards and Technology (NIST) Healthy and Sustainable Buildings Program began the BEES project in 1994. The purpose of BEES is to develop and implement a systematic methodology for selecting construction products that achieve the most appropriate balance between environmental and economic performance based on the decision maker's values. The methodology is based on consensus standards and is designed to be practical, flexible, and transparent. The BEES model is implemented in publicly available decision-support software used by over 9500 people worldwide, and comes complete with actual environmental and economic performance data for a number of concrete construction products [1]. The objective is a cost-effective reduction in construction-related contributions to environmental problems.

In 1997, the U.S. Environmental Protection Agency's (EPA) Environmentally Preferable Purchasing (EPP) Program also began supporting the development of BEES. The EPP program is charged with carrying out Executive Order 13101, *Greening the Government Through Waste Prevention, Recycling, and Federal Acquisition*, which directs Executive agencies to reduce the environmental burdens associated with the $240 billion in products and services they purchase each year, including construction products. BEES is being further developed as a tool to assist the Federal procurement community in carrying out the mandate of Executive Order 13101.

2. BEES Methodology

The BEES methodology takes a multidimensional, life-cycle approach. That is, it considers multiple environmental and economic impacts over the entire life of the construction product. Considering multiple impacts and life-cycle stages is necessary because product selection decisions based on single impacts or stages could obscure other impacts or stages that might cause equal or greater damage. In other words, a multidimensional, life-cycle approach is necessary for a comprehensive, balanced analysis.

It is relatively straightforward to select products based on minimum life-cycle economic impacts because construction products are bought and sold in the marketplace. But how do we include life-cycle environmental impacts in our purchase decisions? Environmental impacts such as global warming, water pollution, and resource depletion are for the most part economic externalities. That is, their costs are not reflected in the market prices of the products that generated the impacts. Moreover, even if there were a mandate today to include environmental "costs" in market prices, it would be nearly impossible to do so due to difficulties in assessing these impacts in economic terms. How do you put a price on clean air and clean water? What is the value of human life? Economists have debated these questions for decades, and consensus does not appear likely.

While environmental performance cannot be measured on a monetary scale, it can be quantified using the evolving, multi-disciplinary approach known as environmental life-cycle assessment (LCA). The BEES methodology measures environmental performance using an LCA approach, following guidance in the International Standards Organization 14040 series of standards for LCA [2]. Economic performance is separately measured using the ASTM international standard life-cycle cost (LCC) approach. These two performance measures are then synthesized into an overall performance measure using the ASTM standard for Multiattribute

Decision Analysis (MADA) [3]. For the entire BEES analysis, products are defined and classified based on UNIFORMAT II, the ASTM standard classification for construction elements [4].

2.1. Environmental performance

Environmental life-cycle assessment is a “cradle-to-grave” systems approach for measuring environmental performance. The approach is based on the belief that all stages in the life of a product generate environmental impacts and must therefore be analyzed, including raw materials acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately, recycling and waste management. An analysis that excludes any of these stages is limited because it ignores the full range of upstream and downstream impacts of stage-specific processes.

The strength of environmental life-cycle assessment is its comprehensive, multi-dimensional scope. Many green construction claims and strategies are now based on a single life-cycle stage or a single environmental impact. A product is claimed to be green simply because it has recycled content, or accused of not being green because it releases toxic chemicals during its manufacture. These single-attribute claims may be misleading because they ignore the possibility that other life-cycle stages, or other environmental impacts, may yield offsetting impacts. For example, the recycled content product may have a high embodied energy content, leading to resource depletion, global warming, and acid rain impacts during the raw materials acquisition, manufacturing, and transportation life-cycle stages. LCA thus broadens the environmental discussion by accounting for shifts of environmental problems from one life-cycle stage to another, or one environmental medium (land, air, water) to another. The benefit of the LCA approach is in implementing a trade-off analysis to achieve a genuine reduction in overall environmental impact, rather than a simple shift of impact.

The general LCA methodology involves four steps. The *goal and scope definition* step defines the context for the study, including its purpose and units of comparison. The purpose of BEES is to assess the life-cycle environmental and economic performance of construction products sold in the United States. The basis for all units of comparison is known as the *functional unit*, defined so that the products compared are true substitutes for one another. In the BEES model, the functional unit for concrete slabs, walls, and paving is 0.09 m^2 (1 ft^2) of product service for 50 years, while the functional unit for concrete beams and columns is 0.76 cubic meters (1 cubic yard) of product service for 50 years. The functional unit provides the critical reference point to which all quantities are scaled. All product alternatives are assumed to meet minimum technical performance requirements (e.g., hydration and strength development).

The *inventory analysis* step identifies and quantifies the environmental inputs and outputs associated with a product over its entire life cycle. As shown in Fig. 1, environmental inputs for any production process include water, energy, and other raw materials; outputs include releases to air, land, and water. In the LCA inventory analysis step, production processes for any given product are identified, as illustrated in Fig. 2, and the environmental inputs and outputs for each are summed. However, inventory analysis is only an intermediate step because it is not these summed inputs and outputs, or *inventory flows,* that are of primary interest. We are more interested in their consequences, or impacts on the environment. Thus, the next LCA step, *impact assessment*, characterizes these inventory flows in relation to a set of environmental impacts. For example, the impact assessment step might relate carbon dioxide emissions, a *flow*, to global warming, an *impact*. The BEES impact assessment model uses state-of-the-art, peer-reviewed impact assessment methods recently developed by the U.S. EPA Office of Research and Development and known as TRACI [5]. Twelve environmental impacts are assessed: global warming potential, acidification potential, eutrophication potential, fossil fuel depletion, indoor air quality, habitat alteration, criteria air pollutants, human health, smog, ozone depletion, ecological toxicity, and water intake.

Once impacts have been assessed, the resulting impact category performance measures are expressed in non-commensurate units. Global warming is expressed in carbon dioxide equivalents, acidification in hydrogen ion equivalents, eutrophication in nitrogen equivalents, and so on. In order to assist in the next LCA step (interpretation), performance measures are often placed on the same scale through normalization. BEES normalizes based on data EPA developed for use with its TRACI impact assessment methods [6]. For each impact, the data estimate its performance at the U.S. level, yielding a yardstick against which to evaluate the *significance* of product-specific impacts. These normalization data are commonly referred to as "footprint" data. By expressing each product-specific impact measure in terms of its contribution to its respective U.S. footprint, all measures are all reduced to the same scale, allowing comparison across impacts.

Finally, at the *interpretation* step, the normalized impact assessment results are evaluated. Few products are likely to dominate competing products in all BEES impact categories. Rather, one product may out-perform the competition relative to fossil fuel depletion and habitat alteration, fall short relative to global warming and acidification, and fall somewhere in the middle relative to indoor air quality and eutrophication. To compare the overall environmental performance of competing products, the performance scores for all impact categories may be synthesized into a single score.

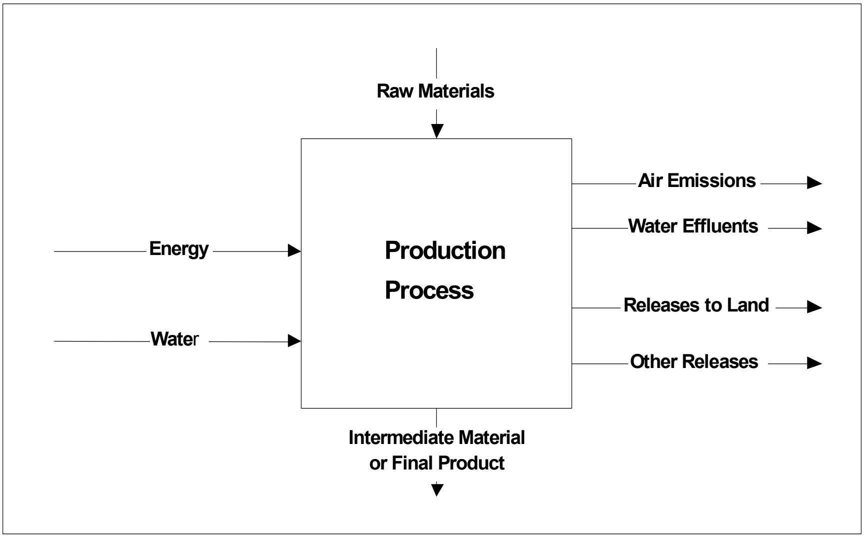

Fig. 1: BEES inventory data categories

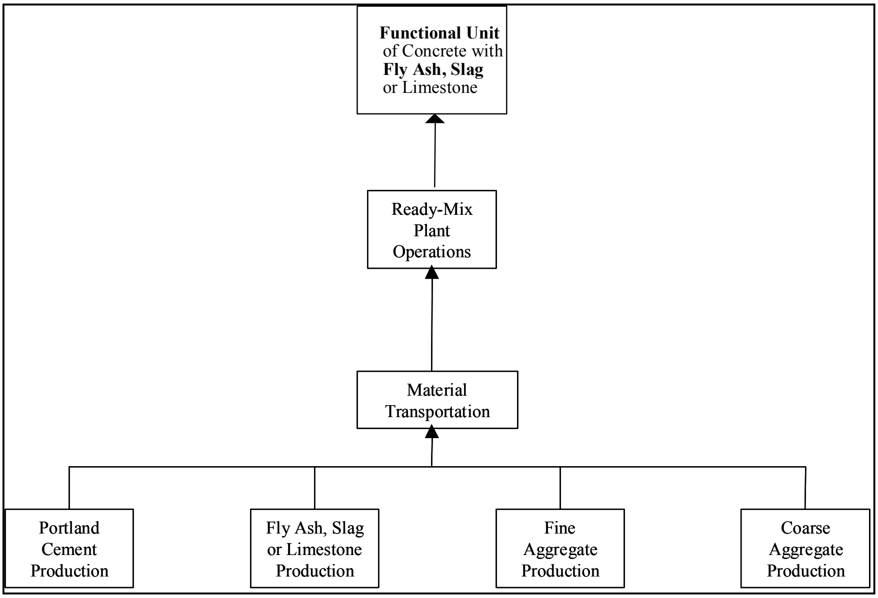

Fig. 2: Concrete production processes

Impact scores may be synthesized by weighting results for each impact category by its relative importance to overall environmental performance, then computing the weighted average impact score. In the BEES software, the set of importance weights is selected by the user. Several derived, alternative weight sets are provided as guidance, and may either be used directly or as a starting point for developing user-defined weights. The alternative weights sets are based on an EPA Science Advisory Board study, a Harvard University study, and a set of equal weights, representing a spectrum of ways in which people value diverse aspects of the environment. Note that in BEES, synthesis of impact scores into a single score is optional.

2.2. Economic performance

Measuring the economic performance of construction products is more straightforward than measuring environmental performance. Published economic performance data are readily available, and there are well-established standard methods for conducting economic performance evaluations. The most appropriate method for measuring the economic performance of construction products is the life-cycle cost method. BEES follows the ASTM standard method for life-cycle costing of construction-related investments [7].

It is important to distinguish between the time periods used to measure environmental performance and economic performance. These time periods are different. Recall that in LCA, the time period begins with raw material acquisition and ends with product end-of-life. Economic performance, on the other hand, is evaluated over a fixed period (known as the study period) that begins with the purchase and installation of the product and ends at some point in the future that does not necessarily correspond with product end-of-life.

Economic performance is evaluated beginning at product purchase and installation because this is when out-of-pocket costs begin to be incurred and investment decisions are made based upon out-of-pocket costs. The study period ends at a fixed date in the future. For a private investor, its length is set at the period of product or facility ownership. For society as a whole, the study period length is often set at the useful life of the longest-lived product alternative. However, when alternatives have very long lives, (e.g., more than 50 years), a shorter study period may be selected for three reasons:

- Technological obsolescence becomes an issue
- Data become too uncertain
- The farther in the future, the less important the costs

In the BEES model, economic performance is measured over a 50-year study period. This study period is selected to reflect a reasonable period of time over which to evaluate economic performance for society as a whole. The same 50-year period is used to evaluate all products, even if they have different useful lives. This is one of the strengths of the LCC method. It accounts for the fact that different products have different useful lives by evaluating them over the same study period.

For consistency, the BEES model evaluates the use stage of environmental performance over the same 50-year study period. Product replacements over this 50-year period are accounted for in the environmental performance score, and inventory flows are prorated to year 50 for products with lives longer than the 50-year study period.

The LCC method sums over the study period all relevant costs associated with a product. Alternative products for the same function, say parking lot paving, can then be compared on the basis of their LCCs to determine which is the least cost means of fulfilling that function over the study period. Costs typically include purchase, installation, maintenance, repair, and replacement costs. A negative cost item is the residual value. The residual value is the product value remaining at the end of the study period. In the BEES model, the residual value is computed by prorating the purchase and installation cost over the product life remaining beyond the 50-year period.

The LCC method accounts for the time value of money by using a discount rate to convert all future costs to their equivalent present value. Future costs must be expressed in terms consistent with the discount rate used. There are two approaches. First, a *real* discount rate may be used with constant-dollar (e.g., 2002) costs. Real discount rates reflect that portion of the time value of money attributable to the real earning power of money over time and not to general price inflation. Even if all future costs are expressed in constant 2002 dollars, they must be discounted to reflect this portion of the time-value of money. Second, a *market* discount rate may be used with current-dollar amounts (e.g., actual future prices). Market discount rates reflect the time value of money stemming from both inflation and the real earning power of money over time. When applied properly, both approaches yield the same LCC results. The BEES model computes LCCs using constant 2002 dollars and a real discount rate. While the user may specify any reasonable discount rate, the BEES tool defaults to a real rate of 3.9%, the 2002 rate mandated by the U.S. Office of Management and Budget for most federal projects [8].

2.3. Overall performance

The BEES overall performance measure synthesizes the environmental and economic results into a single score, as illustrated in Fig. 3. Yet the environmental and economic performance scores are denominated in different units. How can these diverse measures of performance be combined into a meaningful measure of overall performance? The most appropriate technique is Multiattribute Decision Analysis. MADA problems are characterized by tradeoffs between apples and oranges, as is the case with the BEES environmental and economic performance results. The BEES system follows the ASTM standard for conducting MADA evaluations of construction-related investments [3].

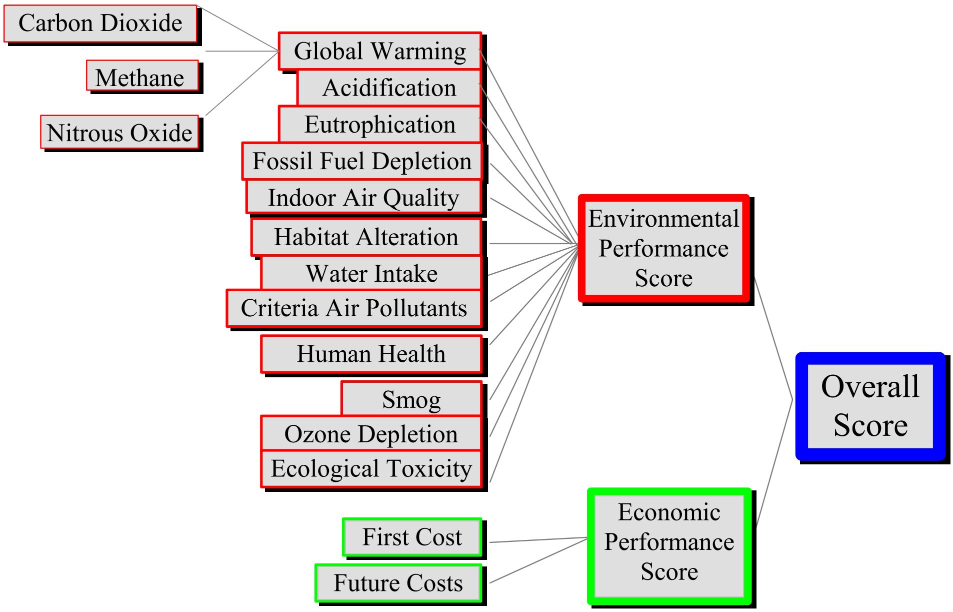

Fig. 3: Deriving the BEES overall performance score

Before combining the environmental and economic performance scores, each is placed on a common scale by dividing by the sum of corresponding scores across all alternatives under analysis. In effect, then, each performance score is rescaled in terms of its share of all scores, and is placed on the same, relative scale from 0 to 100. Then the two scores are combined into an overall score by weighting environmental and economic performance by their relative importance and taking a weighted average. The BEES user specifies the relative importance weights used to combine environmental and economic performance scores and should test the sensitivity of the overall scores to different sets of relative importance weights.

3. Case Example

How can the concrete industry use BEES to evaluate the life-cycle environmental and economic performance of its products? Over the years, cement producers have developed various blended cements to reduce the cost, heat generation, and presumably the environmental burden of concrete. For example, ground granulated blast furnace slag (referred to as GGBFS or "slag"), fly ash, and limestone have been substituted for a portion of the portland cement in the concrete mix. Fly ash is a waste material that results from burning coal to produce electricity, slag is a waste material that is a result of steel production, and limestone is an abundant natural resource. When used in concrete, slag, fly ash, and limestone are cementitious materials that can act in a similar manner as cement by facilitating compressive strength development.

Let's run through an example comparing concrete mixes with and without these supplementary materials. BEES includes life-cycle environmental and economic performance data for both generic (U.S. industry-average) concrete and manufacturer-specific concrete. These two data types allow for both comparison of "real" products against one another and against their hypothetical industry averages. Suppose we're interested in the following concrete mixes for a residential concrete slab application, all with compressive strengths of 21 MPa and installed using plywood forms and steel reinforcing in quantities required for a 7.62-m (25-ft) span:

1. Generic concrete with cement consisting of 100% portland cement (referred to as 100% portland cement)
2. Generic blended cement concrete in which 20% of the portland cement, by mass fraction of cement, is replaced by limestone. Note that for this mix, more blended cement than usual is used in the concrete to achieve a strength equivalent to that for mixes with no limestone replacements (20% limestone cement)
3. Blended cement concrete manufactured by Lafarge North America, in which 10% of the portland cement, by mass fraction of cement, is replaced by silica fume (Lafarge silica fume) [9]
4. *NewCem* blended cement concrete manufactured by Lafarge North America, in which 50% of the portland cement, by mass fraction of cement, is replaced by ground granulated blast furnace slag (Lafarge NewCem (50%))
5. Generic blended cement concrete in which 35% of the portland cement, by mass fraction of cement, is replaced by fly ash (35% fly ash cement)

The first step is to set our analysis parameters using the BEES window shown in Fig. 4. If we do not wish to combine environmental and economic performance measures into a single score, we can select the "No Weighting" option and still compute disaggregated BEES results. Otherwise, we need to set importance weights. In this example, environmental performance and economic performance are of equal importance so both are set to 50%. Next, we need to set relative importance weights for the 12 environmental impact categories included in the BEES environmental performance score. We select the "Equal Weights" set, assigning equal importance to all impacts. Our last parameter is the real discount rate used to convert future concrete product costs to their equivalent present value. Here, we accept the default rate of 3.9% in real terms.

Next, we need to set a final parameter for each of our concrete slab alternatives – the transportation distance from the ready-mix plant to the construction site at which the concrete will be poured. This parameter lets BEES compute an environmental performance score accounting for the significance of using locally produced products. As illustrated in Fig. 5, a transportation distance of 80 km has been selected for the concrete alternatives used in the example.

After this, BEES can compute and display the results. Fig. 6 shows the BEES Environmental Performance Results displaying the weighted environmental performance scores for our example in graphical form. Lower values are better, with each product alternative's score denominated in percentage points representing the weighted contribution to the U.S. environmental footprint of 0.09 m^2 (1 ft^2) of the product over a 50-year use period. In this example, the product results are grouped into two tiers, with the 100% portland cement, 20% limestone cement, and Lafarge silica fume cement yielding slightly higher, or worse, scores (on the order of 0.014 percentage points) than both Lafarge NewCem (50%) and 35% fly ash cement (0.012 percentage points). The figure breaks down the weighted environmental score for each product by its 12 contributing, weighted impact scores. As shown, the weighted impact scores are fairly uniform across concrete mixes, as can be expected for product alternatives with predominately similar constituents. After all, cement—the material being partially replaced with supplementary materials—comprises only 10% to 15%, by mass fraction, of concrete.

Some may be surprised to see no significant difference between the BEES environmental performance scores for 100% portland cement, the traditional concrete mix, and one of the so-called "environmentally friendly" alternatives, 20% limestone cement. Upon closer examination, however, the reasons become clear. With 20% limestone cement, more blended cement than usual is used in the concrete to achieve a strength equivalent to that for mixes with no limestone replacements. Thus, while the limestone blend performs slightly better on ecological toxicity, global warming, and human health due to the limestone content, it performs worse on criteria air pollutants, primarily due to particulates released during limestone mining.

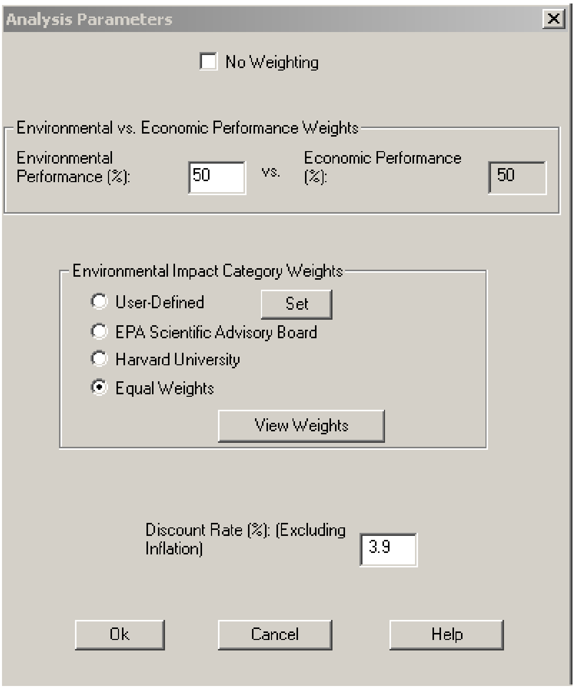

Fig. 4: Setting BEES analysis parameters

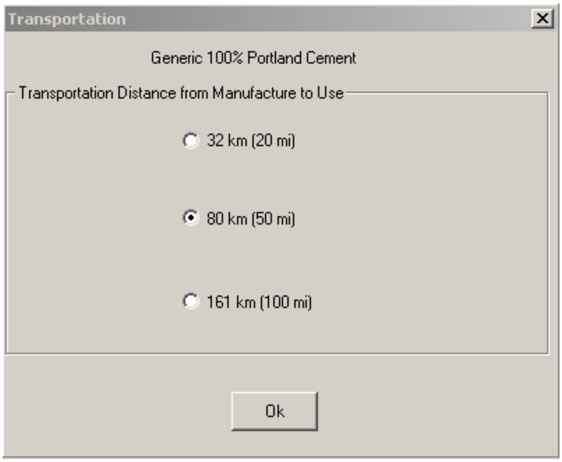

Fig. 5: Setting product-specific parameters

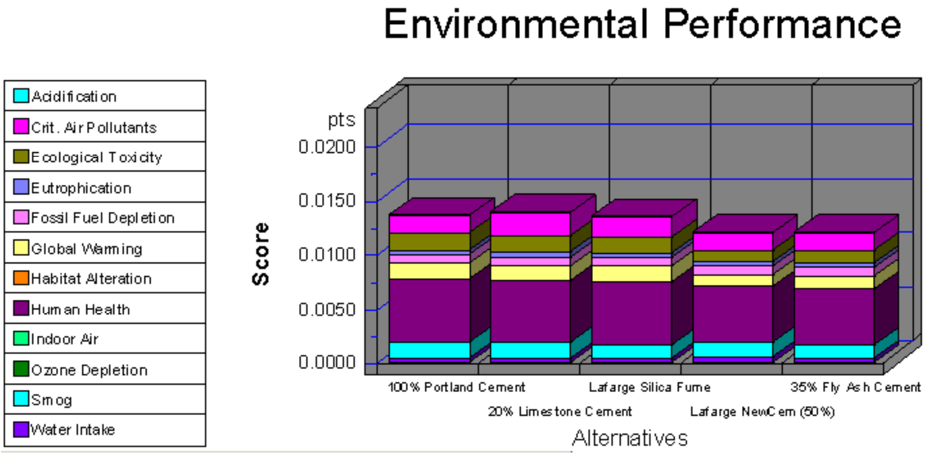

Fig. 6: Viewing BEES environmental performance results

Fig. 7 shows the BEES Economic Performance Results for our example, which plots first costs, discounted future costs, and their sum, the life-cycle cost expressed in present value dollars. Residential concrete slabs require no significant maintenance and repair costs over the BEES 50-year study period. Moreover, these products tend to last more than 50 years; BEES assumes a 75-year useful life for concrete slabs. In such cases where the product life exceeds the length of the study period, BEES *deducts* from the life-cycle cost a residual value representing the product value remaining at the end of the study period. That explains why you see a negative future cost in Fig. 7. Note that even though the residual value in year 50 is fully one-third of the first cost, once discounted to present value dollars it becomes very small.

The BEES overall performance score gives us a way to combine and balance the environmental and economic performance scores. Fig. 8 shows the BEES overall performance results based on our equal weighting of environmental and economic performance. It displays the overall performance score for each product alternative, which is the sum of its weighted environmental and economic performance scores. Since the environmental and economic performance results followed an identical pattern, with products essentially grouped into two tiers, the overall results follow the same pattern. Thus, based on the parameter values we set above, Lafarge NewCem (50%) and 35% fly ash cement are slightly preferable overall to 100% portland cement, 20% limestone cement, and Lafarge silica fume cement.

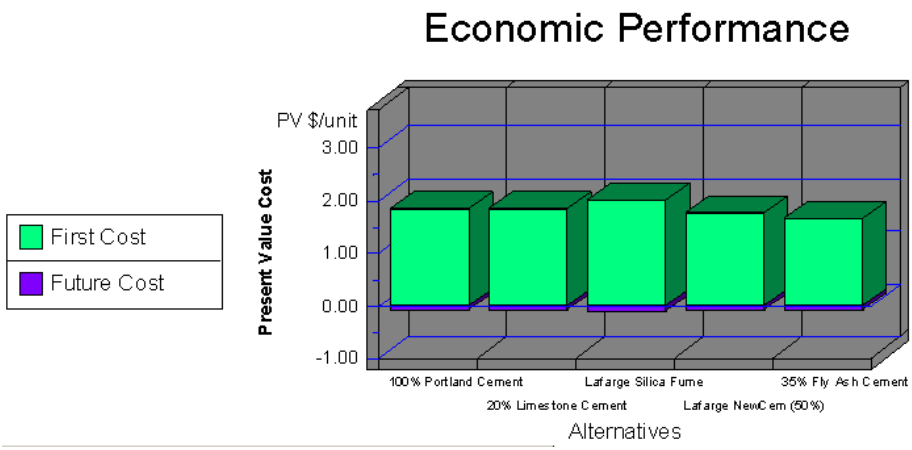

Fig. 7: Viewing BEES economic performance results

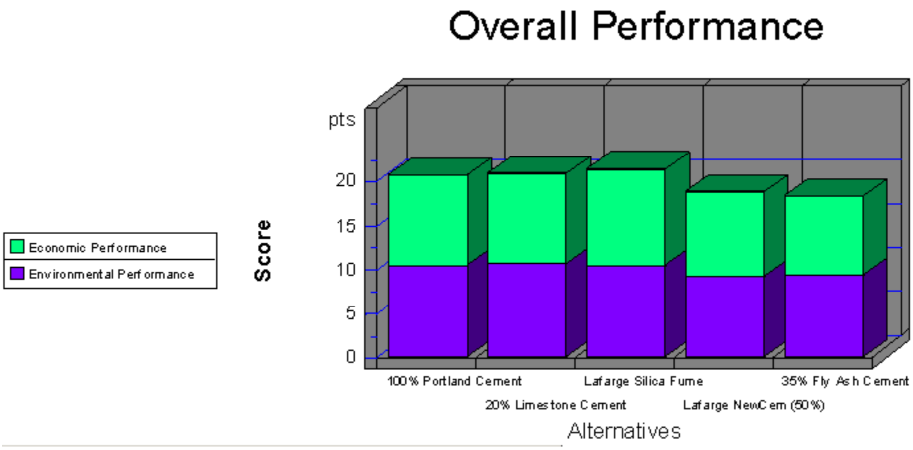

Fig. 8: Viewing BEES overall performance results

Some may be surprised to see no significant difference between the BEES environmental performance scores for 100% portland cement, the traditional concrete mix, and one of the so-called “environmentally friendly” alternatives, 20% limestone cement. Upon closer examination, however, the reasons become clear. With 20% limestone cement, more blended cement than usual is used in the concrete to achieve a strength equivalent to that for mixes with no limestone replacements. Thus, while the limestone blend performs slightly better on ecological toxicity, global warming, and human health due to the limestone content, it performs worse on criteria air pollutants, primarily due to particulates released during limestone mining.

In addition to the summary graphs described above, BEES offers detailed graphs for each environmental impact, broken down both by contributing flow and by contributing life-cycle stage. The detailed graphs help pinpoint the 'weak links' in products’ environmental life cycles. For example, Fig. 9 shows that for human health, the largest environmental impact for all products, cancer-causing dioxin air emissions—primarily caused by electricity production—constitute the largest contributing flow for all products from among the 215 flows tracked in BEES for their potential impact on human health. Similarly, Fig. 10 shows that for smog, the raw materials acquisition life-cycle stage contributes the most, by far, to all products’ smog impacts. This is primarily due to nitrogen oxide air emissions from fuel combustion necessary to power mining equipment.

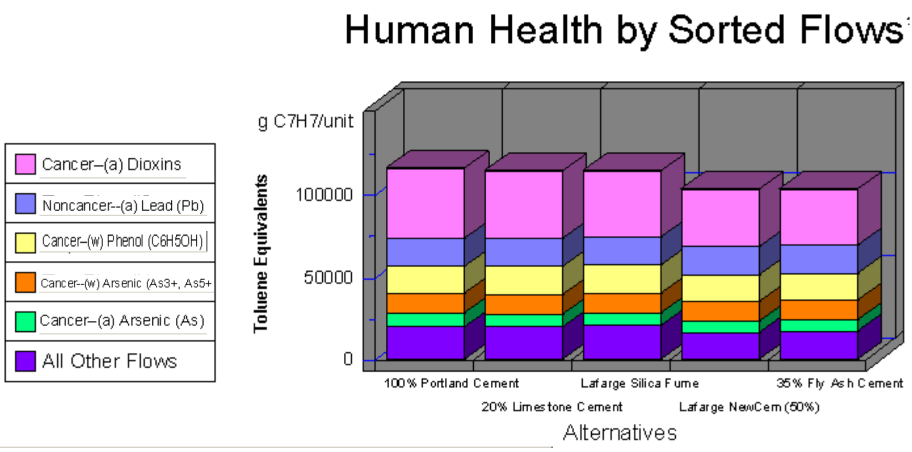

Fig. 9: Viewing BEES results by environmental flow

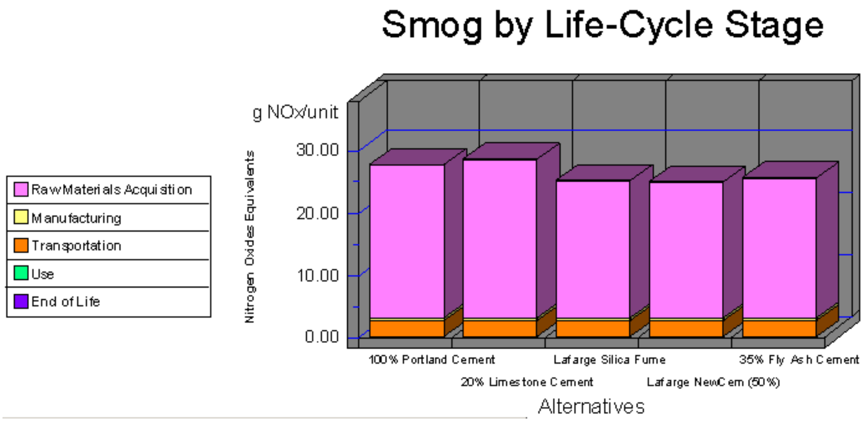

Fig. 10: Viewing BEES results by life-cycle stage

4. Summary

Over the last decade, the construction industry has become increasingly interested in the environmental performance of its products. Unfortunately, this has led to rampant "greenwash" in the market, with manufacturers promoting their products as environmentally friendly on the basis of weak science or popular wisdom. There are several reasons why these claims should be viewed with skepticism. First, they are often based on performance with respect to single impacts, and do not account for the fact that one impact may have been improved at the expense of others. Second, unless comparative claims are made on a *functional unit* basis, the products being compared may not be true substitutes for one another. One concrete mix may be environmentally superior to another on a kilogram-for-kilogram basis, but if more of that "superior" mix is required to fulfill the product function, the results may reverse. The results could also reverse if the mix that is environmentally superior on a kilogram-for-kilogram basis is less durable. Each time the product needs to be replaced, environmental impacts occur through its disposal and the production and installation of its replacement. Third, a product may contain a negative-impact constituent, like cement with its high embodied energy content, but if that constituent is a small portion of an otherwise relatively benign product, its significance decreases dramatically. Finally, a short-lived, low first-cost product is often not the cost-effective alternative. A higher first cost may be justified many times over for a durable, maintenance-free product. In sum, the answers lie in the tradeoffs.

5. Future Directions

To optimize concrete mix designs, environmental and economic performance criteria should be considered alongside other, more traditional, performance criteria. In other words, environmental and economic performance should be simultaneously balanced with desired levels of technical, or functional, performance. NIST is beginning to address this need for an integrated approach through its Virtual Cement and Concrete Testing Laboratory (VCCTL). As shown in Fig. 11, the purpose of VCCTL is to develop a web-based virtual laboratory for evaluating and optimizing the performance of cement- and concrete-based materials. The core of the virtual lab is a computer model for the hydration and microstructure development of cement-based systems that is based on more than 10 years of research at NIST. Much of this research is described in an electronic monograph available at http://ciks.cbt.nist.gov/monograph/. An effort is now underway to integrate BEES into the VCCTL. The goal is to provide material engineers with the tools they need to simultaneously optimize the technical, environmental, and economic performance of concrete mix designs.

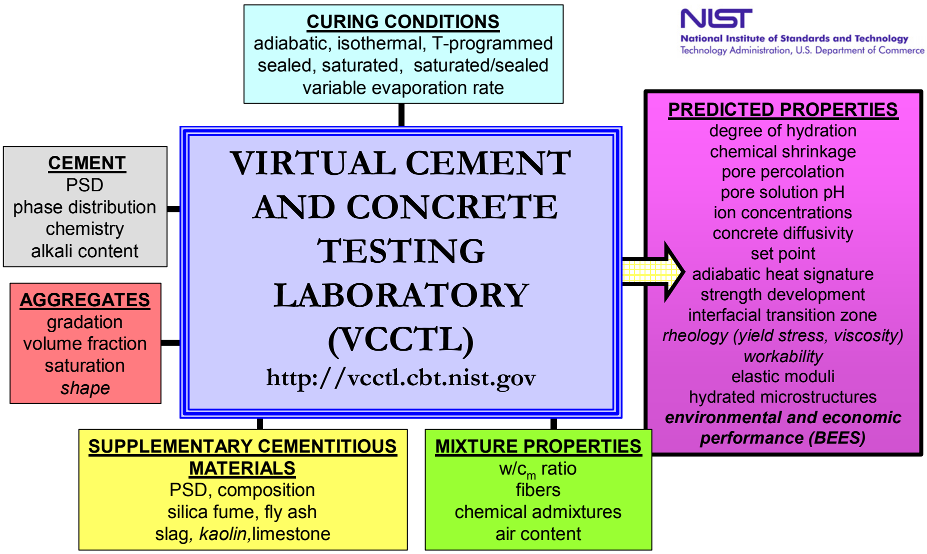

Figure 11. NIST Virtual Cement and Concrete Testing Laboratory: System Overview

References

1. Lippiatt, B.C. *BEES 3.0: Building for Environmental and Economic Sustainability: Technical Manual and User Guide*, NISTIR 6916, National Institute of Standards and Technology, Washington, DC, October 2002. Windows-based BEES 3.0 software available for download free of charge from www.bfrl.nist.gov/oae/bees.html.
2. (a) International Organization for Standardization (ISO). *Environmental Management—Life-Cycle Assessment—Principles and Framework*, International Standard 14040, 1997. (b) ISO. *Environmental Management—Life-Cycle Assessment—Goal and Scope Definition and Inventory Analysis*, International Standard 14041, 1998. (c) ISO. *Environmental Management—Life-Cycle Assessment—Life Cycle Impact Assessment,* International Standard 14042, 2000. (d) ISO. *Environmental Management—Life-Cycle Interpretation—Life Cycle Impact Assessment,* International Standard 14043, 2000.
3. ASTM International. *Standard Practice for Applying the Analytic Hierarchy Process to Multiattribute Decision Analysis of Investments Related to Buildings and Building Systems,* ASTM Designation E 1765-98, West Conshohocken, PA, 1998.
4. ASTM International. *Standard Classification for Building Elements and Related Sitework: UNIFORMAT II,* ASTM Designation E 1557-97, West Conshohocken, PA, September 1997.
5. U.S. Environmental Protection Agency. *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User's Guide and System Documentation*, EPA/600/R-02/052, U.S. EPA Office of Research and Development, Cincinnati, OH, August 2002. For a detailed discussion of the TRACI methods, see J.C. Bare *et al.*, "TRACI: The Tool for the Reduction and Assessment of Chemical and other environmental Impacts." *Journal of Industrial Ecology*, Vol. 6, No. 3, 2002.
6. Bare, J.C., et al. *U.S. Normalization Database and Methodology for Use within Life Cycle Impact Assessment*, submitted to the Journal of Industrial Ecology.
7. ASTM International. *Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems,* ASTM Designation E 917-99, West Conshohocken, PA, 1999.
8. U.S. Office of Management and Budget (OMB). Circular A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*, Washington, DC, October 27, 1992 and OMB Circular A-94, Appendix C, Washington, DC, 2002.
9. The mention of certain trade names and company products does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the product is the best available for the purpose.

SUSTAINABLE DEVELOPMENT USING CONTROLLED LOW-STRENGTH MATERIAL

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Abstract

This paper describes the use of controlled low-strength material (CLSM) in the United States, with an emphasis on the use of by-product and waste materials CLSM for infrastructure applications. CLSM is a self-leveling, cementitious material used as an alternative to compacted fill in applications including backfill, utility bedding, void fill, and bridge approaches. A general overview of the technology is presented, including a summary of current practice by state highway agencies in the United States. Discussions are presented on key technical properties of CLSM, including fresh and hardened properties, durability, excavatability, and environmental impact. This paper illustrates the important role that CLSM plays in safely and efficiently using by-product materials in a range of applications.

1. Introduction

Controlled low-strength material (CLSM) is, as defined by American Concrete Institute (ACI) Committee 229, is a self-compacted, cementitious material used primarily as a backfill in lieu of compacted fill [1]. Several terms are currently used to describe this material, including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry, K-Krete and other various names.

Controlled low-strength materials are defined by “Cement and Concrete Terminology (ACI 116R)” as materials that result in a compressive strength of 8.3 MPa or less [1]. However, most current CLSM applications require unconfined compressive strength of 2.1 MPa or less. Some researchers consider the range of 0.3 to 1.1 MPa as a good index of sufficient strength and easy future excavation. For applications where future excavations are expected, the excavatability of CLSM is critical and this may determine the success of CLSM in practices such as utility bedding.

CLSM is typically specified and used in lieu of compacted fill in various applications, especially for backfill, utility bedding, void fill, and bridge approaches. Backfill includes applications such as backfilling walls (e.g., retaining walls) or trenches. Utility bedding applications involve the use of CLSM as a bedding material for pipe, electrical, and other types of utilities and conduits. Void-filling applications include the filling of sewers, tunnel shafts, basements, or other underground structures. CLSM is also used in bridge approaches, either as a subbase for the bridge approach slab or as backfill against wingwalls or other elements.

There are various inherent advantages of using CLSM instead of compacted fill in these applications. These benefits include reduced labor and equipment costs (due to self-leveling properties and no need for compaction), faster construction, and the ability to place material in confined spaces. The relatively low strength of CLSM is advantageous because it allows for future excavation, if required. Another advantage of CLSM is that it often contains by-product materials, such as fly ash and foundry sand, thereby reducing the demand on landfills, where these materials may otherwise be deposited. This successful and environment-friendly utilization of by-product and waste materials is important to sustainable development and is the focus of this paper.

2. History of CLSM

Soil-cement has been a widely used material in geotechnical-engineering practices for a long time. CLSM is relatively new and is different from conventional soil-cement. Compaction is usually required for soil-cement, which is not the case for CLSM. One of its earliest applications was carried out in 1964 by the US Bureau of Reclamation as the bedding of the 515-km long pipelines in the Canadian River Aqueduct Project, which runs from north of Amarillo to south of Lubbock, Texas [2]. The material used in that project was called plastic soil-cement. The soil used consisted of local blow sand deposits. A new construction procedure was introduced, and the cost of this project was estimated to be 40 percent less than using conventional backfilling techniques. The productivity was increased from about 120 to 305 m of pipe placed per shift.

In the early 1970s, Detroit Edison Company, in cooperation with Kuhlman Corp., a ready-mix concrete producer in Toledo, Ohio, investigated an alternative to compacted granular fill utilizing fly ash and concrete batching techniques. This new backfill material, called flowable fly ash, was used in several applications in the late 1970s [3, 4, 5]. This material was composed principally of fly ash and typically 4 to 5 percent cement, along with an appropriate amount of water. In the Belle River project, it was estimated that more than $1 million was saved by using this new material [3]. One impressive and exciting feature of this material was that it remained cohesive when being placed. Another characteristic was the steep angle of repose when it was placed either above or under water.

Eventually, a company known as K-Krete Inc. was formed. In 1977, four patents for K-Krete were issued to Brewer et al. [6]. A typical K-Krete mixture consisted of 1305 to 1661 kg of sand, 166 to 297 kg of fly ash, 24 to 119 kg of cement, and up to 0.35 to 0.40 m^3 of water per m^3 of product. The four patents included mixture design, backfill technique, pipe bedding, and dike construction. These patents were sold to Contech, Inc., in Minneapolis, Minn., who ceded the patent rights later to the National Ready Mix Concrete Association (NRMCA) with the stipulation that those rights may not be used in a proprietary manner [6, 7]. Since then, ready-mixed concrete producers and contractors have used similar materials to K-Krete without violating legal regulations.

Following K-Krete's emergence as a replacement material for conventional compacted fill, similar materials have been developed and used throughout the United States and Canada. However, the lack of a centralized source for obtaining and disseminating information within the marketplace appeared to cause confusion and reluctance on the part of the engineering community to use these materials. In response to the proposal of Brewer, ACI Committee 229 was established in 1984 under the title "Controlled Low-Strength Materials (CLSM)." After years of efforts, in 1994, the committee published a report called "Controlled Low Strength Materials (CLSM)," which has been referenced widely. In 1999, the revised edition was published.

In 1998, the American Society for Testing and Materials (ASTM) published a book titled "The Design and Application of Controlled Low-Strength Materials (flowable fill)." The articles in this book represented the state of art and practice of CLSM in the field and in the research laboratory at that time. Different types of waste materials were included in CLSM mixtures to recycle waste and reduce the cost. Currently, there are five ASTM testing standards available for CLSM.

3. Utilization of By-Products and Waste Materials

3.1. Use of coal combustion by-product in CLSM

In 2001, 52% of the electricity in the US was produced by coal fired electric utilities (ACAA website). Fly ash is a by-product of coal combustion and has found uses in a wide range of construction applications, including flowable fill, as shown in Table 1 [19]. Fly ash is used mostly in portland cement concrete, but its use in CLSM has grown considerably in recent years.

Table 1: Fly ash applications in construction, 1996 [ACAA 1996]

Applications	Quantity used (million metric tons per year)	% of total used
Cement production and/or concrete products	7.2	60
Structural fills or embankments	1.9	17
Stabilization of waste materials	1.7	14
Road base or subbase materials	0.63	5
Flowable fill and grouting mixtures	0.27	2
Mineral filler in asphalt paving	0.15	2
Approximate total	11.85	100

Although fly ash has become an important construction material, approximately 70 to 75 percent of the fly ash generated annually is still disposed in landfills [20]. Much of this unused fly ash does not meet specifications for use in portland cement concrete (the dominant application), sometimes because of high percentages of unburned carbon, as measured by the loss on ignition (LOI) test. Values of LOI for fly ash used in concrete are typically limited to four percent, whereas some bituminous fly ashes may have LOI values in excess of 15 to 20 percent. Higher unburned carbon contents increase water demand in concrete, and may significantly increase chemical admixture demand (especially air-entraining agents and superplasticizers). Despite the limitations placed on fly ash for conventional concrete, it has been demonstrated that CLSM can be successfully produced using a wide variety of fly ash types and sources, including high-carbon fly ash that is not permitted in concrete.

ASTM C 618 Class F and Class C fly ashes are commonly used in CLSM, in addition to fly ashes that do not meet these or other specifications. There are numerous benefits of using fly ash in CLSM, including improved flowability, reduced segregation and bleeding, and in many cases, reduced material cost.

Bottom ash is another by-product material of coal combustion. Bottom ash is formed by large noncombustible particles that cannot be carried by the hot gases. These particles descend on hoppers or conveyors, at the bottom of the furnace, in a solid or partially molten condition. Then, the particles gradually cool down to form bottom ash. Bottom ash particles are typically porous and angular in shape. As a by-product material, bottom ash is commonly disposed of in ponds. In this process, bottom ash is passed through a crusher to reduce the size of large particles, and it is transported hydraulically through pipelines to the pond shore. The typical range of particle sizes falls between 75 microns and 25 millimeters. Bottom ash can be used in compacted fill when combined with fly ash [21]. Researchers have successfully used bottom ash in CLSM as the fine aggregate [22].

3.2. Use of foundry sand in CLSM

Foundry sand, a by-product of the metal casting industry, has been studied and used successfully in CLSM and its use has increased in recent years [23-28]. Foundry sand is becoming a more viable candidate for use in CLSM because of its lower cost, increasing availability, and satisfactory performance.

It is estimated that for every ton of metal castings produced and shipped that a typical foundry generates approximately one ton of waste sand [29]. The most commonly used waste foundry sand in CLSM is "green sand," a term applied when the original sand is treated with a bonding agent (usually clay) to optimize the efficiency of the sand in the molding process. After molding is completed, the sand is discarded, often in landfills, and typically at a cost of $20/ton to $40/ton [23].

The Federal Highway Administration (FHWA) has issued a report, "User Guidelines for Waste and By-Product Materials in Pavement Construction," which covers in detail the use of foundry sand (and fly ash) in CLSM and provides guidelines for its proper usage [20]. The U.S. Environmental Protection Agency (EPA) has also recognized foundry sand, along with fly ash, as suitable materials for CLSM [10].

An issue of concern with using foundry sand in CLSM is the potential for environmental impact caused by leaching of heavy metals present in the foundry sand. Ferrous foundry sands are more commonly used in CLSM because there are concerns about the heavy metals content of non-ferrous foundry sands. The EPA does not recommend the use of non-ferrous foundry sand in CLSM because of concerns over the potential leaching of phenols and heavy metals, such as cadmium, lead, copper, nickel, and zinc [10]. Additional information on leaching and environmental issues related to the use of foundry sands in CLSM is provided later in this paper

3.3. Other by-product materials

In addition to foundry sand and fly ash, other waste or by-product materials have been tested and used in CLSM, including ground granulated blast furnace slag (GGBFS), and crushed glass. Because slag is not intended to be supplementary cementing material in CLSM, there is no requirement on the pozzolanic property, which is caused through fast quenching. Thus, slag with less quality can be included in CLSM mixtures. Colored glass that cannot be recycled by local bottle manufacturers has been crushed to pass a 12.5-mm sieve and was successfully used in CLSM as an aggregate [30]. Phosphogypsum (a by-product of phosphoric acid production; plentiful in Florida, Texas, and Louisiana) has been tested in laboratory CLSM mixtures [31]. However, the EPA does not permit its use in CLSM field applications because of environmental concerns associated with phosphogypsum, which contains Radium 226, a radioactive material.

A recent study by Naik et al. focused on the use of wood ash or combined-fuel ash in CLSM [32]. Wood ash is the by-product material of burning wood materials with the combination of other fuels, e.g. coal, oil, natural gas, and coke, to generate electricity for business use [32]. The researchers found that the combined fuel ashes could be engineered to produce suitable CLSM mixtures.

In summary, provided that by-product materials do not prevent CLSM from achieving relevant performance criteria, and also provided that they are not harmful to the environment, a wide variety of waste and by-product materials will likely be used in future CLSM applications. Engineers with the assistance of researchers should take the responsibility to contribute to the sustainable of civilization by including as many by-product and waste materials into their practice as possible.

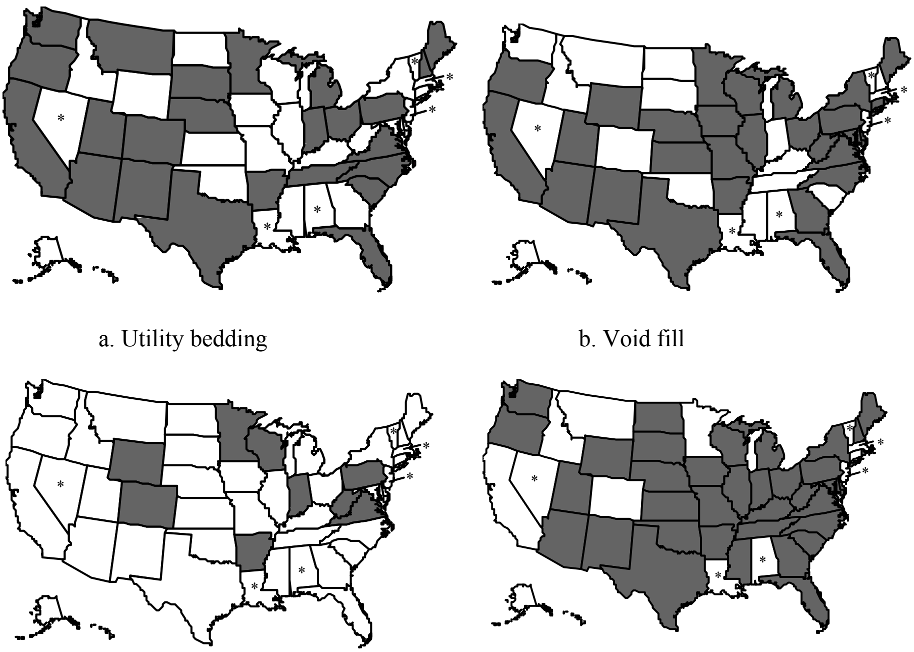
4. National Cooperative Highway Research Program CLSM Research

4.1. Project summary

A comprehensive investigation of CLSM, funded by the National Cooperative Highway Research Program (NCHRP) under Project 24-12 and 24-12(1) ("Controlled Low-Strength Material for Backfill, Utility Bedding, Void Fill, and Bridge Approaches") was started in 1998 and is expect to conclude in the year 2004. The project has culminated in two reports. One report summarized the state-of-the-art and current practice related to CLSM in 1999 and the other report summarized the findings of a comprehensive laboratory investigation of CLSM in 2001 [8, 9]. Results presented in this part are part of these NCHRP-funded efforts and focus mainly on the use of by-product materials in CLSM.

4.2. Survey on the use of CLSM

CLSM is used by state Departments of Transportation (DOTs) in the United States mainly for backfill, utility bedding, void fill, and bridge approach applications. Other applications for CLSM include bedding for granite curbs, engineered fill, and as a lightweight fill to cover swamp areas. Of the forty-four states that responded to the survey, only two states are not currently specifying the use of CLSM. Fig. 1 shows the current applications of CLSM for each state agency [8]. The dominant applications are backfill and bedding material. The majority of CLSM is produced at ready-mixed concrete plants. According to a 1995 survey, it was found that ninety percent of the 3,000 ready-mixed concrete producers in the United States produce some type of flowable fill [10].



a. Utility bedding b. Void fill

c. Bridge approaches d. Backfill

Fig. 1: CLSM application for each state in the United States

4.3. State of practice of CLSM

The benefits of using CLSM as a backfill material are now recognized by at least 42 state DOTs. Engineered CLSM properties are very dependent on the application type. For utility backfill applications, CLSM should be low in strength in the event that the backfill material may require removal for utility repair or replacement. In general, CLSM should be relatively low in long-term strength in order to be excavatable after long durations. Structural backfills do not necessarily require that the CLSM be excavatable, but in some applications this may prove beneficial.

In addition to backfill applications, CLSM is also used as utility bedding and void fill. Advantages of using CLSM as a bedding material include solid, uniform pipe support, reduced labor costs, reduced trench preparation time, and reduction of water ingress to the bedding-pipe interface. One of the largest early applications of CLSM as a bedding material was in 1964 when the U.S. Bureau of Reclamation used a combination of blow sand and cement paste for bedding on 520 kilometers of concrete pipe on the Canadian River Aqueduct Project in Lubbock, Texas [2]. More recently, the city of Denver specified CLSM bedding material for 32 kilometers of concrete drainage pipe at the Denver International Airport [11]. Currently, twenty-seven states use CLSM for bedding of reinforced concrete, cast iron, ductile iron, corrugated steel, and plastic piping systems. Slightly more than one-quarter of the responding agencies use CLSM predominantly for utility bedding.

Void fill is another common application of CLSM products. Although the majority of states use CLSM for void fill applications (~70%), only seven of the forty-four states stated that using CLSM for void fill was their dominant application. This is most likely because the majority of states have more pipe installation work than void fill work, and not necessarily a result of CLSM being more applicable for bedding/backfill applications than void fill applications. Using CLSM for void fill has proven to be very economical in many cases. Sullivan noted that CLSM can be placed at a rate of approximately 60 m^3/hour, at least six times faster than placement of conventional backfill [12]. In addition to the faster placement, the use of CLSM can prevent entry of personnel into confined spaces where safety is of primary importance.

A fairly new application for CLSM is for use as a subbase under bridge approaches. For example, the Delaware Department of Transportation (DelDOT) favors the use of CLSM for many of its bridge approaches. In 1998, the Oklahoma Department of Transportation and Oklahoma State University presented results from a research program that evaluated options to minimize bridge approach embankment settlement [13]. The research program involved construction of three new bridges on U.S. 177 north of Stillwater, Oklahoma. Five different bridge approaches were constructed with different structural fill materials, with one design being a 2.4-m deep CLSM bed. Although there were no reports of differential settlement at the end of the bridge, data collected from the field using indicated that the CLSM settled about 37.5 mm/m. Even though the data indicated that settlement increased until about ten months after placement, the researchers concluded that the majority of the settlement occurred prior to paving. No settlement was observed at the bridge-bridge approach interface. Fox reported that CLSM containing 22-mm maximum size aggregate settled less than 7 mm over a 37-m depth (in a shaft application) [14]. Based on literature and other sources, CLSM appears to be effective, compared to compacted fill, at reducing settlement when coarse aggregates are used.

Due to the high water content of CLSM, subsidence of up to approximately 20 mm/m has been reported. Subsidence is defined as the reduction in volume as a result of losses in water and entrapped air through the consolidation of the mixture. For deep structural fills, subsidence may be significant and contractors should anticipate the reduction in volume. Pons et al. found that CLSM containing accelerators and quick set cement experienced significantly less subsidence [15]. For conventional CLSM, an alternative approach is to initially estimate the subsidence and place the actual elevation of the plastic CLSM above the specified elevation. If data are available and good engineering is performed the CLSM will subside to the specified elevation. A typical example is if the CLSM subsides 21 mm/m and a placement depth of 3 meters is required, placing the fresh CLSM 63 mm above the finish elevation to compensate for the subsidence should be adequate. After the CLSM subsides, the finish elevation should be attained.

Fig. 2 shows a bridge approach constructed with CLSM at the Cypress reconstruction project in Oakland, California [8]. Polystyrene was used as a filler material to reduce subsidence and reduce the weight of the structural fill. Low density CLSM (384–577 kg/m^3) was then used on the bridge approaches. The polystyrene was removed after the CLSM hardened to produce the culvert. It is observed in some locations on the CLSM approach bed that the CLSM material had been left higher than the specified elevations. To build the structure to specification, the contractor trimmed the CLSM after hardening using a motor grader. In this case, the proper grade was achieved mostly by placing the CLSM to the proper elevation, but in cases where the CLSM had been left high, trimming was easily accomplished with standard construction equipment.

Using CLSM to reduce settlement at bridge approaches appears to be a simple and reasonably cost effective method that allows for construction flexibility. There have been many successful uses of CLSM in this application that have reduced or eliminated “the bump at the end of the bridge,” which is often encountered as a vehicle leaves the bridge and enters the approach slab. CLSM tends to reduce long-term settlement in this region and increases the service life of the bridge approach system.

Fig. 2: CLSM used for bridge approach (Oakland, California)

4.4. Engineering properties of CLSM

The following describes some of the technical studies performed on relevant properties of CLSM as part of the NCHRP-funded project. The various studies demonstrate CLSM to be a viable alternative to conventional fill and illustrate the important role by-product materials play in the technology.

4.4.1. Effects of constituent materials on water demand and strength of CLSM mixtures

Research first focused on the effects of material properties on the water demand necessary to obtain minimum flowability values and a range of compressive strength values for CLSM. Three types of aggregate, three types of fly ash, and one ASTM Type I cement were used in this study. Aggregates include river sand, bottom ash and foundry sand. Fly ashes are ASTM Class C, Class F, and off-spec high carbon fly ash. A statistical software was used to optimize the mix design and analyze the results. A total of 31 mixtures were developed and tested. The mixture proportions are shown in Table 2 [16]. The use of different aggregate types and sources was found to be the most significant factor affecting water demand in this investigation, as shown in Fig. 3. Water-cement ratio, aggregate sources, and fly ash type were influencing variables on the compressive strength of CLSM. Equations were developed to predict the compressive strength development of CLSM for the materials used in this research program. The various by-product materials were found to be viable in obtaining the desired CLSM properties.

In summary, the following conclusion were drawn from this study [16]:

- Fine aggregate, especially bottom ash, was the most significant factor affecting the water demand of CLSM.
- The high-carbon fly ash used in this investigation exhibited higher water demand than Class C or Class F fly ash, when used in the same proportions in similar mixtures (a water demand of 315 kg/m^3 for RH33P, compared to 220 kg/m^3 for RF33P). There was no significant difference between the water demands when using Class C or Class F fly ash.
- The variations of fly ash contents used in this study (from 180 and 360 kg/m^3) did not significantly affect water demand.
- The compressive strength of CLSM mixtures varied significantly with specific materials and proportions, especially when the materials increased water demand. For instance, substituting foundry sand for concrete sand in similar mixtures reduced the compressive strength from 3.49 MPa for mixture RF36P to 0.25 MPa for mixture OF36P at 91 days, mainly due to the increased water demand.
- The compressive strength of CLSM can be measured reliably by controlling sample curing, handling, and testing. Of particular importance is selecting a load machine with sufficient accuracy (in the low load range) and control over the load (or deflection, in this case).
- The use of Class C fly ash in CLSM increased the strength considerably when compared with CLSM containing Class F fly ash, mainly due to differences in chemical composition and reactivity (1.12 MPa for mixture OC36P, compared to 0.25 MPa for mixture OF36P at 91 days).

Table 2: Mixture proportions for non-air-entrained CLSM

Mix*	Type I cement (kg/m^3)	Fly ash type*	Fly ash (kg/m^3)	Fine agg. type**	Water demand (kg/m^3)	Flow (mm)	Total bleed (%)	Air content (%)	Unit weight (kg/m^3)
RC13P	30	C	180	CS	211	200	NA	0.9	1965
RC16P	60	C	180	CS	206	200	2.45	0.95	2108
DRC13P	30	C	180	CS	206	210	2.08	0.9	1974
OC33P	30	C	360	FS	486	200	0.13	2.75	1741
BC36P	60	C	360	BA	577	178	4.32	1.65	1754
OH16P	60	H	180	FS	532	240	1.04	3.3	1647
BH13P	30	H	180	BA	628	140	4.81	2.0	1681
OF36P	60	F	360	FS	520	200	0.54	2.5	1684
BF16P	60	F	180	BA	600	178	5.84	2.5	1739
BC33P	30	C	360	BA	572	216	3.64	2.7	1774
RF33P	30	F	360	CS	220	200	0.39	2.2	2199
OF13P	30	F	180	FS	501	200	0.57	2.1	1817
DBC36P	60	C	360	BA	541	200	2.58	2.1	1997
DRF33P	30	F	360	CS	220	216	2.92	1.8	2211
B006H	60	None	None	BA	454	140	1.30	28.5	1382
R006L	60	None	None	CS	200	216	0.70	16.5	1836
RF36P	60	F	360	CS	216	216	1.00	1.3	2174
DRC16P	60	C	180	CS	206	250	0.21	0.5	2291
B003L	30	None	None	BA	582	127	4.35	20.0	1447
BH36P	60	H	360	BA	573	230	6.42	1.7	1743
RH33P	30	H	360	CS	315	200	2.26	1.3	2103
R003L	30	None	None	CS	295	200	2.33	16.0	1922
R003H	30	None	None	CS	170	180	0.62	25.5	1789
R006H	60	None	None	CS	131	200	0.05	26.5	1748
DR006H	60	None	None	CS	136	180	0.43	25.5	1802
DBF16P	60	F	180	BA	600	160	7.20	1.4	1887
DR003L	30	None	None	CS	295	191	2.35	15.5	1874
OC36P	60	C	360	FS	499	200	0	1.8	1902
B003H	30	None	None	BA	492	130	1.08	25.0	1385
B006L	60	None	None	BA	525	130	3.41	18.5	1485
DB006L	60	None	None	BA	525	130	1.44	15.5	1511

* D = repeated mixture; R = river sand; B = bottom ash; O = foundry sand; F = Class F fly ash; C = Class C fly ash; H = high carbon fly ash; P = entrapped air.
** CS=concrete sand; FS=foundry sand; BA=bottom ash.
*** The fine aggregate content was held constant at 1500 kg/m^3.

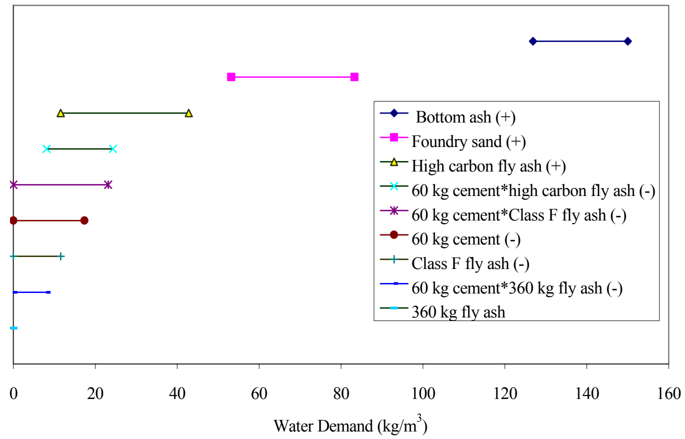


Fig. 3: Pareto-effects graph showing effects of constituent materials on water demand of non-air-entrained CLSM mixtures. The graph shows the deviation from the mean water demand of 446.3 kg/m^3 (+ reflects an increase relative to the mean; - reflects a decrease; no sign indicates that the effect was negligible).

4.4.2. Curing effects on strength development of CLSM mixtures

One important factor hindering the wide acceptance of CLSM is the undesirable long-term excessive strength development. Folliard et al. studied the curing effects on the strengths of CLSM mixtures [17]. Six CLSM mixtures, representing a range of constituent materials and mixture proportions, were included in the study, shown in Table 3. Three curing temperatures (10, 21, and 38 C) and investigated to evaluate their effects on the compressive strength development of CLSM. The splitting tensile strength of selected mixtures was also measured. For each of the curing temperatures, two different relative humidity conditions were assessed to gain an understanding of the effects of temperature and humidity on strength gain at ages of 7, 28, and 91 days. The effects of temperature and humidity were found to largely depend on the constituent materials and mixture proportioning. In particular, the “reactivity” of fly ash was found to be critical in influencing the strength of CLSM mixtures, especially when an ASTM Class C fly ash was used. Some CLSM mixtures containing Class C fly ash exhibited a tremendous increase in strength when cured under the highest temperature condition. Although the dependence of cementitious materials containing fly ash on temperature is well known, the increases in strength of CLSM mixtures containing a high-calcium fly ash (up to a 20x increase in strength for higher temperature curing, i.e., Fig. 4) far exceeded the strength increases typically observed for conventional concrete. CLSM containing fly ash typically has a much higher ratio of fly ash/portland cement and as such, the role of fly ash in strength development is significantly increased. When fly ash was not included in the mixture, i.e., mixture AIR, the effect of high temperature curing was negligible, as in Fig. 5.

Table 3: CLSM mixture proportions for curing effect study

Mixture	Cement content (kg/m^3)	Fly ash type	Fly ash content (kg/m^3)	Concrete sand (kg/m^3)	Water (kg/m^3)	Flow (mm)	Air content (%)	Density (kg/m^3)
FA	60	F	1200	None	492	220	2.4	1631
15F2	15	F	240	1500	197	240	1.2	2191
15C2	15	C	240	1500	175	240	1.4	2212
30C1	30	C	180	1500	181	200	1.2	2163
30F1	30	F	180	1500	188	220	1.4	2210
AIR	60	None	0	1500	123	190	25.5	1603

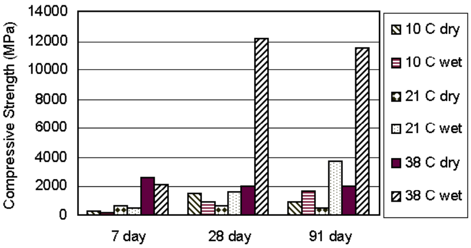


Fig. 4: Compressive strength of mixture 30C1 under different curing conditions

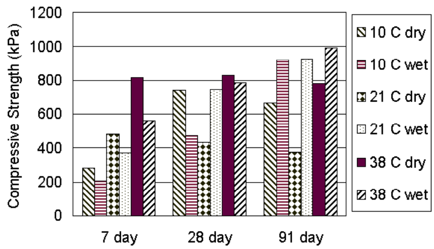


Fig. 5: Compressive strength of mixture AIR under different curing conditions

To emphasize the importance of availability of moisture to the strength development, two curing regimes were employed. Half of the specimens were stripped at the age of three days. The other half specimens were kept in the cast molds until the day of testing. The two scenarios were identified as “dry” and “wet” in the graphs. Under all curing regimes, drying (from an age of three to seven days) generally increased the 7-day strength of CLSM, compared with keeping the cylinders in molds continuously for 7 days. At the age of 91 days, nearly all wet-cured cylinders obtained higher compressive strength than their corresponding dry-cured cylinders at the same curing temperature. This is similar to laboratory air-cured concrete [18]. All dry-cured cylinders at low temperatures (10°C and 21°C) demonstrated strength retrogression from the age of 28 to 91 days. The deteriorating rates of compressive strength were much faster than those of concrete. Dry specimens cured at the high temperature were not significantly affected. But this does not necessarily indicate that these specimens behaved differently from others at low temperatures. It is also possible that these specimens were just at the early stage of strength retrogression at 91 days and the strength could be much lower beyond this age.

An important conclusion from the above investigation is that one must consider the long-term strength gain of CLSM when future excavatability is desired. This importance is paramount when large volumes of fly ash are used in CLSM, especially if a high-calcium fly ash is used. All types of fly ash can be used efficiently in CLSM, but this research showed that trial mixing and testing of cylinders exposed to similar conditions as anticipated in the field application may be prudent to assure the desired long-term properties and to allow for future excavation of CLSM installations.

4.4.3. Corrosion of ductile iron utilities in CLSM mixtures

Another important factor possibly hindering the use of CLSM is the limited information available to the engineering community on the impact of backfilling pipes with this material. Limited studies have been performed on the impact of CLSM on the corrosion performance of pipe materials. Because of the significant efforts and cost required to repair pipes and the significant disruption to the public as a result of the loss of service or road closure resulting from failures caused by corrosion, utility agencies and municipalities are often reluctant to use materials where durability has not been proven. Thus, an important part of this research was to evaluate the corrosion performance of commonly used pipe materials embedded in CLSM.

To evaluate the corrosion performance of ductile iron pipe embedded in CLSM, ductile iron coupons were embedded in 75 x 150 mm cylinders containing all CLSM mixtures shown in Table 1 except mixtures 10 and 20R. Triplicate samples were exposed to a 3.0% chloride solution for 18 months after 28 days of curing (23±2°C and 98% relative humidity). Control samples included coupons embedded in sand. Fig. 6 shows the sample layout. All 13 x 24 x 4 mm coupons (AWWA C151, Grade 60-42-10) were fabricated from one 300-mm diameter ductile iron pipe. After 18 months, the samples were removed from the exposure solution, the coupons were removed from the CLSM (and sand), and the coupons were evaluated for mass loss following ASTM G1-90. These mass loss values are directly correlated to mean corrosion rate as follows:

$$Mean\ Corrosion\ Rate\left(\frac{\mu m}{yr}\right)=\frac{8.76\cdot 10^{7}\cdot W}{A\cdot T\cdot D} \tag{1}$$

where W is the difference in the mass (grams) of the specimen prior to embedment in the CLSM and after removal from the CLSM, A is the original exposed area (mm^2) of the coupon, T is the time of exposure in hours, and D is the metal density $\left({}^{grams}\!/\!_{mm^3}\right)$. Fig. 7 shows the mean corrosion rate for the coupons embedded in CLSM and sand. With the exception of mixtures R003H and B006H, the coupons embedded in CLSM exhibited significantly lower mean corrosion rates than the coupons embedded in the sand. These findings indicate that when CLSM is used as a pipe backfill material and subjected to aggressive chloride environments, significant reductions in corrosion activity can occur. These reductions in the corrosion activity could result in extended service life expectancies for pipelines.

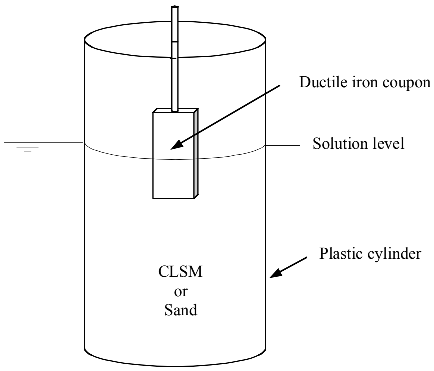


Fig. 6: Sample layout for corrosion testing of ductile iron pipe embedded in CSM & sand

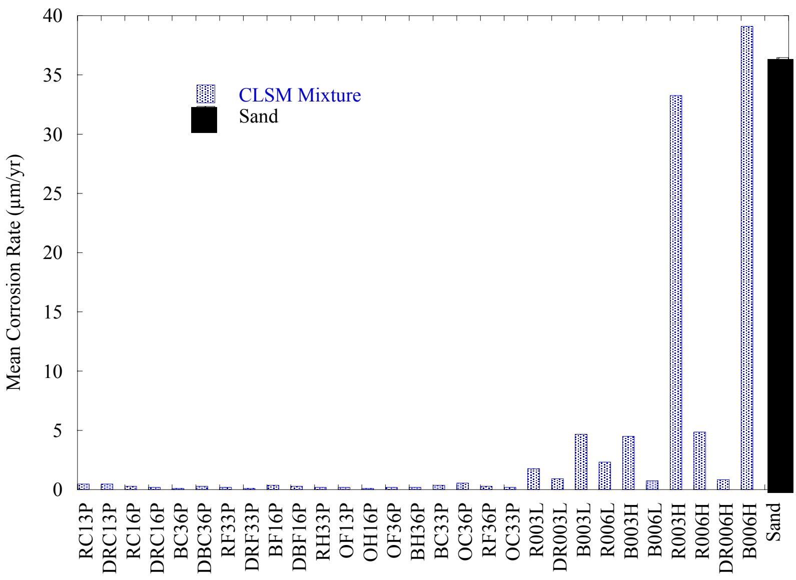


Fig. 7: Mean corrosion rates of ductile iron pipe coupons embedded in CLSM and sand after 18 months of exposure to 3.0% chloride solution

4.4.4. Leaching and environmental impact

The tendency for leaching and subsequent environmental impact may be more critical in the case of CLSM (compared to conventional concrete) because of its higher permeability, and also because of the common use of certain by-product materials, such as fly ash and foundry sand, which may contain heavy metals. Leaching is a relatively slow process and because CLSM is a new technology, sufficient long-term field data and observations are not available to make an informed assessment of CLSM leaching effects.

Research at Purdue University focused on the effects of foundry sands on CLSM leachate and environmental impact [13]. Tests to determine pH and leachate characteristics (using a bioassay method) found that only one of eleven mixtures showed unusually high concentrations of heavy metals in the expressed pore solution. Naik et al. found relatively high concentrations of total dissolved solids in leachate extracted from CLSM containing clean coal ash [22]. Gandham et al. used the toxicity characteristics leaching procedure (TCLP) test (EPA SW-846, Method 1311) to test CLSM containing phosphogypsum [31]. It was found that the toxic contents of the mixtures were well below the EPA leachate standards.

Recent concerns raised by EPA regarding the use of coal combustion products in construction have rekindled the interest in studying the environmental implications of using CLSM containing coal combustion products and other waste materials in the NCHRP 24-12 project [9]. Because the use of by-product and waste materials in CLSM is so common, some research was performed to assess the potential toxicity of materials used in that study and to develop a protocol for assessing materials being considered for use in construction.

The laboratory testing included a full chemical analysis of the by-product and recycled materials included in this project, including fly ash (Class F, Class C, and high-carbon), bottom ash, and foundry sand. The chemical analysis was conducted using inductively coupled plasma emission spectroscopy (ICP), gas chromatography-mass spectrometry (GC-MS), total organic carbon (TOC), and atomic absorption. Information such as the calcium oxide (CaO) content of fly ashes can be very helpful in assessing the potential reactivity and effects on long-term strength gain.

The assessment of the toxicity of the by-product materials used in NCHRP study focused on the identification and quantification of heavy metals. Generally, heavy metals are more of a concern than organics in fly ash, so the limited laboratory study only tested for heavy metals. For each of the by-products included in the study (three fly ashes, one bottom ash, and one foundry sand), the total heavy metal concentration was first determined in accordance with EPA Method 610, where nitric acid and hydrogen peroxide were used to digest the materials. The eight elements analyzed included arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver.

Because this testing determines the total amount of heavy metals, and not the leachable amount, the extraction values may be 20 times the TCLP limits (A "rule of thumb value"). If any of the by-product materials yielded values in excess of the toxicity limits (20 times the TCLP limit), TCLP was then conducted to assess the type and amount of heavy metals that are actually leachable from the materials. Method 40CFR 261.24 was used to extract the samples, and the same 8 heavy metals as previously listed were found.

Testing the raw materials directly, rather than testing the materials encapsulated in CLSM, represents the worst-case scenario for the purpose of toxicity screening. If the constituent materials tested below the TCLP toxicity limits under this worst-case scenario, the materials were classified as non-toxic, and no additional tests were performed. None of the materials tested in this study exceeded the TCLP limits, and thus tests on actual CLSM specimens were not deemed necessary. However, if any materials had exceeded the TCLP limits when tested by themselves, CLSM mixtures would have been cast for subsequent leaching tests. The overall approach to the toxicity and leaching tests performed is shown in Fig. 8.

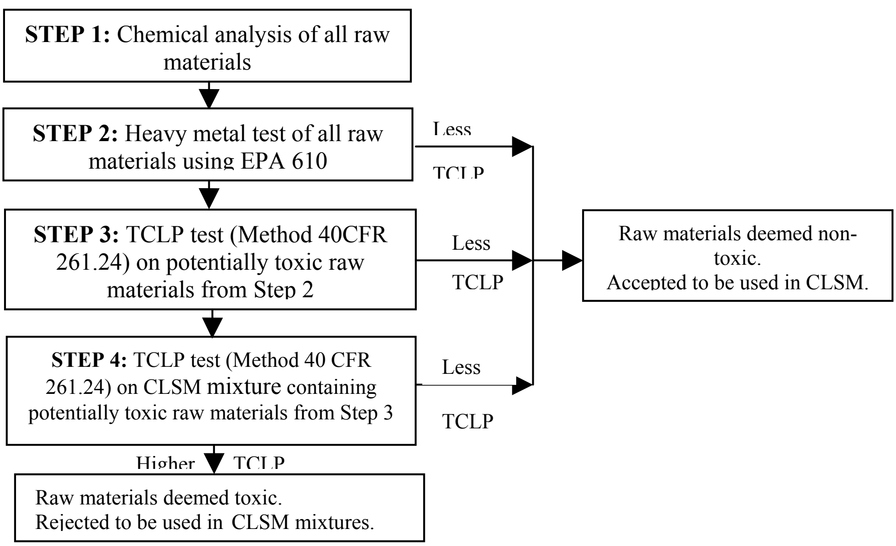


Fig. 8: Flow chart to study toxicity (heavy metals) of CLSM constituent materials

Results representing the total concentration of the eight key heavy metals were obtained. A "rule of thumb" that some practitioners use is that the concentration of total heavy metals can be up to 20 times the standard TCLP limits. According to this guideline, bottom ash, Class C fly ash, and Class F fly ash exceeded the "rule of thumb" value for arsenic. Thus, additional testing was performed (using the TCLP method) to determine the actual amount of heavy metals that are available to leach from these materials. Because the foundry sand and high-carbon fly ash did not have significant amounts of total heavy metals, the materials were classified as non-toxic, and not subsequent leaching tests were performed.

The TCLP results for Class C fly ash, Class F fly ash, and bottom ash are obtained. The concentration of heavy metals that leached from each material was well below the EPA-recommended TCLP limits, and as such, the materials were classified as non-toxic and suitable for use in CLSM. If any of the by-product materials had exhibited significant leaching of heavy metals (above the TCLP limits), the last step would have been to assess the actual leaching of heavy metals from CLSM containing the material(s). This systematic approach can be followed for any material being considered for use in CLSM. Although all the materials used in this study were deemed non-toxic, it may be possible that certain materials considered for a given CLSM application may be more of an environmental concern.

5. Concluding Remarks

As the construction industry continues to recognize the importance of sustainable development, technologies such as controlled low-strength material have come to the forefront as viable means of safely and efficiently using by-product and waste materials in infrastructure applications. This paper provided an overview of CLSM, with an emphasis on by-product utilization. CLSM usage is increasing significantly in the United States, and the amount and types of by-product materials being used continues to increase. It is hoped that this paper provides useful information for those considering CLSM as an alternative to compacted fill and as a vehicle for implementing by-product materials in infrastructure applications to promote sustainable development.

References

1. American Concrete Institute, Committee 229, Controlled Low-Strength Materials (CLSM), ACI 229R-94 Report, 1994.
2. Adaska, W. S., "Controlled Low Strength Materials," *Concrete International*, Vol. 19, No. 4, 1997.
3. Funston, J. J., Krell, W. C. and Zimmer, F. V., "Flowable Fly Ash, A New Cement Stabilized Backfill," *Civil Engineering*, ASCE, 1984.
4. Krell, W. C., "Flowable Fly Ash," *Transportation Research Record*, No. 1234, 1989.
5. Krell, W. C., "Flowable Fly Ash," *Concrete International*, Vol. 15, No. 7, 1989.
6. Larsen, R. L., "Sound Use of CLSMs in the Environment," *Concrete International*, Vol. 15, No. 7, 1993.

7. Larsen, R. L., "Use of Controlled Low Strength Materials in Iowa," *Concrete International*, Vol. 10, No. 7, 1988.
8. Folliard, K. J.,Trejo, D., Du, L., and Sabol, S. A., "Controlled Low-Strength Material for Backfill, Utility Bedding, Void Fill, and Bridge Approaches," NCHRP 24-12 Interim report, 1999.
9. Folliard, K. J.,Trejo, D., Du, L., and Sabol, S. A., "Controlled Low-Strength Material for Backfill, Utility Bedding, Void Fill, and Bridge Approaches," NCHRP 24-12(1) Interim report, 2001.
10. Environmental Protection Agency (EPA), "Back Document for Proposed CPG III and Draft RMAN III." *EPA Report EPA530-R-98-003*, 1998.
11. Hook, W. and Clem, D. A., "Innovative Uses of Controlled Low Strength Material (CLSM) in Colorado," *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*, ASTM STP 1331, West Conshohocken, PA, American Society for Testing Materials, 1998.
12. Sullivan, R. W., "Boston Harbor Tunnel Project Utilizes CLSM." *Concrete International*, Vol. 19, No. 5, 1997.
13. Snethen, D. R. and Benson, J. M., "Construction of CLSM Approach Embankment to Minimize the bump at the End of the Bridge." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*, ASTM STP 1331, West Conshohocken, PA, American Society for Testing Materials, 1998.
14. Fox, T. A., "Use of Coarse Aggregate in Controlled Low Strength Materials." *Transportation Research Record*, No.1234, 1989.
15. Pons, F., Landwermeyer, J. S. and Kerns, L., "Development of Engineering Properties for Regular and Quick-Set Flowable Fill." *The Design and Application of Controlled Low-Strength Materials (Flowable Fill)*, ASTM STP 1331, West Conshohocken, PA, American Society for Testing Materials, 1998.
16. Du, L., Folliard, K.J, and Trejo, D., "Effects of Constituent Materials and Quantities on Water Demand and Compressive Strength of Controlled Low Strength Material," *ASCE Journal of Civil Engineering Materials*, Vol. 14, No. 6, 2002.
17. Folliard, K.J, Du, L., and Trejo, D., "Curing Effects on Strength Development of CLSM Mixtures," *ACI Materials Journal*, Vol. 100, No. 1, 2003.
18. Mindess, S. and Young, J. F., *Concrete*, Prentice-Hall, Inc., 1981, pp. 302-304.
19. American Coal Ash Association (ACCA), "1996 Coal Combustion Products: Production and Use." Alexandria, Virginia, 1997.
20. Federal Highway Administration (FHWA), Chesner, W. H., User Guidelines for Waste and By-Product Materials in Pavement Construction. Federal Highway Administration, Turner-Fairbank Highway Research Center, 1998.
21. Karim, A. K., Salgado, R. and Lovell, C. W., "Compaction of Fly and Bottom Ash Mixtures," *51st Purdue Industrial Waste Conference Proceedings*, 1996.
22. Naik, T. R., Kraus, R. N., Sturzl, R. F. and Ramme, B. W., "Design and Testing Controlled Low Strength Materials (CLSM) Using Coal Ash," *Testing Soil*

Mixed with Waste or Recycled Materials, ASTM STP 1275, West Conshohocken, PA, 1998.

23. Bhat, S. T., Use of Coal Combustion Residues and Foundry Sands in Flowable Fill, Ph. D. Dissertation,Purdue University, 1996.
24. Bhat, S. T. and Lovell, C. W., "Mix Design for Flowable Fill," *Transportation Research Record*, No. 1589, 1997.
25. Bhat, S. T. and Lovell, C. W., "Flowable Fill Using Waste Sand: a Substitute for Compacted or Stabilized Soil," *Testing Soil Mixed with Waste or Recycled Materials*, ASTM STP 1275, West Conshohocken, PA, 1997.
26. Stern, K., "The Use of Spent Foundry Sand in Flowable Fill in Ohio," *Foundry Management & Technology*, Vol. 123, No.9, 1995.
27. Tikalsky, P.; Smith, E.; and Regan, R. W, "Proportioning Spent Casting Sand in Controlled Low-Strength Materials," *ACI materials journal*, Vol. 95, No. 6, 1998.
28. Tikalsky, P., Gaffney, M., and Regan, R., "Properties of Controlled Low-Strength Material Containing Foundry Sand," *ACI materials journal*, Vol. 97, No. 6, 2000.
29. Kennedy, D. O. and Linne, C. L., "Environmental and Economical Aspects of Sand Reclamation System." EPRI, Vol. 2, Palo Alato, CA, 1987.
30. Ohlheiser, T. R., "Utilization of Recycled Glass as Aggregate in Controlled Low-Strength Material (CLSM)," *Testing Soil Mixed with Waste or Recycled Materials*, ASTM STP 1275, West Conshohocken, PA, 1998.
31. Gandham, S., Seals, R.K. and Foxworthy, P. T., "Phosphogypsum as a Component of Flowable Fill." *Transportation Research Record*, No. 1546, 1996.
32. Naik, T. R., Kraus, R. N., and Siddique, R., "Controlled Low-Strength Materials Containing Mixtures of Coal Ash and New Pozzolanic Material," *ACI Materials Journal*, Vol. 100, No. 3, 2003.
33. Bhat, S. T. and Lovell, C. W., "Use of Coal Combustion Residues and Foundry Sands in Flowable Fill." School of Civil Engineering, Purdue University, 1996.

DEVELOPMENT AND RESEARCH OF HIGH BELITE CEMENT DAM CONCRETE WITH LOW HEAT AND HIGH CRACK RESISTANCE

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Abstract

The development and research of high belite cement (HBC) dam concrete with low heat and high crack resistance has been carried out on the basic of the state brainstorm project “HBC New Gelling Materials Research” during the “Ninth-Five.” Through the parallel tests comparing with the moderate heat cement (MHC) concrete used for Three Gorges Dam in the second stage, it is initially demonstrated that the HBC dam concrete has a good working performance, mechanical behavior and durability, and its adiabatic temperature rise is to be reduced by 3-5 degrees under same mixing proportion. The HBC dam concrete possesses good crack resistance ability, and it is a new dam concrete with low heat and high crack resistance that is expected to be popularized and applied for the mass concrete projects in water resource engineering.

The features for both low heat and high crack resistance are always the important and difficult points in dam concrete research, while the research and application in

new gelling materials have become the hotspot that the domestic and overseas cement-concrete materials science develops at present, thus it also becomes the important base for development and research of dam concrete with low heat and high crack resistance. It has successfully researched and developed one HBC mainly comprised by mineral composition of dicalcium silicate (C_2S) in the state “Ninth-Five” brainstorm project “Concrete Safety Research in Major Engineering,” which is launched by the China Institute of Building Materials Research, and participated in by both the Nanjing University of Chemical Technology and the China Institute of Water Resources and Hydropower Research. And the HBC has been listed into the state standards of low heat silicate cement, and put into production in batch mass. Cooperated with the China Institute of Building Materials Research and the China Yangtze River Three Gorges Construction Corporation General, the China Institute of Water Resources and Hydropower Research has undertaken the “Tenth-Five” brainstorm project from state science and technology department, namely the development and research of HBC low heat and high crack resistance dam concrete, and acquired a certain phase fruits.

1. Performance Analysis of High Belite Cement

1.1. HBC makeup

The main mineral composition in portland cement (PC) is the tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF), in which the mineral name for tricalcium silicate (C_3S) is also called as alite, while the dicalcium silicate (C_2S) also call as belite. The high belite cement means the belite content is large in cement composition, and the mineral and chemical compositions for portland cement (PC), moderate heat cement (MHC), and high belite cement (HBC) are shown in Table 1.

Table 1: Chemical composition and mineral makeup for HBC, PC, and MHC

Cements	Chemical composition (%)									Mineral makeup (%)			
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	R_2O	C_3S	C_2S	C_3A	C_4AF
HBC	23.06	4.59	4.57	59.88	1.39	3.12	0.43	0.17	0.54	20.65	50.53	4.44	13.89
PC	22.66	5.31	3.29	65.75	1.21	-	-	-	-	55.10	23.40	8.50	15.80
MHC	21.22	4.68	4.13	62.95	3.95	1.06	0.50	0.18	0.62	53.50	21.64	3.85	16.67
Notes	HBC = Sichuan Jiahua Cement Factory, 525# high belite cement. MHC = Hubei Gezhouba Cement Factory, 525# moderate heat cement. PC = Silicate, 525# cement.												

As observed in Table 1, there is not much difference in chemical composition for three cements, and the CaO content in HBC is a little low. However, there are larger difference in C_3S and C_2S contents for three cements mineral compositions, namely the C_3S content in both PC and MHC is 50%, and the C_2S content only about 20%; while the C_2S content in HBC is 50%, and the C_3S content only about 20%. It is shown through the above that there is much change in cement's mineral composition, and this change is formed as a result of changes for both the formula in cement raw materials and the burning process. The highest burning temperature of PC is not less than 1400°C, but that of HBC is about 1300°C. Hence, the HBC is also regarded as one of the green energy conservation cements in present building materials, which is listed into the state low heat cement standard GB200-2002 at present, and manufactured at appointed place.

1.2. Physical mechanics performance for HBC

The physical, mechanical and thermal characteristics for HBC, PC, and MHC are listed in Tables 2–4 and Figs. 1–3.

Table 2: Physical characteristics for HBC, PC, and MHC

	Fineness (%)	Specific surf. area (m^2/kg)	Density (g/cm^3)	Water required by normal consistency (%)	Stability	Setting time (h:min)	
						Initial setting	Final setting
HBC	0.5	387	3.20	26.9	Passed	2:40	3:50
PC	1.0	367	3.19	27.3	Passed	2:33	3:34
MHC	1.4	288	3.18	25.5	Passed	3:09	4:58
GB175-1999 PC	<10	>300	–	–	Passed	0:45	<6:30
GB200-2002 MHC-LHC	–	>250	–	–	Passed	>1:00	<12:00

Table 3: Strength capabilities for HBC, PC, and MHC Gelatinovs sands

	Curing conditions	Compressive resistance (MPa)				Folding strength (MPa)			
		3d	7d	28d	90d	3d	7d	28d	90d
HBC	SCC	16.1	24.3	63.4	84.0	4.1	5.5	9.5	11.5
	38°	27.4	52.0	75.4	82.6	5.6	8.0	10.0	9.6
PC	SCC	38.4	51.3	61.5	69.6	6.4	7.6	8.3	9.0
	38°	42.1	47.9	52.7	–	–	–	–	–
MHC	SCC	32.4	43.8	63.2	75.2	6.3	7.6	9.4	11.6
	38°	40.5	50.2	65.0	68.0	6.7	8.1	9.1	9.6
Notes	SCC = Standard curing conditions. 38° = Curing conditions under water temperature 38°.								

Table 4: Hydration heat for HBC, PC, and MHC (KJ/kg)

Cement	1d	2d	3d	4d	5d	6d	7d
HBC Sichuan Jiahua cement	159	181	196	208	219	227	234
PC	–	–	247	–	–	–	289
MHC-1 Gezhouba cement-1	201	233	248	257	265	272	278
MHC-2 Gezhouba cement-2	207	238	250	262	270	276	280
MHC-3 Shimen cement	180	220	238	248	256	262	267
MHC-4 Huaxin cement-1	193	228	245	256	264	271	277
MHC-5 Huaxin cement-2	167	205	228	242	252	260	267

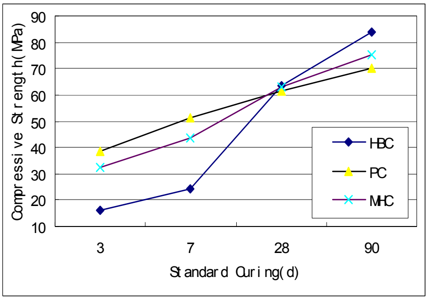

Fig. 1: Standard curing strength for different cements

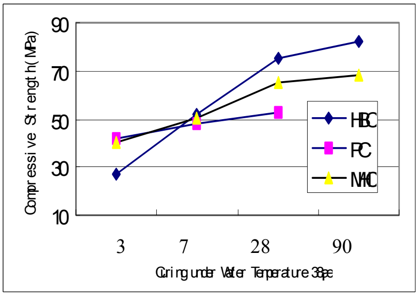

Fig. 2: Curing strength for different cements under temperature 38°

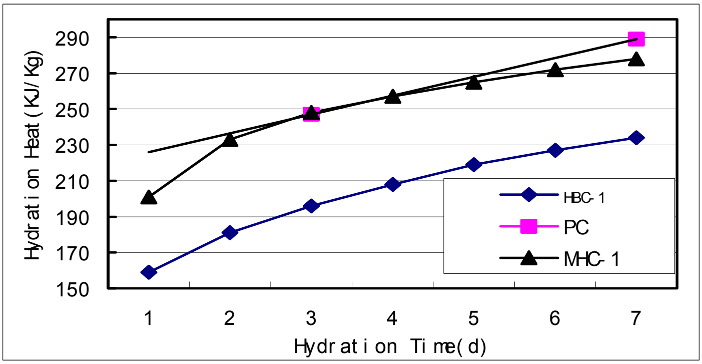

Fig. 3: Hydration heat curves for HBC, PC, and MHC

From the results in Table 2 and Figs. 1–3, we can see the following:

- The physical characteristics for HBC, PC, and MHC conform to the requirements stipulated in both GB175-1999 and GB200-2002.
- Under the same strength-grade of 42.5, and the standard curing conditions (under temperature 20°, and relative humidity of exceeding 90%) of HBC: The earlier strength prior to 7 days is low, the strength at 28 days as same as that of PC and MHC, and the strength at the 90 days is increased by 12%-20% of PC and MHC strengths.
- If raised the earlier curing temperature (e.g., the concrete within dam), then the earlier strength prior to the 7th day is similar to that of PC and

MHC, the strength at 28 days is raised by 16%-45% than that of PC and MHC, hence the higher curing temperature promotes developing the earlier strength of HBC.

- The hydration heat for HBC is obviously lower than that of PC and MHC, the hydration heat of HBC at 3 days is approximately lower for 20% than that of MHC (at about 50 KJ/kg), and the hydration heat of HBC at the 7 days lower for 15.8%-18.7% than that of MHC (at about 44-45 KJ/kg). Hence HBC belongs to the low heat silicate cement.

Through making a comparison between the cement composition and its physical mechanics performance of HBC and that of both PC with the same strength-grade (42.5) and MHC used for the dam, it can be seen that the HBC is a energy conservation cement with low heat and high performance, and it is also a new cement possible for being used for the dam concrete to raise its crack resistance and lasting quality.

2. Development and Research of HBC Dam Concrete

2.1. Research methods

The dam concrete in the Three Gorges of the Yangtze River adopts with the Moderate Heat Cement, and its design and performance for mixing proportion of dam concretes have achieved the international advanced level. This research is adopted with the raw material from the dam concretes at the Three Gorges and mixing proportion as the basic, and the varieties of cements have changed into HBC from the original MHC to compare with the characteristics of HBC dam concrete.

2.2. Working performance

The testing results of working performances on HBC and MHC dam concretes are listed in Table 5.

Table 5: Working performance of HBC and MHC concretes

Concrete	Demands of all materials in concrete (Kg/m^3)							Slump (cm)	Air content (%)
	C+F	W	S	A					
				80-150mm	40-80mm	20-40mm	5-20mm		
MHC-00	231.0+0	127.0	621.5	455.0	455.0	300.0	300.0	4.7	1.1
HBC-00	231.0+0	127.0	621.5	455.0	455.0	300.0	300.0	7.5	1.1
MHC-20	290.5+72.5	127.0	653.0	–	–	718.5	588.5	5.5	4.7
HBC-20	290.5+72.5	127.0	653.0	–	–	718.5	588.5	7.5	4.6
MHC-30	133.8+57.2	86.0	555.0	497.5	497.5	330.0	330.5	4.7	4.5
HBC-30	133.8+57.2	86.0	555.0	497.5	497.5	330.0	330.5	6.4	5.4
MHC-40	98.2+61.7	85.0	607.5	490.0	490.0	325.0	325.0	4.5	5.1
HBC-40	98.2+61.7	85.0	607.5	490.0	490.0	325.0	325.0	6.7	5.6

Notes: The serial numbers, such as -00, -20, -30 and -40, are represented for the fly ash adulterating quantity. The number 00 means the fiducial concrete has not adulterated any admixture, and other numbers represent they have been added for ZB-1A+DH_9.

Through the testing results, we can see that the slump and air content of HBC dam concrete are basically similar with that of MHC dam concrete whether adulterating or un-adulterating fly ash or the adulterating quantity changes between 20%-40% under the conditions of the same raw materials and mixing proportion. However, the slump for HBC dam concrete is slightly larger than that of MHC dam concrete. This shows that the HBC dam concrete can satisfy the requirements of dam construction, and its flowability is slightly better than that of MHC dam concrete.

2.3. Mechanical behavior

The testing results in mechanical behavior upon HBC and MHC dam concretes are listed in Table 6.

Table 6: Mechanical behavior upon HBC and MHC dam concretes

	Compressive strength (MPa)			Axial tension strength (MPa)		Elastic modulus (×10^3 MPa)		Limits tension (×10^{-4})	
	7d	28d	90d	28d	90d	28d	90d	28d	90d
MHC-30	26.0/100	35.4/100	46.2/100	2.30/100	3.02/100	29.1/100	38.8/100	0.99/100	1.03/100
HBC-30	9.2/35	36.1/102	53.1/115	2.58/100	3.18/105	32.3/111	37.5/97	1.01/102	1.08/100
HBC-30*	18.7/72	38.7/109	58.1/126						

*The curing temperature is 38°, and the concrete mixing proportion is the same as in Table 5.

From Table 6, we can see the following:

- The earlier strength for HBC dam concrete is lower, the strength at 28 days equal to that of MHC dam concrete, and the later strength (at 90 days) larger than that of MHC. The compression resistant marking for HBC dam concrete is of 15%, and its axial tension marking of 5%. Therefore, HBC dam concrete processes a good latter performance.
- The limit stretching strain and elastic modulus for HBC dam concrete are basically similar to that of MHC dam concrete.

2.4. Secular distortion performance

The secular distortion performance mainly including the setting shrinkage, creepage, itself volumetric deformation, and testing results is listed as following Table 7 and Figs. 4–7.

Table 7: Secular distortions and testing results for HBC and MHC

	Dry shrinkage (×10^{-6})				Creep degree (×10^{-6}) 28d/90d (loading time)				Volumetric deformation (×10^{-6})			
	7d	28d	90d	180d	7d	28d	90d	180d	3d	7d	28d	60d
MHC	79.9	260.0	336.1	350.6	15.38/6.65	21.68/10.39	26.17/13.85	31.16/17.21	12.08	9.75	18.92	24.86
HBC	94.9	292.8	362.6	383.1	17.13/6.08	21.59/9.34	25.45/13.47	29.67/16.37	10.64	4.41	1.36	-14.93

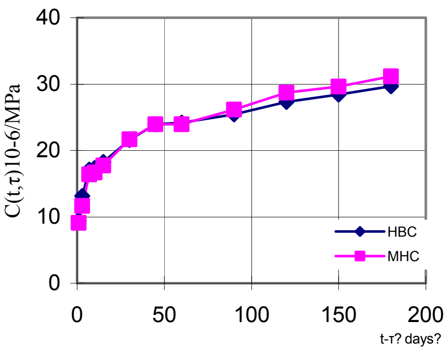

Fig. 4: Creep deformation for concrete (28 days)

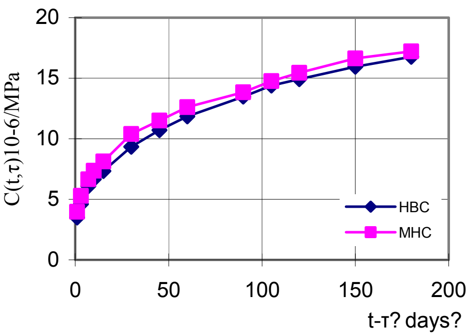

Fig. 5: Creep deformation for concrete (90 days)

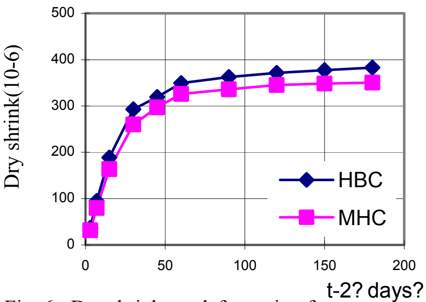

Fig. 6: Dry shrinkage deformation for concrete

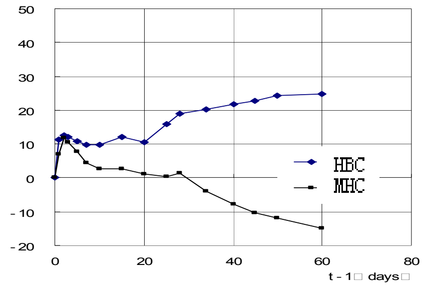

Figure 7 Itself Volumetric Deformation for Concrete

The testing results show the following:

- The drying shrinkage deformation for HBC dam concrete is basically similar to that of MHC dam concrete, namely the dry shrinkage value for 180 days equal to 350-380×10^{-6}, which is further less than that of PC dam concrete. And the dry shrinkage value of PC dam concrete within 180 days will reach to approximately 500×10^{-6}.
- Whether 28 days or 90 days loading period, the creep deformation for HBC dam concrete is also similar to that of MHC dam concrete, basically. If adopted 28 days loading period, then the creep deformation for 180 days is equal to approximately 30×10^{-6}; if adopted 90 days loading period, then the creep deformation for 180 days equal to approximately 17×10^{-6}.
- The self-volume deformation for HBC dam concrete belongs to a micro-expansion type, so its self-volume deformation in 60 days is equal to 24.86×10^{-6}. However, MHC dam concrete belongs to a micro-shrinkage type, so its self-volume deformation in 60 days is equal to -14.93×10^{-6}.

2.5. Lasting quality

The testing results upon freezing-proof and anti-filtration durability for both HBC and MHC dam concretes are listed in Table 8.

Table 8: Freezing-proof and anti-filtration results upon HBC and MHC dam concretes

	Freezing-proof test quickly froze for 300 times		Anti-filtration grade (kg/cm^2)
	Relatively moving and elastic modulus (%)	Weight loss (%)	
HBC-30	82.26	0.95	>10
MBC-30	90.49	0.85	>10

Notes: The quick-freezing evaluation standard upon concrete is understood as following: When the relatively moving and elastic modulus is less than 60%, and the weight loss not less than 5%, it is regarded that the concrete has arisen the frozen abruption.

The testing results demonstrate the following:

- In the event of adopting 30% fly ash adulterating quantity, the dam concretes for both HBC and MHC are able to satisfy the requirements to be quickly frozen for 300 times, and they are dispensed into a high freezing-proof concrete to conform with the designing requirements of concrete freezing-proof F300 at water-level changing areas of the Three Gorges Dam.
- Similar to the MHC dam concrete, the anti-infiltration grade of HBC dam concrete can achieve exceeding W10 to satisfy the design requirements of Three Gorges Dam engineering.

2.6. Analysis upon thermal characteristics and crack resistance performance

2.6.1. Adiabatic temperature rising tests for HBC and MHC dam concretes

HBC and MHC dam concretes have taken their interior concretes as an example, and the testing results upon adiabatic temperature rising from both HBC and MHC are shown in Table 9 and Fig. 8.

Table 9: Adiabatic temperature rising for HBC and MHC dam concretes

	3d	7d	14d	28d
HBC	9.1	12.4	16.4	19.2
MHC	13.1	17.8	20.7	21.2

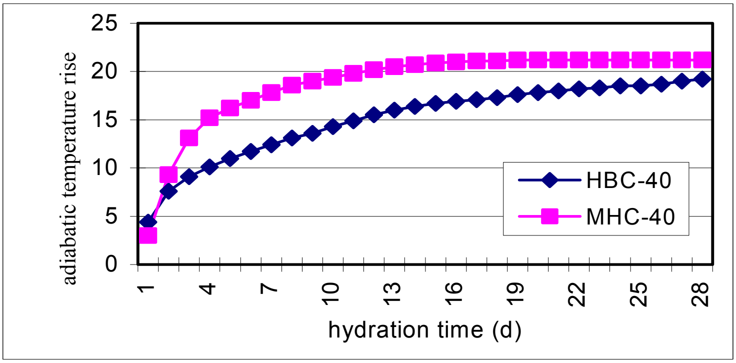

Fig. 8: Adiabatic temperature rising for HBC and MHC concretes

It can be seen through the testing results that the adiabatic temperature rising for HBC dam concrete should be lower than that of MHC dam concrete in the event of the same mixing proportion, and the descending amplitude for adiabatic temperature rising is about 3-5. This is very favourable to reduce the temperature stress from larger volume concrete, and decrease the temperature cracking.

2.6.2. Crack resistance analysis for HBC and MHC dam concretes

The crack problem in dam concrete is a pertinacious disease that is not easy to completely overcome, while the crack resistance analysis upon dam concrete is also one difficult problem in water resource engineering. So far, it has not achieved the consistently common understanding in this field. And this research carries out the crack resistance analysis on HBC and MHC dam concretes against the following three ways.

A. Limit tensile strength

In the temperature controlling design for dam, the most visual evaluation upon σ is to make the limit tensile strength in concrete as a estimation on resistibility.

$$\sigma = \varepsilon_p E \tag{1}$$

where σ = limit tensile strength in concrete (MPa), ε_p = limit tensile deformation in concrete, and E = tensile elastic modulus in concrete (MPa).

In the limit tensile deformation for concrete (ε_p), it includes either the elastic deformation, or a smaller part of plastic deformation. Hence this method is also called as the elastic and plastic method. And the crack resistance abilities (σ) for HBC and MHC dam concretes are listed in Table 10.

Table 10: L crack resistance abilities for HBC and MHC concretes (σ)

Concrete	Crack resistance ability for concrete $\sigma = \varepsilon_p \times E$ (MPa)	
	28d	90d
MHC-00	3.4	4.3
HBC-00	4.5	4.8
MHC-20	3.4	4.5
HBC-20	3.7	5.0
MHC-30	2.9	3.9
HBC-30	3.3	4.2
MHC-40	2.2	3.2
HBC-40	2.3	3.7

Table 10 shows that the crack resistance abilities of HBC concretes are larger than those of MHC concretes.

B. Safety factor against cracking (K)

The safety factor against cracking (K) for concrete can be represented with the formula (2):

Safety factor against cracking K= Crack resistance σ/destructive force P (2)

where K > 1, the concrete can not arise a crack and K < 1, the concrete can arise a crack.

According to both the derivation from the concrete anti-cracking calculation of "mass concrete" against a bulky basic restricting areas in water resource engineering and the statistical data upon concrete testing at the Three Gorges Dam, the calculation results upon safety factor against cracking (K) for both HBC and MHC dam concretes are listed in Table 11.

Table 11: Safety factor against cracking (k) for both HBC and MHC concretes

Concrete	Time (d)	A_1	A_2	Destructive force (MPa) $P = \sigma_1+\sigma_2$		Anti-cracking ability σ (MPa)	Safety factor against cracking $k = \sigma/P$
				σ_1	σ_2		
HBC-35 basic position	7	0.597	0.500	1.03	0.02	1.1	1.05
	28	0.570	0.479	1.60	0.04	2.3	1.40
	90	0.545	0.459	2.24	0.10	3.7	1.58
MHC-35 basic position	7	0.600	0.503	1.33	-0.06	1.0	0.79
	28	0.577	0.484	1.76	-0.08	2.2	1.31
	90	0.551	0.43	2.92	-0.10	3.1	1.10

Notes: The A1 and A2 are the average constraint factor for even temperature difference in placement block and constraint factor for uneven temperature difference, respectively.

From the results in Table 11, we can see that the anti-cracking coefficients K of HBC dam concrete, whether in 7, 28, or 90 days, are more than that of MHC dam concrete, which further represents that the crack resistance of HBC dam concrete gains advantage over that of MHC dam concrete.

C. Anti-cracking coefficient during temperature deformation R

It is considered that the cracks for mass concrete are mainly caused by the temperature stress, while the temperature stress comes from the dam basic concrete or external concrete constrained by the foundation base or internal concrete during temperature drop. If the permissible stretching strain ability for concrete includes the limit tension, creep deformation, self-volume deformation and drying shrinkage deformation, and they are more than the concrete shrinkage deformation during temperature drop, then the concrete can not arise the crack. And the concrete anti-cracking coefficient R during temperature deformation is listed as following formula (3) and Table 12.

$$R = \varepsilon_a/\varepsilon_b \quad (3)$$

where ε_a = self-deformation ability for concrete (strain) and ε_b = shrinkage strain of concrete during temperature drop.

Table 12: Anti-cracking coefficient for HBC and MHC concretes R

Concrete	Time (d)	Anti-cracking coefficient for concrete R		
		ε_a= k_1×Instantaneous deformation for concrete +k_2×Creep deformation -k_3×Self-volume deformation -k_4×Drying shrinkage deformation (×10^{-6})	ε_b= k_5×Temperature deformation for concrete (×10^{-6})	Anti-cracking coefficient R
HBC-35 basic position	7	47.92	65.74	0.73
	28	73.34	97.92	0.75
	90	81.36	108.63	0.75
MHC-35 basic position	7	47.28	87.62	0.54
	28	72.59	118.58	0.61
	90	76.77	120.82	0.64

Notes: The k_1-k_6 means the weight coefficients, and they are 0.80, 0.15, 0.04, 0.01, and 0.60, respectively.

From the results in the Table 12, we can see that the anti-cracking coefficients R of HBC dam concrete at different time are more than that of MHC concrete. This is further represented that the crack resistance of HBC dam concrete gains ascendancy over that of MHC concrete. The anti-cracking coefficient R in temperature deformation is either applicable for the dam basic concrete, or applicable for the external concrete. However, it is only a relative comparison of crack resistance in materials.

The crack resistance analysis in three ways above suggests that the anti-cracking ability of HBC dam concrete used, especially the anti-cracking ability against temperature stress, would outmatch over that of MHC dam concrete.

3. Conclusions

- This project is listed into the key task project in scientific and technological research during the “Tenth-Five.” Through existing research fruits, we can see that HBC is a environmental protection and energy conservation cement with low heat and high performance, which is expected to be popularized and applied for mass concrete in water resource engineering.
- HBC dam concrete is not only possessing a good working performance, mechanical behavior and deformability, but also possessing a high crack

resistance and durability, which is a new dam concrete with low heat and high crack resistance.

- This testing research work is to be further supplemented and perfected, which is expected to fulfil trial application in the Three Gorges engineering.

Acknowledgments

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References

1. Wu Zhongwei. “Challenge and Chance for Science and Technology Workers in Cement Concrete ” and “Concrete and Cement Products,” January 1996.
2. Structural Material Institute under China Institute of Water Resource and Hydropower Research. *Mass Concrete*. Hydraulic and Electric Power Press, 1991.
3. Concrete Testing Code in Water Resource Engineering DL/T 5150-2001. China Electric Power Press.

HONG KONG EXPERIENCE OF USING RECYCLED AGGREGATES FROM CONSTRUCTION AND DEMOLITION MATERIALS IN READY MIX CONCRETE

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Abstract

The construction activities in Hong Kong generate about 14 million tons of construction and demolition (C&D) materials each year. Recycling the C&D materials is one of the measures to reduce the burden on public fill capacities. This paper discusses the latest application experience of using recycled aggregate in construction projects in Hong Kong and recommends a broader scope of use of recycled aggregates in areas other than ready mixed concrete.

1. Introduction

The rapid development of Hong Kong in the last two decades led to the generation of huge volumes of construction and demolition (C&D) materials. In the past, the inert portions of these C&D materials, such as rock, concrete and soil, had been beneficially reused as fill materials in forming land for Hong Kong's development. However, the increasing opposition to sea reclamation by the general public has rendered most reclamation projects either delayed or much reduced in scale. If these materials have to be disposed of at landfills, it will accelerate the depletion of the already limited precious landfill spaces. Hong Kong is now facing a crisis on how to accommodate these surplus materials. Apart from putting more efforts in minimizing its generation and the setting up of temporary fill banks, recycling is one of the most effective means to alleviate the growing problem [1].

2. Recycling

In mid-July 2002, the Hong Kong SAR government established a pilot C&D materials recycling facility in Tuen Mun to produce recycled aggregates for use in government projects and for research and development works [2]. The plant has a designed handling capacity of 2,400 tonnes per day. The processing procedure for recycled aggregate comprises the following processes: (1) a vibrating feeder/grizzly for sorting the hard portions from the inert C&D materials which are suitable for subsequent recycling; (2) a jaw crusher (primary crusher) for reducing the sorted materials to sizes of 200 mm or smaller which can be handled by the secondary crushers; (3) a magnetic separator, manual picking gallery and air separator for removal of impurities before the materials are fed into the secondary crusher; (4) cone crushers (secondary crusher) for processing the clean materials into sizes smaller than 40 mm; (5) vibratory screens for separating the crushed recycled aggregates into different sizes; and (6) storage compartment for temporary storage for recycled aggregates. The facility is able to produce Grade 200 rockfill and recycled aggregates of various sizes, ranging from 40-, 20-, and 10-mm coarse aggregates to fine aggregates (<5 mm) for different applications.

Due to the varying sources of the incoming materials, a prudent quality control approach has been adopted by the recycling plant. Only suitable materials (e.g., crushed rocks, concrete) are processed at the plant. Brick and tiles are generally not allowed. The produced recycled aggregates are sampled and tested daily. Since production commenced in July 2003, the facility has already produced approximately 240,000 tons of recycled aggregates with consistent high quality that meets the specification requirements.

3. Specifications and Applications

Internationally, the RILEM specification is the most commonly accepted standard for recycled aggregates [3]. But in Hong Kong, due to our limited experience in using recycled aggregates and Hong Kong's different nature of building construction, a more prudent approach has been adopted. After detailed laboratory investigations and plant trials [4], the government has formulated two sets of specifications governing the use of recycled aggregates for concrete production [5].

For lower grade applications, concrete with 100% recycled coarse aggregate is allowed. Recycled fines are not allowed to be used in concrete. The target strength is specified at 20 MPa and the concrete can be used in benches, stools, planter walls, concrete mass walls and other minor concrete structures. The specification requirements for recycled aggregate are listed in Table 1.

Table 1: Specification requirements for recycled aggregate for concrete production in Hong Kong

Requirements	Limit	Test method
Min. dry particle density (kg/m^3)	2000	BS 812: Part 2
Max. water absorption	10%	BS 812: Part 2
Max. content of wood and other material less dense than water	0.5%	Manual sorting in accordance with BRE Digest 43
Max. content of other foreign materials (e.g., metals, plastics, clay lumps, asphalt, glass, tar)	1%	
Max. fines	4%	BS 812: Section 103.1
Max. content of sand (< 4 mm)	5%	BS 812: Section 103.1
Max. sulphate content	1%	BS 812: Part 118
Flakiness index	40%	BS 812: Section 105.1
10% fines value	100 kN	BS 812: Part 111
Grading	Table 3 of BS 882: 1992	
Max. chloride content	Table 7 of BS 882 – 0.05% by mass of chloride ion of combined aggregate	

For higher grade applications (up to C35 concrete), the current specifications allows a maximum of 20% replacement of virgin coarse aggregates by recycled aggregates and the concrete can be used for general concrete applications except in water retaining structures.

As of the end of October 2003, there have been over 10 projects registered to consume over 22,700 m^3 of concrete from Grades 10 to 35 using recycled aggregates. The usage varies from reinforced pile caps, ground slabs, beams and parameter walls, external building and retaining walls, to mass concrete.

4. Case Study: Hong Kong Wetland Park

Hong Kong Wetland Park is located at the north-western part of Hong Kong and is close to the border between Hong Kong and Shenzhen of the Mainland. After completion in 2005, the park will have a 10,000 m^2 visitor center comprising exhibition galleries, AV theatres, souvenir shops, cafes, children play areas, classrooms and a resources center. In the project, recycled aggregate is employed to replace part of the virgin aggregate in the majority of the structural concrete. The highest concrete grade used is C35. The designed slump is 100 mm but in some cases, 75-mm slump concrete is also used. The concreting work of the Phase II project started in April 2003 and up to September 2003, a total volume of about 5,000 m^3 of ready mixed concrete using recycled aggregates has been placed.

Based on the specifications, the replacement levels of recycled coarse aggregate were 100% and 20% for concrete grades C20 (or below) and C25 to C35, respectively. Because of the limited experience in using recycled aggregates in concrete in Hong Kong, at the beginning of the project, the cement contents for the concrete mixes were deliberately increased by around 4% to compensate for the higher initial free water content required by the recycled aggregates so as to maintain a similar water/cement ratio.

The statistical results listed in Table 2 show that the average 28-day cube strength and the standard deviation of recycled aggregate concrete used in the project were about the same as those of ordinary concrete. The similar standard deviations show that the quality of concrete using recycled aggregates can also be controlled to a similar stability as that of ordinary concrete.

Table 2: Statistical results of recycled and natural aggregate concretes

Concrete grade	Slump (mm)	RA (%)	Cement (kg/m^3)	w/c	28-day cube strength (MPa)	S.D. for running 40 samples
C35	100	20	395	0.466	47.3	2.8
C35	100	0	380	0.473	48.2	4.1
C35	75	20	380	0.468	47.1	4.8
C35	75	0	365	0.479	45.8	4.5
C30	75	20	360	0.486	44.7	4.4
C30	75	0	345	0.507	42.1	4.7
C20	75	100	300	0.607	31.4	5.0
C20	75	0	290	0.603	32.8	4.4

In Hong Kong, most concrete batching plants were originally designed and built for concrete production with virgin aggregates only. In order to accommodate the recycled coarse aggregate, additional storage compartments had to be installed with all the necessary feeding and batching accessories. Also, as the water absorption rate of recycled aggregates was much higher than that of virgin aggregates, and to avoid excessive slump loss, the recycled aggregates were required to be pre-wetted both at the stockpiles of the recycling plant and by sprinkling water mist on the recycled aggregates during unloading at the receiving hopper at the batching plant before feeding to the overhead bin. The moisture content in the recycled aggregate was then compensated during the mix design. Chemical admixtures that would facilitate good workability retention were also added. But soft materials such as old cement mortar that were originally adhered to the old aggregates were quite easily broken off during mixing of the concrete which further contributed to the slump loss. The slump of the concrete produced therefore tended to be rather unstable, although the performance could still be controlled within the limits of acceptance. Also, the rate of slump loss was high which meant the workable time of the concrete was also reduced. As such, when recycled aggregates are used in ready mixed concrete production, it is advisable to adopt a higher initial design workability to compensate for the higher anticipated slump loss.

5. Ongoing Research

More research and development work is required to promote the use of recycled aggregates. Continuing research is being conducted by Government, universities and the industry to extend the scope of applications of recycled aggregates in Hong Kong. This includes studies on the production of precast bricks and blocks [6], the influence of the initial moisture states of recycled aggregates on the properties of concrete produced [7], the use of pfa, and the production of C45 recycled aggregate concretes. A recent study at the Hong Kong Polytechnic University aims to study the properties of recycled aggregate concrete prepared under a steam curing regime. Preliminary results indicate that compared with concretes cured under normal water temperature, steam curing increased the early strengths but reduced the long-term strengths for all normal and recycled aggregate concretes. But the detrimental effect of using steam curing on the 28-day strength decreased with increase in recycled aggregate contents. Furthermore, the drying shrinkage and creep of the steam cured recycled aggregate concrete were less than that of the normal cured counterparts. This result suggests that one of the most practical ways to utilize a high percentage recycled aggregate in structural concrete is in precast concrete products produced with an initial steam curing regime after casting.

6. Conclusion

Hong Kong is running out of both reclamation sites and landfill space for the disposal of construction & demolition materials/waste. It is important for Hong Kong to adopt a strategy to reduce and recycle C&D materials/waste and handle it in a more environmentally responsible way. Recycled aggregates have been demonstrated to be able to produce quality concrete for structural applications. More research and development is needed to further promote the recycling concept and widen the scope of applications of recycled aggregates.

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References

1. Cheng, N.T. *Technical Note 2/2000: Investigation of Opportunities for Recycling Inert Construction and Demolition Materials in Hong Kong.* Civil Engineering Department, HKSAR Government, June 2000.
2. Chan, C.Y.. and Fong, F.K. "Management of Construction and Demolition Materials and Development of Recycling Facility in Hong Kong." *Proceeding of International Conference on Innovation and Sustainable Development of Civil Engineering in the 21st Century*, Beijing, HKIE, July 2002.
3. RILEM Recommendation. 1994. "Specifications for concrete with Recycled aggregates." *Materials and Structures* 27, pp. 557-559.
4. Standing Committee on Concrete Technology and Concrete Producers Association of Hong Kong. *Study Report on the Use of Recycled Aggregates in Ready Mixed Concrete*. 2001.
5. Works Bureau of Hong Kong. *Specifications Facilitating the Use of Recycled Aggregates*. WBTC No. 12/2002. 2002.

6. C.S. Poon, S.C. Kou, and L. Lam. "Use of Recycled Aggregates in Molded Concrete Brick and Blocks." *Construction and Building Materials*, Vol. 16, 2002, pp. 281-289.
7. C.S. Poon, Z.H. Shui, L. Lam, H. Fok, and S.C. Kou. "Influence of Moisture States of Natural and Recycled Aggregates on the Properties of Fresh and Hardened Concrete," accepted by *Cement and Concrete Research* for publication.

IMPROVEMENT OF CONCRETE DURABILITY BY COMPLEX MINERAL SUPER-FINE POWDER

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Abstract

The green concrete capable for sustainable development is characterized by application of industrial wastes to reduce consumption of natural resources and energy and pollution of the environment. KG powder is a complex mineral superfine powder made by grinding the mix of calcined coal gangue and slag in certain proportion. Through reaction with the concrete admixture, KG powder improved pozzolanic reaction, micro-aggregate filling, and concrete durability. The concrete cement content was reduced by 40%-60%. The concrete resistance to sulfate attack and acid rain was enhanced greatly. Application of complex mineral superfine powder is an effective way to reduce environment pollution and improve durability of concrete under severe conditions.

1. Introduction

Coal gangue is a rock included in the coal bed and a waste discharged during coal mining and transportation as well as the most industrial waste discharged in China. It is estimated [1, 2], that the amount of gangue calculated as 15% of the coal output, there would be 100 million ton increment annually. Most of the coal gangue is a clay rock; its main mineral composition consists of clay mineral, followed by primary mineral quartz, feldspar, mica and pyrite, carbonate. After calcination under high temperature of 700-900°, the clay mineral is dewatered and disintegrated, the carbon component is removed with the deteriorative impurity burned out [3]. The crystal is disintegrated and transformed into amorphous non-crystal; this makes the coal gangue active. The activity depends on the phase composition of coal gangue and temperature of calcination as well [1, 4]. The calcined coal gangue is ground to a specific surface of more than 4500 cm^2/g and content of SiO_2 and Al_2O_3 more than 80%. The active SiO_2 and Al_2O_3 in it can react with $Ca(OH)_2$ and produce CSH gel, calcium aluminate and calcium sulfoaluminate hydrates [5, 6].

2. Raw materials and Test Methods

2.1 Raw materials

2.1.1 Cement

In the tests the PO425 cement manufactured by Chongqing Tenghui Diwei Cement Plant was applied with specific surface 3300 cm^2/g.

2.1.2 Coal gangue

The coal gangue is from the Huaying Mountain mine and treated by calcinations and grinding; its chemical composition is given in Table 1.

Table 1: Chemical composition of coal gangue and slag

	SiO_2	AL_2O_3	Fe_2O_3	CaO	MgO	SO_3	IL	Specific surface (cm^2/g)
Slag	36.90	9.73	3.85	35.93	2.33			4300
Coal gangue	58.10	24.54	5.31	5.73	1.05	2.97		4100
Fly ash	41.10	25.9	1.02	3.2	0.55	0.56	7.9	3900

2.1.3 Slag

The blast furnace slag is from the steel plant of Chongqing Steel and Iron Corporation and is dried and ground. Its specific surface is 4300 cm^2/g and the chemical composition is given in Table 1.

2.1.4 Fly ash

The fly ash is a dry one from the Chongqing Jiulongpo Electric Power Plant; its properties conform to the Chinese Standard GB1596-91, "Fly ash for cement and concrete," as standard class II.

2.1.5 Fine aggregate

Medium size sand from Sichuan Jianyang with a modulus of fineness Mx = 2.32; normal grading with the silt content 0.8%.

2.1.6 Coarse aggregate

Crushed limestone is from Xiaoquan, Chongqing City with a size of 5-20 mm and normal continuous grading. The content of flaky and elongated particles is <3% and the crushing index ≤6%.

2.1.7 Admixture

A complex retarding super-plasticizer FDN with slight air entraining, water reduction rate 23% and other properties conforming to the requirements for first class one in Chinese standard "Admixtures for concrete" (GB8076-2000), the dosage of the admixture is 1.2%.

2.1.8 KG powder

The KG powder is a mix by grinding the calcined coal gangue with slag, fly ash and silica fume. Its specific surface is 4900 cm^2/g.

2.2 Mix proportion of concrete

Based on properties of raw materials, the control mix proportion is given in Table 2 and taken as basic one. The mix proportion for the test is regulated on this basic one.

Table 2: Control mix proportion of concrete

Cement	Sand	Stone	Water	Admixture	Sp (%)
510	612	1140	168	6.12	35
1	1.20	2.24	0.33	0.012	

3. Test Results and Discussions

3.1 Workability and strength of KG powder concrete

Table 3: Workability and strength of KG powder concrete

No.	Initial set h:min	Final set h:min	Slump/spread (mm)			Compressive strength (MPa)		
			Initial	1h	2h	3d	28d	90d
1	7:35	8:28	210/490	200/430	160/350	49.0	67.9	70.2
2	7:52	8:47	210/525	210/472	180/395	46.3	68.2	75.6
3	8:10	9:31	225/530	215/483		43.2	69.8	80.2

Note: Substitution of cement by KG powder for mixes No.1 - 0%, No.2 - 20%, and No.3 - 50%.

The workability and strength of KG powder concrete are given in Table 3.

- Due to the micro filling and dispersing effects of the KG powder, the slump loss for the concrete mix with KG powder is less than that of one without addition. For example, the slump loss for concrete mix without additives at 2 hours reached 50 mm and that for concrete with 20% addition is 30 mm and for 50% addition 15 mm. The reduction of spread has the same character. Such effect is beneficial to the ready mixed concrete.
- Due to the secondary hydration of active additive, in comparison with the concrete without addition, the strength of the concrete with KG powder is decreased at early age with increase of dosage of the gangue powder and about the same at later age. The increment of strength for concrete without addition $(R_{90}-R_3)/R_3$ = (70.2-49.0)/49.0 = 40.7%; for concrete with 50% addition $(R_{90}-R_3)/R_3$ = (80.2-43.2)/43.2 = 85.6%.

The authors suggest that a slightly less strength of concrete at early age, in some degree, is beneficial to the durability of the concrete. The development of strength of the KG powder concrete depends on its mix proportion, that is, the mark and type of cement, w/c, content of coal gangue, fineness of additive, type and dosage of admixture, temperature of the environment, curing condition etc. In general, a high-strength concrete can be obtained provided that high quality material is used and a proper mix proportion is chosen. The KG powder concrete will have a high strength at later age. A careful curing at early age is beneficial to the development of the strength.

3.2 Durability of the KG powder concrete

3.2.1. Permeability of KG powder concrete

Test on permeability of the KG powder concrete was carried out according to the Chinese Standard GBJ82-85, "Test methods for long term properties and durability of ordinary concrete." Due to that the low w/c for high-performance concrete and the pozzolanic and filling effects of the ground KG powder, there is more cementitious material formed with dense structure, therefore, it is easy to prepare a high impermeable concrete in case of using crushed stone with excellent grading and addition of proper admixture [7]. See Table 4.

Table 4: Test results of permeability for KG powder concrete

Compressive strength (MPa)	Impermeable pressure (MPa)	Description	Depth of penetration
67.8	2.0	The pressure up to 2.2 MPa and kept for 10 hours, no leakage found.	On split specimen the depth of penetration at bottom is in average 3-5 cm and maximum 11 cm.

Note: Addition of KG powder 30%.

3.2.2. Resistance of KG powder concrete to sulfate attack

In our tests, the resistance to sulfate attack was studied by storage of specimens cured under standard condition for 28 and 90 days in 5% solutions of sodium sulfate and magnesium sulfate, then, the ratio of flexural to compressive strength of specimens was determined after 28 and 90 days corrosion, the results were compared with those of specimens stored in fresh water.

The mix proportions of mortar specimen are given in Table 5, the forming of specimen was carried out according to the methods for cement mortar specimens.

Table 5: Mix proportions of mortar specimens

No.	Cement (PO425)	KG powder	Sand	Water
1	100	0	300	40
2	80	20	300	40
3	65	35	300	41
4	50	50	300	42

Table 6: Compressive strength of mortar specimen

No.	28-day compressive strength (MPa)	Compressive strength after 28-day storage (MPa)				
		Fresh water	Na_2SO_4	%	$MgSO_4$	%
1	51.3	53.7	42.3	0.79	40.1	0.75
2	47.0	54.2	56.1	1.04	53.7	0.99
3	48.3	55.7	57.8	1.04	58.1	1.04
4	53.9	61.3	66.4	1.08	62.9	1.03

Table 7: Compressive strength of mortar specimen

No.	28-day compressive strength (MPa)	Compressive strength after 90-day storage (MPa)				
		Fresh water	Na_2SO_4	%	$MgSO_4$	%
1	51.3	55.2	41.0	0.74	36.5	0.66
2	47.0	57.3	57.1	1.00	51.6	0.90
3	48.3	56.6	57.9	1.02	52.6	0.93
4	53.9	62.7	65.9	1.05	60.2	0.96

It can be seen from the test results with storage in 5% sodium sulfate solution and 5% magnesium sulfate solution for 28 days that the corrosion resistance of mortar specimen with KG powder is much better than that of control specimen, the effect is better for those with more additives. This is due to that the active SiO_2 in KG powder can react with the Ca $(OH)_2$ in concrete to form secondary calcium silicate hydrate and make it chemically stable and structurally dense, the impermeability of concrete is enhanced as well. In addition, the KG powder can reduce the content of calcium aluminate in cementitious material, leading to increase of sulfate resistance of concrete. From the results after 90-day immersion, the mortar specimens with KG powder in 5% sulfate solution have similar effect with those immersed for 28 days, but for those in 5% magnesium sulfate, the influence of addition on anticorrosion factor is not obvious (the test results of flexural strength are similar to those of compressive one).

3.2.3 Resistance of KG powder concrete to acid rain

According to the monitoring data from Chongqing Bureau of Environmental Protection [8], the weighted means of pH value for annual precipitation (rain, snow) in Chongqing was in range of 4.09-4.70. The frequency of acid rain was over 70%. The minimum pH value reached 2.85 in 1990. In precipitation of Chongqing, the polluting component anion is mainly the sulfate ion, which takes about 75% of all measured anions. So the acid rain attack is characterized by sulfuric acid one and in laboratory the resistance of concrete to acid corrosion is carried out in diluted solution of sulfuric acid.

Table 8: Mix proportion of cement mortar

No.	Cement (PO525)	KG powder	w/c ratio	c/s ratio
1	100	0	0.4	1:3
2	90	10	0.4	1:3
3	80	20	0.4	1:3
4	70	30	0.4	1:3
5	50	50	0.4	1:3

Table 9: Mix proportion of concrete

No.	OPC : KG powder : W : admixture	Sand percentage (%)	28-day (MPa)
1	1 : 0 : 0.35 : 1.0%	38	61.1
2	1 : 0.3 : 0.35 : 0.8%	38	67.3
3	1 : 0.45 : 0.36 : 1.1%	38	71.2

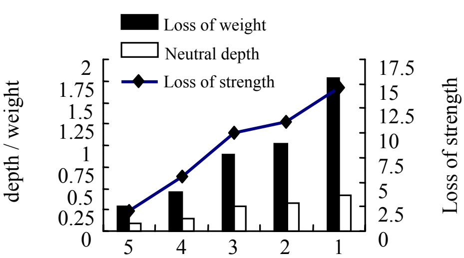

Fig. 1: Neutral depth, loss of strength, and weight of mortar attacked by sulfuric acid

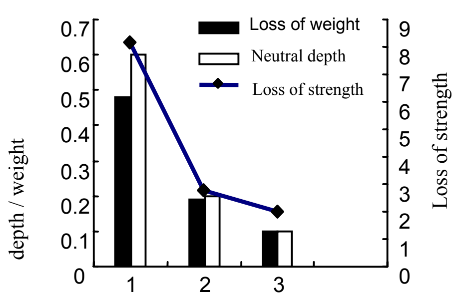

Fig. 2: Neutral depth, loss of strength, and weight of concrete attacked by sulfuric acid

The mortar and concrete specimens were cured for 28 days in sulfuric acid solution with pH value of 3.0 for corrosion test. During storage, the color of specimen surface changed into yellow, then white. There were loss in weight and strength of specimen occurred, the depth of neutralization varied with the additives. After washing the loose material covered on the surface, there was some cement paste on the surface fallen off and part of the aggregate exposed, which is similar to that found in concrete structure attacked by the acid rain in Chongqing [8].

From Figs. 1 and 2 it can be seen that the resistance of OPC to acid corrosion is rather poor, the strength loss of mortar specimen reached 14.6% after immersion in sulfuric acid solution with pH value of 3.0 for 90 days and the strength loss for concrete specimens is 8.15%. For specimens with additives, those with KG powder have good performance in acid resistance and better than specimens without additives both in the depth of neutralization and loss in weight and strength. As for mortar and concrete, the depth of neutralization is in linear relationship with the loss in weight and strength.

It can be seen from the test results that the KG powder concrete is better than ordinary Portland cement concrete. This is due to that there is more active component in KG powder. In addition, due to less cement content, the amount of Ca $(OH)_2$ in KG powder concrete mix reduced by 30%-50% in comparison with that in OPC paste, the CSH gel in paste at later stage of hydration is much more than that for OPC. The rate of formation of Ca $(OH)_2$ during hydration is low with fewer amounts than that for OPC. Consequently, it will have more strength and better stability, the composition of cementitious material in cement paste and the interface between cement paste and aggregate are improved. Thus, the stability of the concrete in respect of resistance to acid corrosion is enhanced.

4. Conclusion

The fully calcined coal gangue ground in mix with slag and fly ash can serve as additives for high performance concrete. Piling up of coal gangue in large amount seriously caused the pollution of environment and there is latent danger of self-combustion. However, the utilization of coal gangue fell behind that of other industrial wastes such as fly ash, slag etc. the authors carried out a series of experiments and it is verified that like other similar industrial wastes, the coal gangue can be used for concrete, provided that the proper mix proportion is chosen and high quality admixture is used to improve the properties of concrete, even the high performance concrete can be prepared with the characteristics of green concrete.

References

1. State Bureau of Environment Protection. *Building Materials on Industrial Wastes*. China Environmental Science Press, 1992.
2. Wu Zhong-wei and Lian Hui-zhen. *High Performance Concrete*. China Railway Press, 1999.
3. Hunan University. *Building Materials*. China Building Industry Press, 1997.
4. Chen Jian-xiong et al. "Investigation on Durability of Buildings under Severe Acid Rain." *Concrete*, 2001 (11), 44-47.
5. Feng Nai-qian. *High Performance Concrete*. China Building Industry Press, 1969.
6. Li Min, and Xu Yu-yan. "Utilization of Aggregate from Self-combusted Gangue." *New Building Materials*, 2001, 3.
7. Xu Bin et al. "Study on Permeability of Cement Concrete with Large Amount of Gangue." *Shanxi Building Materials*, 1969, 4.
8. Chen Gui-zhi et al. "Distribution of Acid Precipitation: Acidic Rain, Fog and Dew and Pollutant in Chongqing Area." *Chongqing Environmental Science* 15 (5), 1993, 25-29.

DEVELOPING CONCRETE TECHNOLOGY ALONE MAY NOT BE HELPFUL FOR SUSTAINABLE DEVELOPMENT ACCORDING TO THE HOLISTIC VIEWPOINT

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Abstract

The advancement of concrete technology can reduce the consumption of natural resources and energy sources and lessen the burden of pollutants on the environment. However, if the price of environment resources and thereby the cost of concrete still keeps relatively low, then because of the economic rules governing the market's behavior preferring cheaper resources and something with good quality but a lower price, more environment resources and concrete materials will be used and they will not be cherished and saved, which will result in the worsening of environment. An accurate method is to add a suitable environmental cost of producing concrete into the current price by adjusting the price of environment resources to elevate concrete's price, which will be helpful for protection of the environment and will promote the advancement of concrete technology. The holistic viewpoint is applied in this paper. The problems of sustainable development should be considered on the society-economy-technology level.

1. Introduction

When 1-ton cement clinker is produced, about 1-ton carbon dioxide gas, a kind of greenhouse gas, is emitted. When more than 100 kilograms of standard coal is consumed, a lot of sulfur dioxide gas, nitrogen oxide gas and mill dust are emitted, which can harm the health of people. Secondly, exploitation of clay as a raw material of cement production, and sand and stone as an aggregate of concrete has destroyed the natural environment, which has resulted in soil and water loss, as well as caused the changes of stream ways. Furthermore, use of a large quantity of fresh water for concrete is a heavy burden, especially in this water crisis era. In addition, concrete will turn into huge non-degradable solid waste after it is out of commission. It is a very crucial problem for human society and the environment in which we are living.

Because of the above reasons, the concrete industry has threatened sustainable development. So we must advance concrete technology to meet the needs of today's generation without endangering the possibilities of future generations to satisfy their needs.

Although concrete is not a green product as a whole, it has been used to construct a wide variety of structures due to its irreplaceable capability in many aspects. As an artificial engineering material with relatively good quality but lower price, nowadays concrete still prevails among construction materials. Its used quantity per year is over 8 billion tons.

However, the pollution caused by producing concrete and the consumption of natural resources is so serious that the position of the traditional concrete industry has to be improved to insure sustainable development. But the total quantity of pollution and consumption of resources and energy has not decreased with the advancement of concrete technology, which has caused a debate over whether only the development of concrete technology can arrive at the goal of sustainable development.

2. Concrete Technology Contribution to Sustainable Development

2.1. Advancement of technology and energy consumption

With the advancement of technology, unit energy consumption for cement has decreased on the whole. Fig. 1 indicates the trend of energy consumption for cement in China. But because of the increase in cement production (see Fig. 2), the total energy consumption has increased. Fig. 3 shows the increase of total coal consumption for cement in China. In the world, the cement production has increased nearly linearly, which leads to the reduction of unit energy consumption (see Table 1) but cannot hold back the increasing trend of total energy consumption. Other aspects such as emissions of carbon dioxide gas have had these similar conditions as well. (Source of data in Figs. 1 and 2.: *China Energy Statistical Yearbook* [1997-1999] and *China Industry Economy Statistical Yearbook* [2002].)

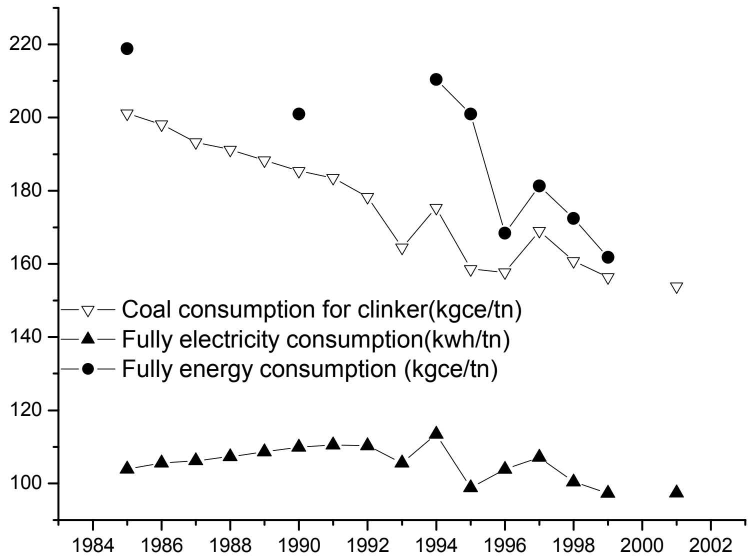

Fig. 1 Energy Consumption for Cement in China

Although reduction of unit energy consumption helps to cut down a large quantity of energy consumption with the rapid increase of cement production, the rise in total energy consumption has not been effectively controlled. While it cannot be denied that concrete technology has made prominent progress during the last half of the twentieth century, neither can it be denied that the exigent situation of the environmental problem has harmed the sustainable development of society. That is to say, if the concrete technology continues to progress in its current path (here only the technology is considered), then the problem of sustainable development cannot be resolved yet.

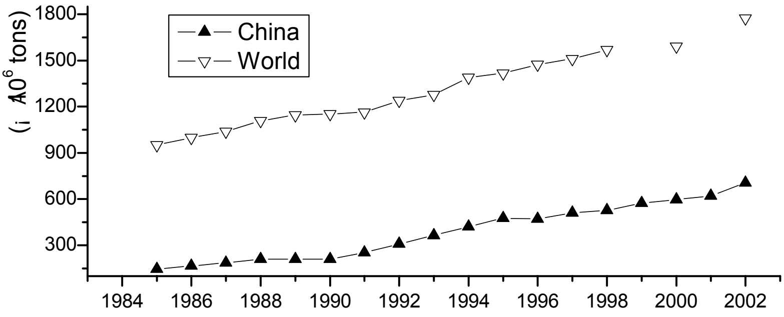

Fig. 2 Cement production

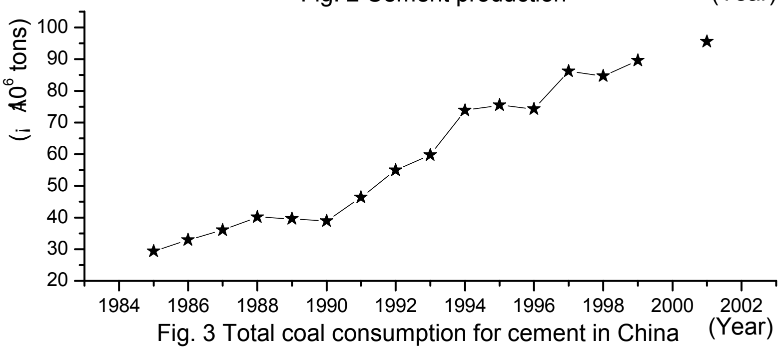

Fig. 3 Total coal consumption for cement in China

Table 1: Energy consumption in Japan and Germany

Japan	**Fully energy consumption for cement (kgce/tn)**			
1980 (y)	1990 (y)	1995 (y)	1997 (y)	1999 (y)
135.7	122.6	124.4	124.6	124.4
Germany	**Fuel energy consumption (specific in kJ/kg cement)**		**Electrical power consumption (specific in kWh/tn cement)**	
1999 (y)	2800		102.0	
2000 (y)	2835		101.5	
2001 (y)	2790		99.8	

Source: *China Energy Statistical Yearbook* (1997-1999) and *Environmental Data of the German Cement Industry.*

2.2. Environmental cost and concrete technology

In environment economics, environment is regarded as a necessary resource for production and also has value and use-value like other resources. Here environment resources include natural resources and environment services. Environmental cost is defined as payment for use and consumption of the environment resources. Fig. 4 shows that environment resources play a necessary pole in concrete production process.

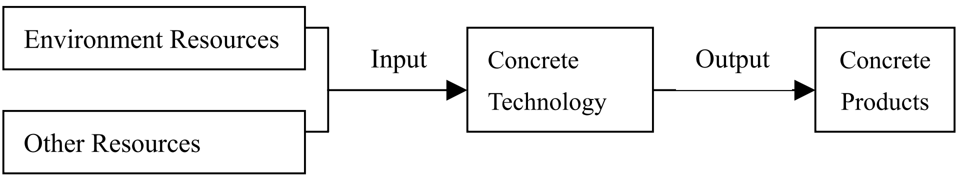

Fig.4: Environment is used as a resource in concrete production process

If the prices of environment resources are undervalued, that is to say, no or a little environment cost is reckoned in the total cost of concrete products, two results will be caused: (1) Because of lower price of environmental cost, more natural resources and environment services will be used. In order to reduce consumption of environment resources, more other resources, for example, manpower resources, green technology and equipments, power, etc. tend to be used. This expenditure is a part of environment-protection cost. Obviously cheaper resources would be firstly chosen and more used; (2) Because of lower price of concrete products, the materials will especially not be cherished and saved.

Here we define the term Green Factor to describe the degree of concrete technologies' contribution to sustainable development. The concrete technology with higher green factor will use less environment resources.

Some concrete technology has a relatively higher green factor, which directly contributes to sustainable development. For example, reduction of the quantity of cement clinker in the condition of the same strength grade by mixing fly ash or slag instead of partial cement, saving the energy used for concrete, and circular utilization of concrete that is out of service could all contribute to this goal.

As a result of the fact that many concrete technologies with high green factor may increase the cost by using less of cheaper environment resources and more of more expensive other resources, they may be unacceptable while those with low green factor may prevail.

When the cost paid for use and consumption of environment is cheap, the advancement of concrete technologies, even those technologies with high green factor, is helpless for lavishing natural resources and environment services, but may be helpful for improvement of concrete performance. Thus concrete becomes a material with good quality but a lower price.

Therefore, a concrete technology is unwelcome unless it could use less environment resources than before without elevating the price of concrete and largely harming the concrete performance at least. For example, if we use the old concrete from structures that are out of service as recycled aggregates of new concrete, it must be guaranteed that the cost for obtaining these recycled aggregates is not more than that of natural aggregates and the concrete performance won't be greatly harmed.

Therefore, the criteria for evaluating whether advancement of a concrete technology is completely helpful for sustainable development or not are below:

- Use less environment resources without increasing the cost of concrete products.
- Use less environment resources without greatly harming concrete performance.

A concrete technology will really contribute to sustainable development only when both of the criteria are satisfied. The first criterion, to a large extent, is depended on economic rules and policy while the second one is completely a technology problem.

2.3. Advancement of concrete technology on condition of lower environmental cost
Now the prices of natural resources mainly contains exploitation cost and no or a little environmental cost. A little expenditure has been paid for environment services in processing, circulation and consuming of products.

Nowadays, one of the reasons why concrete products are used so widely is their lower price. This is primarily because most of the environmental cost has not been reckoned in the practical total cost or only a little of it has been considered. For example, the cost of the greenhouse effect caused by the huge volume of carbon dioxide gas emitted by the concrete industry is shared by the whole society and even future generations. It is unfair to those who do not reap the benefits brought by the concrete industry, yet suffer the consequences. Fairness just should be one of most important principles of sustainable development.

Since the total cost of concrete includes either no or a little environmental cost and the technologies with higher green factor, as mentioned above, shall add the environment-protection cost to the price of concrete in practice, manufacturers would prefer to support technologies without a green factor more than those with a higher green factor. Thus the concrete product can still keep a lower price after it is provided with good performance. This is one of the main reasons for a lower price level of concrete. Here is an example concerning the lower price of concrete: in the year 2000, the total income on sales increased only 5% in the condition of 4.2% increase of cement production in China [1].

Thus, an economic rule governing the market's behavior preferring something with good quality but lower price, will inspire people to select more concrete material for construction instead of other building materials probably with higher green factor. Concrete materials will especially not be cherished and saved, which will widen the gap between the concrete industry and sustainable development.

The rule dominates the economic activity in the concrete industry so that the influence of technology is relatively weak compared with policies of technology and economy.

In other words, the development of concrete technology alone may not be helpful for sustainable development. In fact, it may even sharpen the conflict between the concrete industry and sustainable development.

The advancement of technology with higher green factors is one of the most effective ways to resolve the problem that the concrete industry has hindered from sustainable development. The technology has played an important role in narrowing the gap between the concrete industry and sustainable development. However, in order for these technologies to be effective, some measures should be taken to insure real price of environment resources.

2.4. Reckoning in environmental cost and its advantage

An accurate method is to add suitable environmental costs of producing concrete by adjusting the price of environment resources into the current price to elevate concrete's price, which will be helpful for protection of the environment and will promote the advancement of concrete technology. In fact, once given an environmental cost, the concrete will not be a cheap product and will have a higher scarcity than before in the market. On one hand it would encourage users of concrete to cherish and frugally use it and thereby reduce irrational use of concrete or look for other preferable construction materials with advantages both in economy and in environmental protection. On the other hand, it would encourage manufacturers to afford funds to support the study of concrete technology by which the environmental cost can be lowered and therefore excess profit can be gained. This is helpful for the scientific research on concrete and even development of new building materials. In this sense, sustainable development not only brings challenge but also offers a hard-won opportunity for concrete technology.

In fact, the reasons why technologies with higher green factors have not made great progress may partially be ascribed to less attention being paid by relevant organizations. Enterprises, the key players in the market, have not responded to the fact that a lower price of concrete can not attract enough attention in economic activity. In addition, environmental costs may be regarded as the currency value of the needs for sustainable development and reflect the justice of society among contemporaries and future generations as well.

Conversely, the essence of the environmental problem is that, in economic activity, the gaining speed of a resource from nature exceeds the regenerating speed of the natural resource and its replaceable resource. However, the expelling amount of waste due to human activity into the environment exceeds the depurating capability of the environment itself [2]. Therefore, the environmental problem essentially is an economic one.

Exorbitant environmental costs may resolve the environmental problem but may stifle the economic development; therefore, environmental cost must shoot for achieving a balance between economic development and environmental protection.

In fact, as a result of higher environmental cost in developed countries, their needed cement is imported from developing countries where the price of environment resources is relatively lower.

3. On the Holistic Viewpoint

The harmony of concrete technology and sustainable development must be discussed according to a holistic viewpoint. An idea that may be right in a certain domain, may be wrong in a wider spectrum. Just as in this case, the advancement of technology seems helpful for sustainable development but may not be integrated in the system of society-economy-technology.

Sustainable development is a global project including all realms and trades. Therefore, the relationship among the economy, society, and technology should be considered properly when we make our efforts to improve the technology.

In holism, whole is emphasized. However, the concept of whole is relative rather than absolute: A whole is the part of another larger whole. In different levels, there are different wholes. Therefore the holistic viewpoint is confused unless the level and range is applied and defined. An accurate conclusion that is identical with reality to a great extent depends on the basis of an accurate definition of level and range.

Nowadays, the issue of sustainable development should be considered in society-economy-technology level. In this level, the cost of concrete, including the consumption of natural resources, environment services and energy and use of manpower, equipments and facilities, and so on, should be analyzed during the whole lifetime of the material with the method of life-cycle assessment (LCA). It is in this level that the problems of the development of concrete technology besteading sustainable development can be resolved through the composite effect of economy, society and technology. This includes the decrease of consumption of resources and energy, the reduction of drainage pollutants, the improvement of durability of concrete materials, the use of recycled concrete and the invention of new materials with higher green factors.

In addition, according to the viewpoint of eastern philosophy, the holistic viewpoint should be a capacity through which a thing can be intuitively grasped on the whole. It is an approach through which the key of a problem can be caught but those secondary details are overlooked. The holistic viewpoint encompasses wisdom with which you can go out of the situation and survey the problem at a higher level.

4. Conclusion

According to a holistic viewpoint, despite the decrease of unit energy consumption, the total quantity cannot be reduced if the concrete production increases due to a lower price. This economic consequence would result from an advancement of technologies with little green factor and a lack of suitable environmental costs. Other aspects of the concrete industry such as emissions of carbon dioxide gas have had similar repercussions as well. The development of concrete technology without the support of the relevant policies of economy and law may be not helpful for sustainable development. Thus it can be seen that a holistic approach is important for science and technology research.

Acknowledgments

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References

1. *China Building Industry Yearbook*, 2002.
2. Luo Yong and Zeng Xiaofei. *Economic Means for Environment Protection*. Peking University Press, 2002.

A STUDY ON COMPLEX ALKALI-SLAG ENVIRONMENTAL CONCRETE

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Abstract

In this paper, the environmental and mechanical properties of alkali-slag concrete are discussed. The concrete is prepared by activating the slag as industrial by-product, using the alkali component as activator. Then, the complex slag and complex alkali component are investigated and a new complex alkali-slag environmental concrete has been prepared. Based on the evaluation of environmental effect as well as analysis and comparison of the concrete materials, the authors suggest that this concrete will be a new environmental material, which is in coordination with the environment and can keep a sustainable development.

1. Introduction

Alkali-slag concrete, or JK concrete as it is called in China, is made from slag powder and alkali component as main constituents of cementitious material. The slag powder may be one or a mix of the following: blast furnace slag, phosphorous slag, titanium-containing slag, manganese slag, basic cupola furnace slag, aqueous slag from power plant, nickel slag, silica aluminate. The alkali component as an activator is a compound from the elements of first group in the periodic table, so such material is also called as alkali activated cementitious material or cement. The common activators are NaOH, Na_2SO_4, water glass, Na_2CO_3, K_2CO_3, KOH, K_2SO_4 or a little amount of cement clinker and complex alkali component; therefore, its activity is more than that of compound from the elements of second group as commonly used in traditional cementitious material. The ions with strong ionic force formed during dissociation of alkali metal compound, promote the disintegration of slag powder and hydration of the ions, and then, such ions take part in the structure formation of cement paste, so the cement has properties of rapid hardening and early strength gain [1, 2, 5]. For such type of concrete there is less $Ca(OH)_2$ and high alkali hydrates in hydration products of cement, in case of high Al/Si ratio, there will be some mineral of zeolite type resulting in its high resistance to corrosion [3, 4]. Due to perfect pore structure, small total pore volume, proper distribution of pore diameters, dense structure and good bond of interface between cement and aggregate [3], the special concrete and concrete with the strength of 20-120 MPa can be obtained. The concrete mix has a good workability with slump of 0-22 cm without water reducing agents. The concrete has a high hardening rate with low heat of hydration, consisting of only 1/2 to 1/3 of that for OPC; its impermeability is 1.0-4.0 MPa; the frost resistance reached 300-1000 cycles. There is strong protection of reinforcement with excellent corrosion resistance [1, 2]. It can be used for various building elements and monolithic concrete. Structural tests on concrete elements show that their deformation, bearing capacity and cracking resistance conform to the requirements of the China's standard [2, 4, 6]. For preparing the cementitious material of JK concrete, only the grinding is required with no calcinations. As for the concrete aggregate, the aggregate with large content of mud or fine particles, heavy loam, sea sand, super fine sand, machined sand etc can be used. It is a low cost, energy saving, low resource consumption material, which can promote the recycling of the waste and make an environmental concrete with clean production of cement, environment friendly and in good coordination with the environment.

2. Mechanical Properties of Slag-alkali Environment Concrete

2.1 Mechanical properties of slag-alkali high-strength concrete

Tables 1 and 2 give the examples showing the main components and strength of the representative slag-alkali (JK) concretes.

Table 1:Properties and strength of alkali-slag concrete

No.	Aggre-gate	Slump (cm)	28-day density (g/cm^3)	Compressive strength (MPa) at age of				
				1d	3d	28d	360d	Other
1	A, D	20	2.476	9.6	44.1	77.7	81.9	3.5 years: 95.6
2	A, D	1	2.533	9.6	49.2	90.2	98.4	
3	A, D	16	2.481	18.6	48.5	79.6	88.2	
4	A, D	11	2.521	46.8	70.3	98.0		
5	A, D	7	2.495	38.4		78.5	99.4	
6	A, D	1	2.507	4.6	35.2	80.2	92.2	
7	A, D	8	2.471	3.3	8.8	62.5	91.3	
8	A, D	0	2.447	2.8	2.8	35.1	73.2	
9	A, D	4	2.481	2.4	2.8	37.4	68.2	
10	A, C	3	2.363	27.8	56.4	90.3	100.8	
11	A, D	1	2.522	24.8	41.8	76.7	101.7	
12	A, D	0	2.457	48.5	72.3	90.7	114.7	
13	A, C	3	2.550	56.1	71.3	102.3	112.2	
14	A, C	0	2.524	60.9	80.8	99.0	113.7	
15	A, D	2	2.500	61.5	79.0	99.0	114.4	
16	A, C	1	2.468	68.1	96.2	117.0	132.2	
17	A, D	0	2.436			25.3	75.2	
18	A, C	–	2.458			114.5		R_2 = 106.8
19	A, D	22	2.498	33.6	65.4	86.0		
20	A, D	5	2.548	1.4	9.8	60.4	101.1	Ra = 88.6

Note: A = crushed limestone; B = crushed granite; C = medium sand with FM = 0.24; D = sand powder with FM = 0.56-0.63; Ra = strength of autoclaved specimen.

Table 2: Mechanical properties of high and super high strength JK concrete

No.	1	2	3	4	5	6
f_{cu} 28d (MPa)	52.9	61.2	76.5	81.6	91.2	120.5
f_c (MPa)	4.04	4.04	4.22	4.58	4.71	
f_f (MPa)	6.71	7.87	7.59	7.43		
f^t_c (MPa)	46.6	49.6		64.6	78.6	
f_c / f_{cu}	0.076	0.068	0.055	0.056	0.052	0.046
f_{cu} / f_c	13.094	14.606	18.128	17.817	19.369	21.595
f_f / f_{cu}	0.127	0.129	0.099	0.091		
f'_c / f_{cu}	0.881	0.810		0.791	0.861	0.826
f'_c / f_{cu}	11.84	11.84		14.01	14.93	15.98
Bond (MPa)	6.00	5.48	6.05	6.21		
E×10^4 (MPa)	3.77	3.89	4.01	3.82	3.82	2.95

Notes: For Nos. 1-5 the aggregate is limestone and fine sand (FM = 0.63). For No. 6 the aggregate is granite and medium sized sand. f_{cu} = compressive strength; f_c = splitting strength; f_f = flexural strength; f^t_c = axial compressive strength.

2.2 Development of strength and impermeability of alkali-slag concrete

The strength of alkali-slag concrete at later age developed quite well, especially for the ordinary concrete. For the concretes of 15-30 MPa, the strength increased to 40-83 MPa after 6-12 years; the increment is as high as 198%-107%. For the concretes of 70-96 MPa, strength increased to 101-122 MPa, or 11%-57% of the increment. The impermeability increased from 0.5-1.0 MPa to over 1.8-2.0 MPa with an increment of 100%-200%. An investigation on JK concrete elements and structures after 22 years of service shows that no marks of external damage or trace of reinforcement corrosion found [7, 8, 9]. Due to enhancement of durability and prolongation of the service life, the cost of life cycle was lowered and the expense for maintaining reduced greatly.

3. Characteristics of Environmental Materials Based on Alkali-Slag Concrete

3.1 Environmental characteristics for preparing the cementitious materials and concrete

For preparing the JK cementitious material, only the drying of wet slag and one grinding are needed, without high temperature calcination and two grindings: for raw materials, then for clinker and additives as in the traditional cement manufacture. Therefore, the equipment expenses, energy consumption for its preparation will be reduced greatly. The alkali component can be added as admixture or in case of solid alkali in mixed grinding with the slag. The dosage of alkali component takes only about 3%-6% of the activated material. The natural alkali component or industrial alkali containing waste can be used. In manufacture there is no CO_2 emission; the utilization rate of the slag is as high as 80%-100% and reduction of coal consumption by 66%-86% and electricity consumption by 50% [5, 10]. The concrete production and construction can be realized with existed mixers and equipments for construction work. There will be clean production for the cement and concrete by energy saving and low consumption with lowering the noise and dust during its production. Even in case of a little amount of cement clinker used as activator, the CO_2 emission will be reduced by 90%.

3.2 Turning the slag into a resource

For preparing the alkali activated cement concrete, except for granulated blast furnace slag, other industrial slag can be used as well, for example, there could be alkali fly-ash slag concrete [11], alkali titaniferous slag concrete, alkali alumo-silicate concrete and alkali phosphorous slag concrete etc prepared. It may be a combination of several kinds of slag. So such application is significant for making the slag into a resource.

3.3 Full use of low grade aggregate

For alkali slag concrete the low grade aggregate can be used, such as heavy loam, sea sand, aggregate with powder content up to 20%, aggregate with clay content over 5%, slowly cooled slag, color metal slag, recycled aggregate, powdered sand with fineness of modulus of 0.56-0.62. A concrete with 28-day compressive strength of 20-99 MPa can be produced with these aggregates, thus to expand the scope of the resource. This type of concrete has more increment of strength at later age and good durability.

3.4 Contribution of high durability to the energy and resource use, operating function and maintenance

In former Soviet Union, there was an irrigation canal built from JK concrete with strength of 15 MPa, using heavy loam. Twelve years later, its strength reached 40 MPa and the freeze thaw cycle was up to 900. For concrete road cover with sea sand as aggregate, the strength increased from 16 to 47.6 MPa. For assembled pile and breakwater, the strength was increased from initial 30 MPa to final 71.8 and 62.0 MPa, and frost resistance up to 600 and 570 cycles, respectively. The impermeability increased by 100%-200% [8, 9]. The engineering practice in Ukraine shows that the reinforcing steel bar embedded in drainage elements from alkali-slag concrete with protective cover only 3mm hasn’t been corroded after 20 years of service. Using the powder sand with fineness of modulus 0.62 from Yangtze River in Chongqing and crushed limestone, a JK concrete with 28-day compressive strength of 99 MPa and after one year 114.4 MPa has been prepared, its impermeability reached over 3.5-4.0 MPa [1, 5]. Such JK concrete has excellent resistance to sulfate corrosion, after its immersion in 2% solution of $MgSO_4$ for 2 years, the strength increased by 22.1%-39.2% and in 0.234 N HCl for 2 years, the strength increased by 33.1%-48.3%, only damaged in concentrated hydrochloric acid [5, 6]. Due to that the JK concrete kept a high increment of strength during its service, making itself a high or even super high strength one, its resistance to deterioration increased with the age. Consequently, the service life of construction prolonged and the function could be guaranteed with great saving in resource consumption and maintenance expense and lowering the life cycle cost. It would have an active effect on the environmental load.

4. Titaniferous slag and concrete with mixed alkali activated slag powder

4.1 Characteristics of titaniferous slag as a raw material

Among various slag, the acidic one and titaniferous one are considered as non-active ones and are difficult to be used. Their chemical composition is given in Table 3 [4, 12]. Activated by alkali or physico-chemical treatment, a mixed slag environmental concrete can be prepared from titaniferous slag.

Table 3: Comparison of titaniferous slag and granulated blast furnace slag

No	Slag	Chemical composition									K
		CaO	MgO	MnO	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	SO_3	Loss	
1	BF slag	42.7	5.4	1.6	31.72	10.3	1.8	1.59	1.07	0.42	1.67
2	Ti slag	25.1	8.1	2.9	27.1	15.6	5.3	14.8	0.39	0.42	1.09
3	Ti slag	32.11	7.57	0.11	26.09	15.64	0.78	17.90	0.30	0.66	1.25
4	Ti slag	29.03	8.43	-	23.4	16.43	0.44	22.30	0.27	0.64	1.17
5	Ti slag	26.46	8.11	0.24	23.08	15.64	3.06	23.80	0.29	0.98	1.06

Note: The quality factor K= CaO + MgO + Al_2O_3/ SiO_2 + MgO + TiO_2.

With the increase of TiO_2 in titaniferous slag, its difference from other slag is enlarged. When the TiO_2 content is more than 15%-25%, the activity of the slag is quite poor, especially for the melted one, as for water soaked one obtained by long distance transport and discharge into water, its activity would be poor, this is due to that there would be perofskite crystal formed with no hydraulic activity and improper water quench with a little amount of glass phase formed. Such slag has been piled up as much as a mountain, making the river blocked. Usually, it was used as filling material for the road [1, 2]. In order to fully utilize such slag, the alkali and physical activation was applied and a good result is obtained. If the fluorite would be added during iron smelting to improve the quality of water quench, even the industrial waste with high titanium containing slag could be used as a resource.

4.2 Mechanical properties of alkali activated concrete with titaniferous slag and mixed powder

Water soaked titaniferous slag with 20%-25% of TiO_2 is a non-active additives, if it is used as additives for portland cement the dosage should be less than 15%. If it is used for preparing the alkali activated concrete, the addition could reach 50%-100%. Based on chemical activation, in addition of heat activation, the strength could reach about 90 MPa. In this study, the JK concrete was prepared with water soaked titaniferous slag, which will promote the utilization of industrial slag as a resource. In Table 4, the mechanical properties of alkali-activated concrete with titaniferous slag and mixed slag are given. Its special application and specific properties are under investigation.

Table 4: Mechanical properties of alkali activated concrete with titaniferous slag and mixed powder

No.	Type of aggregate	Content of slag (%)			Type of alkali	Compressive/flexural strength (MPa)				
						Normal curing			Steam curing	Auto-claved
		Ti	BF slag	Other slag		3d	7d	28d		
1	A, D	100			I, III	7.1		24.2	80.8	92.4
2	A, D	100			I, II	7.5				97.3
3	C	100			I, III	15.9/ 4.3	30.5/ 5.9	54/ 10.1	–	–
4	C	50	50		I, I	23.6/ 4.8	46.2/ 57.6	75/ 10.6	–	–
5	C	95		5	I, II, III		27.2/ 5.2	52/ 8.2	–	–
6	C	50	50		I, II, III	3.0/ 2.3			83/ 7.5	

Notes: Nos. 1 and 2, water quenched titaniferous slag with TiO_2 content of 24%-25%; Nos. 3, 4, 5 and 6, water soaked slag with TiO_2 content of 24%-25%. A = crushed limestone; C = medium sand, FM = 2.4; D = powder sand, FM = 0.56-0.63.

5. Conclusion

The JK concrete prepared from pozzolanic slag activated by alkali has excellent mechanical properties and durability, turning the slag into a resource. During cement production, it can lower the environmental load and increase the utilization rate of the slag due to low energy consumption without emission of CO_2 and using the mixed slag. During concrete production, the aggregate with high content of silt and powders can be used as well as sea sand and powder sand, so the environmental characteristics is quite good and can become a new environmental material coordinated with the environment and capable of sustainable development.

References

1. Pu Xin-cheng, Gan Chang-cheng, Wu Li-xian, and Chen Jian-xiong. "Study on a New Structural Material—High Grade JK Concrete." *Silicate Building Products*. 1988.
2. Chen Jian-xiong, Pu Xin-cheng, and Gan Chang-cheng. "Experimental Study on High Strength Alkali-slag (JK) Reinforced Concrete Beam." *Journal of Chongqing Institute of Architecture and Engineering*, 1992.
3. Wu Li-xian, Pu Xin-cheng, Gan Chang-cheng, and Chen Jian-xiong. "Study on Micro-structure of Alkali-slag (JK) Concrete." *Sichuan Building Materials*, 1989.
4. Chen Jian-xiong, Pu Xin-cheng, Gan Chang-cheng, and Wu Li-xian. "Experimental Study on Structural Performance of Alkali-slag (JK) Concrete Elements." *Industrial Construction*. 1989, 11.
5. Pu Xin-cheng, Gan Chang-cheng, Wu Li-xian, and Chen Jian-xiong. "Properties of Alkali-slag (JK) Concrete." *Ceramic Bulletin*. 1989, 8.
6. Pu Xin-cheng, Chen Jian-xiong, and Gan Chang-cheng. "Experimental Study on High and Super high-Strength Alkali-slag (JK) Concrete and Reinforced Concrete Beam." *Effective Prestressed Concrete Engineering Practice*, P389.
7. Pahomov, V.A. *Alkali Slag Concrete Construction*. Golovnoe Publisher, 1984.

8. "All-union Conference on Alkali-slag Cement, Concrete and Construction." *Cement*, 1985, 3.
9. Gluhovskii, V.D. "Alkali Slag Cement." *Cement*, 1985, 3.
10. "Today and Tomorrow of the Alkali-slag Cement." *Chemistry and Life*, 1986, 1.
11. Liu Hong-fei and Hu Heng. "Study on Construction Performance of Alkali-Slag Fly-ash Concrete." *Study on Durability and Engineering Application of Concrete for Key Projects*. China Building Industry Press, P.409.
12. Xu Chu-zhao and Chen Guang-bi. "Study on Activity of Blast Furnace Slag with High Content of Titanium." *Journal of Chongqing University*, 1988, 13.

APPLICATION OF GROUND GRANULATED BLAST FURNACE SLAG IN HIGH-PERFORMANCE CONCRETE IN CHINA

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Abstract

This paper introduces studies and the application of ground granulated blast furnace slag (GGBS) in China. The performance of GGBS is measured and the effect of GGBS on fresh concrete and harden concrete is analyzed. GGBS concrete is characterized by high strength, lower heat of hydration, and resistance to chemical corrosion.

1. Introduction

Annual granulated blast furnace slag (GBFS) production capacity in China is around 15 million tons. GBFS powder has been successfully applied as the raw material of cement block, pavement block, and slag cement.

GBFS is usually used as additives in Portland cement production in China. Traditional production technology is to grind cement clinker, GBFS and gypsum together. Because GBFS is more difficult to grind than clinker, specific surface area of GBFS in cement is under 300 m^2/g. The grain size of GBFS is mostly over 60 um; thus its activity in early age is limited and cannot been brought into full play. Concrete mixed with this kind of slag cement has some shortage, such as low early strength, poor durability, and ease of bleeding.

At present, with the quick development of high efficient grinding apparatus, GBFS is produced to ground granulated blast furnace slag. GGBFS is different to the GBFS used as additive in slag cement. Its specific surface is more than 350 m^2/kg, some even more than 800 m^2/kg. Nation standard GB18736-2001, *Mineral Admixture for High-Performance Concrete (HPC),* regulates the properties of GGBFS, which can be used in HPC. When used in concrete, it make concrete has good workability, high strength, and good durability. GBFS is a kind of industry waste. Through advanced processing technology, the material turns into GGBFS, which can act as an economical and ecological resource for modern concrete. Research, production and application of GGBFS in HPC promote the comprehensive utilization of slag into a new stage in China.

2. Influence of GGBFS on the Effect of Superplasticizer

2.1. Materials

- GGBFS: S1 (350 m^2/kg), S2 (450 m^2/kg), S3 (550 m^2/kg), produced by Wuhan Iron & Steel Group Co.
- Cement Q: 42.5 portland cement, Jidong Cement Company
- Cement W1: 70%Q + 30%S1
- Cement W2: 70%Q + 30%S2
- Cement W3: 70%Q + 30%S3
- Superplasticizer:
  - BW (naphthalenesulfonic acid based admixture)
  - SM (sulfonated melamine formaldehyde based admixture)

2.2. Influence of GGBFS on absorption to admixture

Absorption of cement Q, W3, slag S1 and S3 were tested. W/S = 5, and admixture concentration is 2 g/L. The initial absorption volume and the admixture concentration after 1 hour are list in Table 1.

Apparently, the absorption of slag S1 and S3 to BW and SM are both smaller than cement Q. If the content of admixture is fixed, there would be much more superplasticizer to disperse the cement particle when use GGBFS to replace part of cement. That is to say, absorption of cement particle to superplasticizer will be larger.

Table 1: Absorption of cement and slag to admixture

	Initial absorption (mg/g)		Concentration of admixture after 1 hr (g/l)	
	BW	SM	BW	SM
Cement Q	3.25	5.3	0.58	0.29
CementW3	3.12	4.4	0.62	0.42
Slag S1 (350)	2.61	2.14		
Slag S3 (550)	2.80	2.38		

2.3. Influence of GGBFS on ζ- potential between cement particles

The repulsion between cement particles can be expressed in ζ-potential of cement particles. We tested ζ-potential of a series of cement paste that included slag. The results are in Table 2.

Table 2: Influence of GGBFS to ζ-potential (mv)

	Admixture	
	BW	SM
Q	-37.25	-35.63
Q + 10%S1	-40.46	-38.67
W1 (Q + 30%S1)	-42.49	-42.11
Q + 50%S1	-46.52	-47.19
W2	-42.93	-42.91
W3	-43.38	-43.54

With the increase of specific surface and content of the GGBFS, the ζ-potential increases apparently. That means that the repulsion between cement particles increases too at that case. This is one of the reasons that GGBFS can improve workability of concrete.

Influence of specific surface of GGBFS on paste workability is expressed in Figs. 1 and 2. Influence of GGBFS content on paste workability is expressed in Figs. 3 and 4.

From the four mentioned figures, we can find that: when add GGBFS (10%-30%) into cement, the saturation dosage of superplasticizer changes a little, the flow of cement paste improves and the loss of flow decrease at the recommended dosage of the two superplasticizers. When the specific surface of GGBFS changes from 350 to 550 m^2/kg, the saturation dosage of superplasticizer is almost the same, the flow of cement paste improves and the loss of flow decrease.

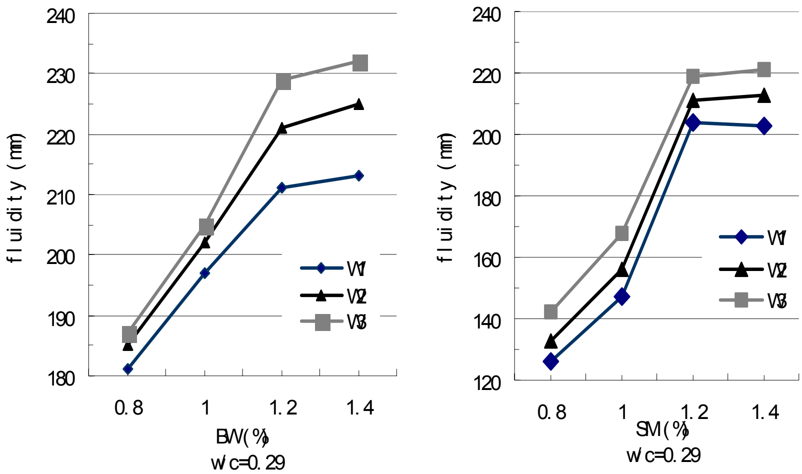

Fig. 1: Influence of slag fineness to solution dosage of admixture

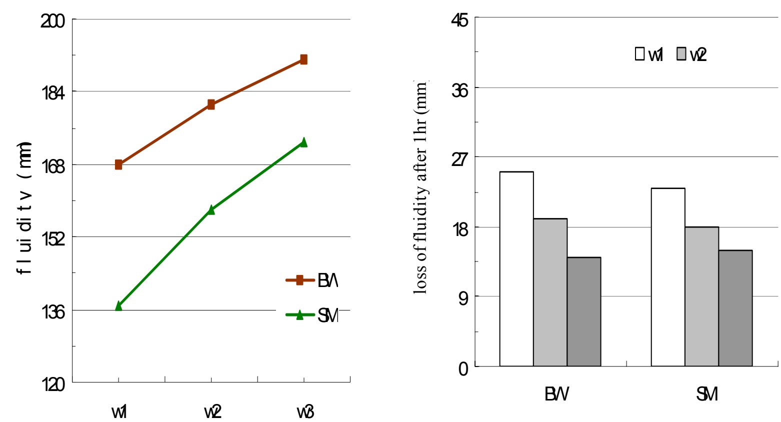

Fig. 2: Influence of slag fineness to flow and flow loss of cement past

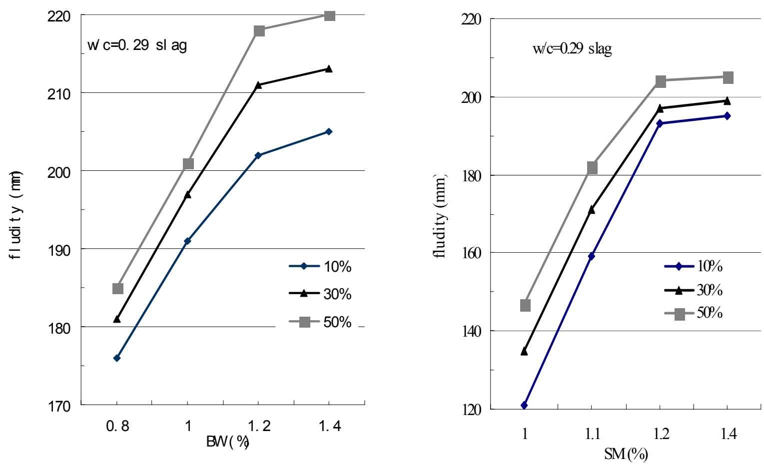

Fig. 3: Influence of slag content to solution dosage of admixture

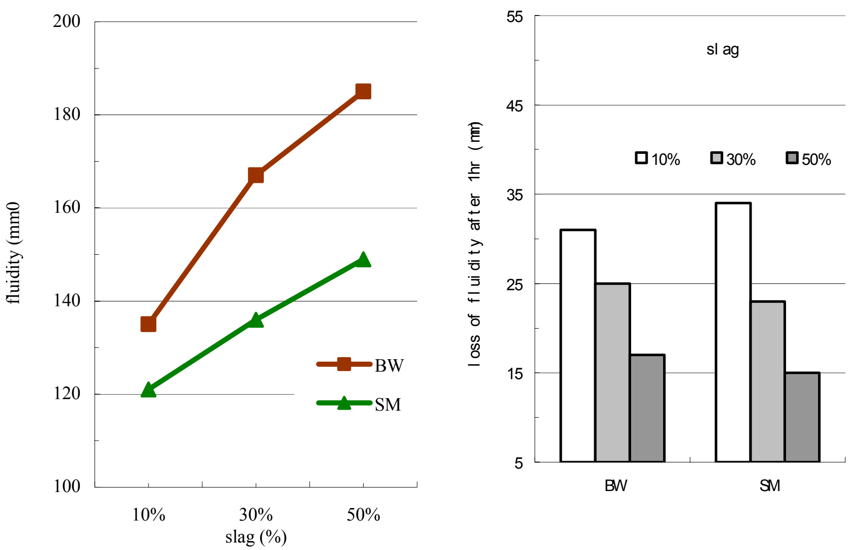

Fig. 4: Influence of slag content to flow and flow loss of cement past

3. Application of GGBFS in High-Strength HPC

If the specific surface of GGBFS is grinded to 500-800m^2/kg, it shows very different properties with lower fineness slag (<400 m^2/kg). High specific surface slag can replace 20%-50% cement to mix high strength concrete (>C60). When it adds into concrete, workability and strength of concrete will change a lot.

3.1. Materials

- GGBFS: specific surface 400, 500, 700, and 800m^2/kg, produced by Wuhan Iron & Steel Group Co.
- Cement: 42.5 portland cement, Jidong Cement Company
- Superplasticizer: JB-1 (naphthalenesulfonic acid based admixture)
- Sand: Mx = 2.9
- Stone: 5-20-mm gravel

3.2. Test results

Typical mix proportion of high strength HPC and the properties are in Table 3.

Table 3: Mix proportion (kg/m^3) and properties of high strength HPC

No.	Cement	Slag (m^2/kg)				Water	Stone	Sand	Admixture (%)	Slump (cm)	Compressive strength (MPa)			
		300	500	700	800						3d	7d	28d	60d
1	500	–	–	–	–	150	1085	665	1.3	23.0	56.4	60.0	70.7	74.1
2	350	150	–	–	–	150	1085	665	1.3	22.0	61.5	70.0	79.5	84.3
3	350	–	150	–	–	150	1085	665	1.3	23.0	64.7	74.2	81.3	84.1
4	350	–	–	–	150	150	1085	665	1.3	23.0	76.7	88.3	93.6	99.0
5	600	–	–	–	–	150	1134	610	1.5	22.5	63.0	71.2	81.1	–
6	480	–	–	120	–	150	1134	610	1.5	24.0	65.6	79.9	93.0	–
7	420	–	–	–	180	150	1134	610	1.5	24.5	69.3	83.2	100.4	–

From Table 3, we can see that strength of concrete at each age increase with the increase of GGBFS fineness when the substitute contents are the same. Control the cementitious materials to 500 kg/m^3, compressive strength of 3 and 28 days are increase 9% and 12%, respectively, when using GGBFS of 400 m^2/kg; and in the meantime the compressive strength of 3 and 28 days are increase 35% and 32%, respectively, when using GGBFS of 800 m^2/kg. At very early age, the very fine GGBFS acts as assistant cementitious in concrete, it has *pozzuolana role*. On the other hands, GGBFS grain has a *filling role,* which can improve the hydration structure, the strength, and the durability of HPC.

4. Application of GGBFS in Middle-Strength HPC

Research on HPC in China is different to most of the European countries. It is believed that the range of HPC cannot be restricted only in high strength concrete. To make the C30-C50 concrete, high performance is also a focus of HPC research in China. Proportion of concrete of C10-C25, C30-C50, and C55-C75 are 31.6%, 67.1%, and 1.3%, respectively, in Beijing in the second quarter in 2003. Situation in the other province in China is almost the same. C30-C50 concrete is almost 70% of all concrete output.

Slag in C30-C50 concrete should not have very high specific surface due to cost and economy reason. GGBFS with 350-500 m^2/kg is very appropriate.

4.1. Materials

- GGBFS: specific surface 450 m^2/kg, produced by Shougang Group Corporation
- Cement: 42.5 portland cement, Beijing Cement Company
- Superplasticizer: TK-1 (naphthalenesulfonic acid based admixture)
- Sand: $M_x = 2.9$
- Stone: 5-25-mm gravel

4.2. Test results

The fresh and hardened concrete properties of GGBFS concrete (C30-C50) were tested and illustrated in Figs. 4-6. Strength of concrete with different slag content is according to substitute content and water cementitious ratio. When the substitute content is higher, the early strength is lower, but the 28- and 60-day strength is almost the same.

Table 4: Influence of GGBFS to compressive strength of middle strength HPC (cementitious materials 390 kg/m^3, W/B = 0.46)

	Compressive strength (MPa)			
Substitute content of GGBFS (%)	3d	7d	28d	60d
45	19.8	30.6	53.8	60.5
50	18.3	29.8	53.3	56.5
55	18.0	29.4	51.9	60.7
60	17.0	29.4	50.6	56.2
65	14.7	28.1	49.2	53.8

Table 5: Influence of GGBFS to compressive strength of middle strength HPC (cementitious materials 438 kg/m3, W/B = 0.40)

	Compressive strength (MPa)			
Substitute content of GGBFS (%)	3d	7d	28d	60d
45	27.2	36.1	57.3	67.4
50	26.6	35.5	58.9	63.5
55	25.8	35.0	58.0	66.4
60	24.1	34.0	56.5	64.4
65	23.8	32.6	57.8	68.0

Table 6: Influence of GGBFS to compressive strength of middle strength HPC (cementitious materials 500 kg/m^3, W/B = 0.35)

	Compressive strength (MPa)			
Substitute content of GGBFS (%)	3d	7d	28d	60d
45	34.4	45.6	65.6	73.6
50	31.	43.8	67.6	72.3
55	30.9	44.7	68.0	71.8
60	28.7	40.9	64.4	76.3
65	28.6	41.6	61.8	75.4

Curing temperature is a key factor of strength of slag concrete, especially to the early strength. If the temperature is raised, strength at 1 day may be bigger than reference concrete. So curing of GGBFS concrete should be controlled under fit temperature and wet condition. GGBFS concrete is more sensitive to curing condition than Portland cement concrete. Due to lower hydration rate of slag, curing time should be prolonged than portland cement concrete.

GGBFS HPC is an important breakthrough to traditional concrete in China. It is characterized by energy savings, cement savings, low cost, environmental protection, and environmental and social benefits as well as economic profit. This kind of new building material can be called green concrete. It has good properties and its application should be more widespread.

STUDIES ON SMALL IONIC DIFFUSIVITY CONCRETE

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Abstract

Many results of systematic analyses of concrete deterioration in marine environment show that nearly all deteriorations are concerned with the ionic diffusion. In order to increase its life-serving, concrete materials in marine environment should satisfy the mechanics qualities required by structural design, but also be a kind of small-ionic-diffusivity concrete (SIDC). In this paper, one kind of SIDC had been manufactured by means of the compounding of mineral admixture and high effective water reducer. The results of experiments indicate that the addition of mineral admixture decreases greatly the speed of ionic diffusion. The effective chloride diffusion coefficient of the SIDC can be lowered two orders of magnitude compared to control concrete. Furthermore, the relative expansion ratio of concrete with the compound of fly ash and micro silicon is only 53.9% of that of control concrete in ASTM C1012-95A at the 54th week.

The composition and microstructure of SIDC had been studied in this paper. It is shown by tests that the addition of mineral admixture leads to the thinning of pore size of cement paste, reduction of unfavorable crystal phase and increase of chloride ion binding, which result in the improvement of anti-ion diffusion character of SIDC.

1. Introduction

The engineering quality and theoretical study of marine and coastal concrete materials are the foundation to improve service life of the marine engineering projects as well as coastal buildings. Many results of systematic analyses of concrete deterioration under multiple corrosion-factor effect show that nearly all deteriorations are concerned with the ionic diffusion. Chloride diffusion and sulfate attack are without question two main deteriorating factors concerned with the ionic diffusion. The chloride-induced corrosion can cause significant deterioration of reinforced concrete structures, resulting costly repair [1]. On the other hand, in many regions of the world, soil and water contain adequate sulfate to cause deterioration of structure concrete [2]. For this reason, the development of high-performance concrete with capability of resisting chloride diffusion and sulfate attack has been the subject of research for many years.

In order to enlarge its service life under multiple corrosion-factor effect, concrete materials should satisfy the physical mechanics qualities required by structural design, but also have a good resistance to all kinds of ions [3]. This is to say, it should be a kind of small-ionic-diffusivity concrete (SIDC). In former papers, mineral admixtures such as fly ash, slag, and silica fume had been incorporated into the mixes to increase concretes' resistance to chloride diffusion or sulfate diffusion. However, the information on its influence on chloride diffusion and sulfate diffusion in concrete is scarce.

In the present paper, the resistance to chloride diffusion and sulfate diffusion for different concrete mixes with and without mineral admixtures was studied. The composition, structure and the influence on durability of SIDC had been studied by means of SEM, MIP, etc.

2. Raw Materials and Experimental Procedure

2.1. Raw materials

Cement used in this test was ASTM Type 1 portland cement (OPC) with a relative density of 3.15 and fineness of 350 m^2/Kg. The loose density of silica fume adopted was 0.2 g/cm^3 with average size of 0.4 μm. The chemical admixture adopted in the study was FDN. The coarse aggregate used was crushed limestone with a maximum size of 20 mm. The fine aggregate used was natural river sand with a fineness modulus of 2.8. The compositions and specific surface area of cement and mineral materials were showed in Table 1. The spectrum of fly ash A and B were shown in Figs. 1 and 2.

Table 1: Chemical component and specific surface area of cement and mineral admixtures

Chemical component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	R_2O	IL	BET surface area (m^2/Kg)	Blaine specific surface area (m^2/Kg)
Cement	21.47	5.80	4.04	56.64	3.24	2.08	0.54	2.44	1162	350
Fly ash A	49.99	37.12	3.06	3.38	0.52	0.67	0.56	3.12	2617	510
Fly ash B	50.61	23.43	14.61	1.17	0.72	0.91	1.10	3.87	5662	480
Slag	28.48	12.56	1.56	39.50	7.40	8.48	0.64	0.50	/	430
Silica fume	90.54	0.77	1.77	0.33	1.68	0.40	1.70	2.78	/	2000

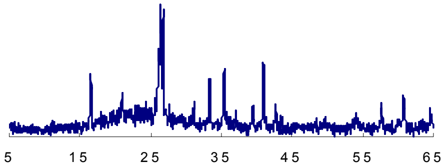

Fig. 1: XRD spectrum of fly ash A

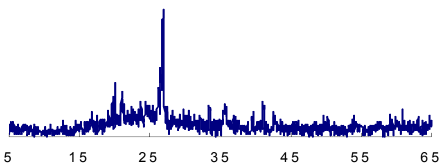

Fig. 2: XRD spectrum of fly ash B

2.2. Experimental procedure

The studies designed nine mixes. Details of mixes were showed in Table 2. Every mix contained nine 100*100*100-mm cubic specimens, three Φ100*100-mm cylindrical specimens, and three 75*75*280-mm prism specimens. Compressive tests were carried out on 100*100*100-mm cubic specimens at age of 7, 28, and 90 days.

The chloride diffusion test was carried out according to the diffusion tank test [4]. Three cylindrical specimens were used to prepare Φ100*20-mm slice specimens for the chloride diffusion test by cutting out the central part of the specimens. The resistance to chloride diffusion was evaluated with the amount of chloride penetrating through concrete slice.

The 75*75*280-mm specimens immersed in 5% Na_2SO_4 solution were used to do the sulfate attack experiment. The expansion values of specimens are used to assess concretes' resistance to sulfate attack according to ASTM C1012-95A.

The scanning electron microscope (SEM) image was observed by SX-40 SEM. Cumulative pore size distributions were obtained by mercury intrusion using an automatic scanning porosimetry (9420)

Table 2: Mixture of concrete

Sample	OPC	Water	Fly ash A	Fly ash B	Slag	MS	F-agg	C-agg	FDN
A	1	0.4					1.844	2.666	1%
B	1	0.5	0.25				1.844	2.666	1%
C	1	0.6	0.5				1.844	2.666	1%
D	1	0.5		0.25			1.844	2.666	1%
E	1	0.6		0.5			1.844	2.666	1%
F	1	0.48			0.25		1.844	2.666	1%
G	1	0.56			0.5		1.844	2.666	1%
H	1	0.54	0.25			0.1	1.844	2.666	1%
I	1	0.52	0.25			0.05	1.844	2.666	1%

3. Experimental Results and Discussion

3.1. Compressive strength

The compressive strengths of concrete at ages of 7, 28, and 90 days were shown in Fig. 3. It can be observed from the figure that there is some decrease in the early age strengths of concretes mixed with mineral admixtures. But at the age of 90 days, the compressive strengths of mixes with mineral admixture nearly reach the compressive strengths of the control mix (mix A) except mixes with the addition of 50% fly ash, even exceed that of the control mix.

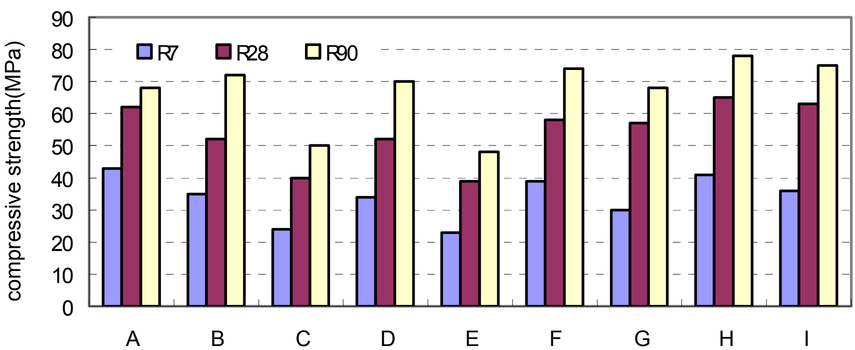

Fig. 3: Compressive strengths of concrete at various stages

3.2. Resistance to chloride diffusion

The amounts of chloride penetrating through various concrete slices were shown in Figs. 4-7. As shown in Fig. 4, the chloride-ion concentrations of mix B and mix C are much lower than those of mix A during the test period of 1 year. Except the inclusion of fly ash A, all other ingredients in mix B and mix C and mix A are the same. This indicates that some amount of fly ash A in concrete can improve obviously the concrete resistance to chloride diffusion. Results shown in Fig. 5 indicated that some addition of fly ash B can also improve the resistance to chloride diffusion. But the effect of fly ash B is lower than that of fly ash A. It may be relate to high content of aluminum of fly ash A.

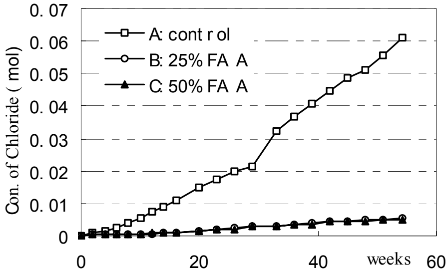

Fig.4 Comparison of mixes B, C and A

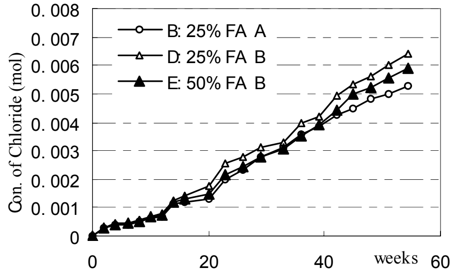

Fig.5 Comparison of mixes D, E and B

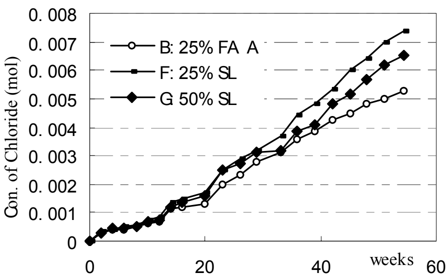

Fig.6 Comparison of mixes F, G and B

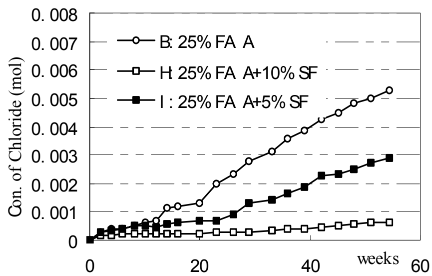

Fig.7 Comparison of mixes B, H and I

Concentrations of chloride ions penetrated through species containing various additions of slag and fly ash A were shown in Fig. 6. As slag was added into the concrete, the chloride-ion concentrations decreased. It shows that addition of slag can improve concrete resistance to chloride diffusion. In the range of 25%-50% by mass of cement, the improvement of slag increases with the dosage of slag increasing.

The influence of microsilica (MS) in combination with fly ash on chloride diffusion can be evaluated by comparing chloride-ion diffusion concentration of set H, I, and B, shown in Fig. 7. Fig. 7 indicates that the mixes' resistance to chloride diffusion is improved by addition of microsilica, and this improvement is increased as more microsilica is incorporated.

As shown in Figs. 4-7, the curve of chloride concentration became linear after a certain time about 33 weeks. That is to say, the chloride diffusion had reached a steady state at that time. According to Fick Rule, the diffusion coefficient of concrete can be calculated in steady state [3]. The calculated diffusion coefficients of mixes were shown in Table 3. Table 3 indicates that the diffusion coefficients of mix B and D are, respectively, 7.7% and 11.1% of that of mix A, which means 25% addition of fly ash by mass of cement improves greatly resistance to chloride diffusion. As fly ash combined with microsilica, the improvement is more obvious. The diffusion coefficient of mix H is only 0.84% of that of mix A, reduced two orders of magnitude. Table 3 also shows that the improvement of slag isn't higher than that of fly ash.

Table 3: Chloride diffusion coefficients

Mix	Linear equation of 33rd-54th week chloride concentration	R^2	$D_{eff}\times10^{-10}$ (cm^2/s)
A	$Y=13.16\times10^{-4}X—108.95\times10^{-4}$	0.9966	110.87
B	$Y=1.13\times10^{-4}X—4.32\times10^{-4}$	0.9699	9.52
C	$Y=0.99\times10^{-4}X—1.28\times10^{-4}$	0.9617	8.34
D	$Y=1.46\times10^{-4}X—13.92\times10^{-4}$	0.9858	12.30
E	$Y=1.29\times10^{-4}X—10.22\times10^{-4}$	0.9770	10.87
F	$Y=1.56\times10^{-4}X—15.82\times10^{-4}$	0.9841	13.14
G	$Y=1.36\times10^{-4}X—11.12\times10^{-4}$	0.9791	11.46
H	$Y=0.11\times10^{-4}X + 0.28\times10^{-4}$	0.6645	0.93
I	$Y=0.73\times10^{-4}X—10.16\times10^{-4}$	0.9568	6.15

3.3. Resistance to sulfate attack

In this study, the relative expansion values of all specimens immersed in 5% sulfate solution were measured for one year. In Table 4, the measured results indicate that 25% addition of fly ash A, fly ash B and slag by weight of cement all improve sulfate resistance of concrete. The improvement of slag is the best among three mineral admixtures, and the relative expansion value of mix F with 25% addition of slag is only 65.4% of the relative expansion value of mix A at the 54th week. As the dosage of admixtures reach 50% weight of cement, the improving effect of all mineral admixtures have a certain degree of decline. The mix with slag has the least decline among all mixes with 50% mineral admixture by weight of cement. The reason is maybe that the expansion of concrete is related to the strength of concrete at a certain degree. As the mixes have upper strength and same permeability, mixes of upper strength can't easily display their expansion relative to mixes of lower strength.

Table 4: Expansion ratios of mixes under sulfate attack at 54th week

	A	B	C	D	E	F	G	H	I
Expansion ratio (%)	0.0573	0.0394	0.0412	0.0429	0.0438	0.0375	0.0381	0.0309	0.0379

In addition, the addition of 25% of fly ash in combination with 5%-10% of microsilicon reduces greatly the relative expansion ratios. Mix H compounded with 25% of fly ash and 10% of microsilicon has the least expansion values at every measuring time in one year. At the 54th week, the relative expansion value of mix H is only 53.9% of the relative expansion value of mix A. It is necessary to point out that the mixes with the incorporation of fly ash and microsilicon also have upper resistance to chloride diffusion. It can be concluded that incorporation of combination of fly ash and microsilicon is one of the best ways to achieve a superior resistance to ion diffusion.

3.4. Analysis of micropore structure

The volume of pores in hardened cement paste decreased greatly with the hydration of clinker. During the course, the structure of the paste becomes more and more dense; however, the various sizes of pores exist at all hydration ages, such as large spherical pores, capillary pores, micro pores and gel pores. The effect of large spherical pores and capillary pores on the strength and permeability of hardened cement paste is higher [5].

In this study, the incorporation of mineral admixture into mixes obviously improved the resistance to ion diffusion. To study the mechanism of the improvement, the mercury intrusion porosimeter test was carried out with samples from mix A and B at the age of 3 and 90 days. The results are shown in Figs. 8 and 9. In Fig. 8, it can be observed that the volume of pores whose diameters vary from 20 nanometers to 90 nanometers in sample B is lower than that in sample A at the age of 3 days. It demonstrates that the addition of fly ash increases the pile compaction of cement particles and fly ash particles in mix B. In Fig. 9, with the hydration of clinker, we can see that the structure of the paste becomes more and more dense. Another observation is that the pore ratio and diameter in group b are lower than those in group A at the age of 90 days. The addition of fly ash thins the pore size of cement paste. It seems that the change of pore ratio and diameter caused by the addition of mineral admixtures leads to the improvement in the resistance to ion diffusion.

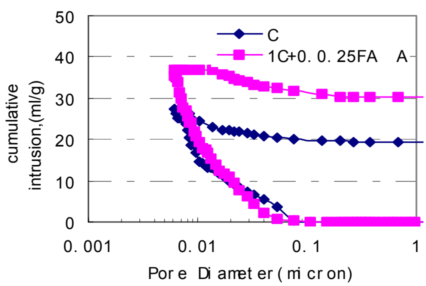

Fig.8: MIP results for the different pastes at 3 days

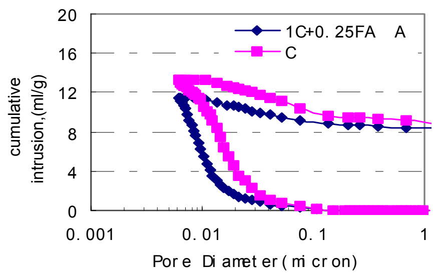

Fig.9: MIP results for pastes at 90 days

3.5. SEM analysis of hydrated structure and raw materials

3.5.1. SEM images of hydrated structure

Figs. 10-11 and Figs. 12-13 are, respectively, SEM images of pure cement and cement in combination with 25% fly ash A at the age of 90 days. It was shown in Figs. 10-11 that main hydrate productions of pure cement are C-S-H (gel) and a few $Ca(OH)_2$. From Figs. 10 and 12, it can be observed that they don't have obvious difference between micro structures of sample A and sample B except that there are some fly ash particles in various diameters in sample B and some of them had reacted with $Ca(OH)_2$. Fig. 13 shows the inner hydrate productions and outer hydrate productions of fly ash. The

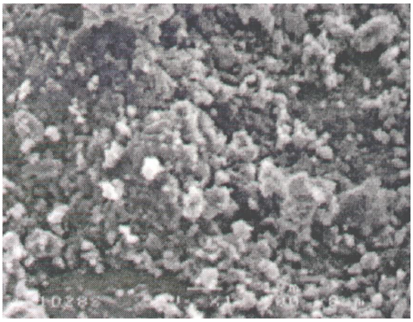

Fig.10: SEM images of Sample A(1000×)

pozzolanic reaction increases the permeability of concrete and decreases the content of unfavorable crystal phase. What's more, the second hydration reaction improves the bond of particles. Especially, the decrease in the content of unfavorable crystal phase directly reduce reagent of sulfate attack. All of those are helpful to improve the resistance of concrete with mineral admixture to ion diffusion.

Fig. 14 is SEM image of slice specimen of sample B, which was taken after the chloride diffusion test. In Fig. 14, it's demonstrated that C-A-H had reacted with chloride ion and formed "Friedel salt" (chloroaluminate crystals). The chloride had been bound into hydrate productions, which decreased the pace of chloride ion diffusion. It is maybe the reason why the improvement of fly ash A in the resistance to chloride ion diffusion is better than that of fly ash B.

Fig.11: CSH and $Ca(OH)_2$ in sample A (10000×)

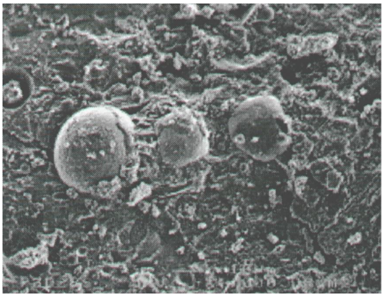

Fig.12: SEM images of sample B (1000×)

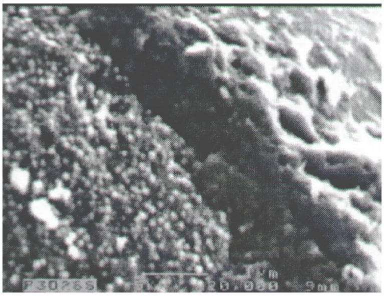

Fig. 13: Hydrating surface of fly ash particle in sample B (20000×)

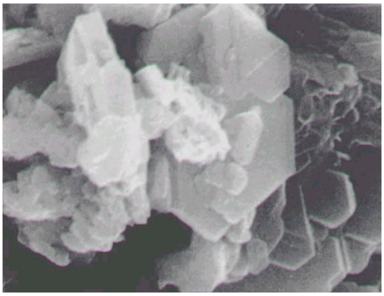

Fig. 14: Micrograph of chloroaluminate crystals (6800×)

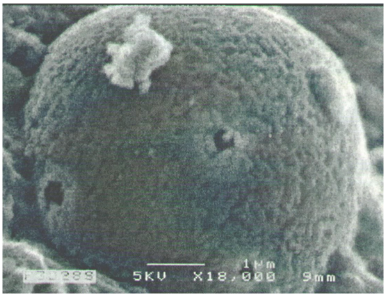

Fig.15: Air pores and absorption products on the surface of fly ash particle (18000×)

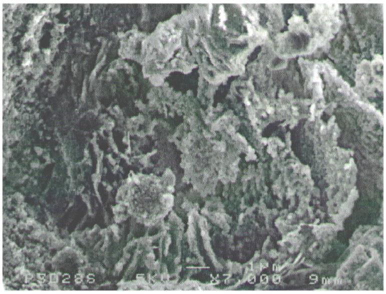

Fig.16: Inner structure of fly ash particle (7000×)

3.5.2. SEM images of fly ash

In the current paper, the addition of fly ash obviously improved the resistance to chloride ion diffusion. The effect of fly ash is even better than that of slag. To study the mechanism of the phenomena, the SEM test was carried out with the microstructure of fly ash A. Figs. 15-16 are SEM images of fly ash A. It's demonstrated in Figs. 15-16 that the particles of fly ash are mostly spherical particles and have complex inner surface structure. That BET surface area of fly ash is far larger than that of cement (in Table 1) also proves that fly ash has complex inner surface structure. In Fig. 8, it' s shown that much mercury was remained in concrete in MIP test. It also testifies that there are many non-connected pores in fly ash. The complex inner surface and non-connected pores have the function of absorbing chloride ion. It's helpful to decrease the speed of chloride ion diffusion.

4. Conclusions

The following conclusions could be obtained based on the test results of this study:

- The addition of mineral admixtures decreases the compressive strengths of concrete at the early age. But at the age of 90 days, the compressive strengths of mixes with mineral admixture nearly reach that of the control mix, even exceed that of the control mix.

- The additions of mineral admixtures such as fly ash, slag and microsilicon, improve greatly the concrete resistance to ion diffusion. Especially, the addition of 25% fly ash in combination with 10% microsilicon by weight of cement can reduce the chloride diffusion coefficient two orders of magnitude compared to control concrete, and also decrease the relative expansion ratio to 53.9% of control concrete in ASTM C1012-95A. It can be concluded that incorporation of combination of fly ash and microsilicon is one of the best ways to achieve a superior resistance to ion diffusion.
- The addition of mineral admixtures leads to the thinning of pore size of cement paste, compact of hydration productions phase and reduction of unfavorable crystal phase. All of those result in the increase of the resistance to ion diffusion.
- The improvement of fly ash in the resistance to chloride diffusion is better than that of slag, while the improvement of slag in the resistance to sulfate diffusion is better than that of fly ash.
- The inner surface structure and the non-connected pores of fly ash have the function of absorbing chloride ion, which is helpful to decrease the speed of chloride ion diffusion.
- C-A-H can react with chloride ion and form “Friedel salt” (chloroaluminate crystals). It is maybe the reason why the improvement of fly ash A in the resistance to chloride ion diffusion is better than that of fly ash B.

Acknowledgments

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References

1. Berke, N.S., D.W. Pfeifer, and T.G. Weil. "Protection Against Chloride-Induced Corrosion." *Concrete International* 10(12), December 1988, pp. 45-55.
2. Metha, P.K. "Effect of Fly Ash Composition on Sulfate Resistance of Cement." *ACI Materials Journal* 83(6), November-December 1986, pp. 994-1000.
3. He Xingyang. "Research on small ionic Diffusivity Concrete." Dissertation, Wuhan University of Technology, Wuhan, 2001 (in Chinese).
4. Zongjin Li, Jun Peng, and Baoguo Ma. "Investigation Chloride Diffusion for High-Performance Concrete Containing Fly Ash, Micro silica and Chemical Admixtures." *ACI Materials Journal* 96(3), May-June 1999, pp. 391-396.
5. Powers, T.C., and T.L. Brownyand. "Studies of physical properties of hardened portland cement paste" (nine parts). *Proceedings ACI*, Vol. 43, October 1946.

STUDY ON REACTIVE POWDER CONCRETE USED IN THE SIDEWALK SYSTEM OF THE QINGHAI-TIBET RAILWAY BRIDGE

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Abstract

The Qinghai-Tibet railway lies in the west area of China at an altitude of more than 4,000 meters. The 576-km railway is being built on frozen earth. The bad climate and sandstorms of the tundra require the concrete of the bridge to have superior mechanical properties and high durability. By adding portland cement, silica fume, superfine fly ash, and superplasticizers, reactive powder concrete (RPC) is used in the sidewalk systems of bridges with compressive strength of 160 MPa. The research shows that RPC has high strength, excellent frost durability, and impermeability. Therefore, RPC is the best choice for the Qinghai-Tibet railway.

1. Introduction

The Qinghai-Tibet railway lies in Qinghai-Tibet plateau in the west area of China, at an altitude of more than 4,000 meters and in a high intensity earthquake region. The 576-km railway is being built on frozen earth. The climate conditions are harsh in that area: low air temperature, concentrated rain and snow, and heavy sandstorms. The area also has complicated geology conditions, and groundwater causes corrosion. The conditions mentioned above require the concrete used for the bridges to have superior mechanical properties and high durability.

As the subsidiary facility of the railway bridge, the sidewalk system needs to support the load from the passersby and from some small machines and equipment for maintenance of the bridge. The traditional sidewalk system of the railway bridge is composed of angle steel brackets and a concrete flat. The traditional sidewalk system will be prone to be out of order due to low durability of concrete and angle steel bracket and thus needs a great deal of maintenance to keep it in service. Therefore, it is not suitable for the bridges in the Qinghai-Tibet region. A new type of sidewalk system with low weight and high durability is needed for the Qinghai-Tibet railway. To adapt to severe conditions on the Qinghai-Tibet plateau and to meet the requirements of railway developments, reactive powder concrete (RPC) has been developed by the common production process workflow with national material in this research. RPC has high strength and high durability, including excellent impermeability of chloride and frost-resistance. At the same time, the structure members of sidewalk system for the Qinghai-Tibet railway, including flats, brackets, and rails, have been manufactured.

2. Material and Mechanics Function of the Reactive Powder Concrete

2.1. Material preparation

This research concerns $42.5^{\#}$ portland cement, active mineral powder, including high-quality silica fume whose ratio surface exceeds 200,000 cm^3/g, low-need water superfine fly ash, superplasticizers that have good compatibility with cement, whose rate of reducing water is above 32 percent, and quartz sands whose grain size are 0.16 to 0.315 mm, 0.315 to 0.63 mm, 0.63 to 1.0 mm, and that make up the most close-grained preparation. It is detected that grain size of the two materials is very different, and they form discontinuous preparation in the course of arranging cementitious property and aggregates. Therefore, higher mineral powder whose grain size is between cementitious properties and aggregates has been produced.

2.2. Methods of experiment and equipments

The test of concrete compressive strength, elastic modulus, and bending strength is carried under the guidance of "methods of experiment for mechanics function of common concrete." The size of specimens is 100×100×100 mm, 100×100×300 mm, and 100×100×400 mm. However, the velocity of increasing load of compressive strength has been changed to 10 kn/s.

The equipment used for this experiment includes a SJD-30 compelling concrete agitating machine, a high frequency concrete vibrating table, a BYS-3 automatic temperature control instrument, a HJ-84 concrete accelerating cure box, a 3,000-kn electronic hydraulic pressure machine, a 1,000-kn electronic hydraulic universal testing machine, an agitating sand testing machine, an and elastic modulus testing machine.

2.3. Mechanics function of the reactive powder concrete

In order to study the influence of the different mixture ratio on the RPC material function, the following has been studied: the influence of w/b ratio, admixture of mineral additive, compounding between different preparation aggregates and cementitious property, admixture of additive, admixture of steel fibers, curing temperature, and curing system. Through hundreds of mixture ratio experimentation, the optimal mixture ratio, whose w/b ratio is 0.16, whose curing temperature is 75°C, and whose mechanics function, is confirmed on the basis of routine agitating and moulding technology. It is known that concrete's 28-day compressive strength is 168.6 MPa, bending strength is 20.6 MPa, and elastic modulus is 46.8 Gpa, as shown in Table 1.

Table 1: Experimentation result of the optimal mixture ratio

	Compressive strength (MPa)		Bending strength (MPa)		Elastic modulus (GPa)	Slump (mm)
	3d	28d	3d	28d		
Result	169.4	168.6	18.4	20.6	46.8	125

3. Durability of Reactive Powder Concrete

In such severe conditions as on the Qinghai-Tibet plateau, the durability, security, and service life of structures will be distinctly reduced due to the reasons such as the initial flaw of the concrete cast in-suite in a low temperature, subjectivity of the concrete to frosting and thawing, and erosion caused by groundwater brine. What is most important for the concrete structures of the Qinghai-Tibet railway is the good frost-resistance and impermeability of chloride. In order to test frost durability and impermeability of chloride of RPC, the experiments have been done according to the experiment method for frost durability and impermeability of chloride of conventional concrete, which can be found in the GBJ 82-85.

Chloride impermeability is the ability of concrete to resist high-pressed liquid such as water penetrating the concrete. The wearing off of concrete, either physical or chemical, is concerned with water penetration. So, impermeability of chloride almost becomes the core problem of durability of most concrete.

3.1. Chloride impermeability

The experiment was done to investigate the chloride impermeability of RPC on six specimens based on optimal mix proportion. There was no water leakage through RPC in the six specimens when hydraulic pressure varies from 0.1 to 1.6 MPa with increase of 0.1 MPa/8h. When hydraulic pressure was taken away, there was only 2.7-mm penetration in a specimen with initial flaw. As a result, the conclusion can be reached that RPC has excellent chloride impermeability, caber-resistance, and corrosion-resistance.

3.2. Frost resistance

The freeze-thaw test was done to investigate frost-resistance of RPC on two series of specimens. These specimens were dropped in 20^{o}C water for 4 days. The size of the specimens used in the experiment was 100×100×400 mm^3. The test temperature for one series of specimens ranged from negative 17^{o}C to negative 13^{o}C, while another from 4°C to 8°C, and every cycle lasted 4 hours. After 800 cycles of freezing and thawing, relative modulus of elasticity of RPC was still 100%, whereas the lost weight ratio was 0, and the durability ratio was 2.67. From the results, the conclusion can be reached that RPC has excellent frost-resistance. Therefore, RPC is more suitable for the bridges of Qinghai-Tibet Railway than conventional concrete.

4. Study on the RPC Sidewalk System

There are a lot of different problems with conventional concrete sidewalks such as corrosion, rust of reinforcing steel bars, and breakability of concrete slab. The steel brackets rust in a conventional concrete sidewalk. As a result, a conventional concrete sidewalk system requires maintenance every year. Dead weight of the traditional sidewalk system is greater than that of the RPC sidewalk system, which makes bridges have a bad dynamic performance. To improve the conventional sidewalk system, RPC sidewalk system has been developed in Beijing Jiaotong University.

An RPC sidewalk system composed of pre-cast slabs, brackets, and rails is assembled in-suite. RPC, based on optimal mixture ratio, meets the design requirements of sidewalk that the compressive strength should be greater than 120 MPa, and the split tensile strength should be greater than 12 MPa. Based on the optimal mix proportion mentioned above, the production process workflow for structural members used for RPC sidewalk system has been studied in a bridge manufacture. The slump of RPC is greater than 180 mm. With an excellent workability, RPC can meet the requirements of construction. The main mechanical properties of RPC samples are listed in the Table 2. At a reliability of 95%, the compressive strength is greater than 7.0 MPa according to qualification test of RPC. Therefore, mechanical properties of RPC can meet the design requirements of the sidewalk system. One pre-cast bracket of RPC sidewalk system is shown in Fig. 1. The sidewalk system made of RPC has such merits as small deadweight, excellent durability, low cost, and minimum maintenance. Thus, RPC is more suitable for the sidewalk system of Qinghai-Tibet Railway than conventional concrete.

Table 2: Main mechanical properties of RPC

Compressive strength (MPa)		Split tensile strength (MPa)		Elastic modulus (GPa)
6d	28d	6d	28d	28d
157.0	147.3	15.0	21.1	48.5

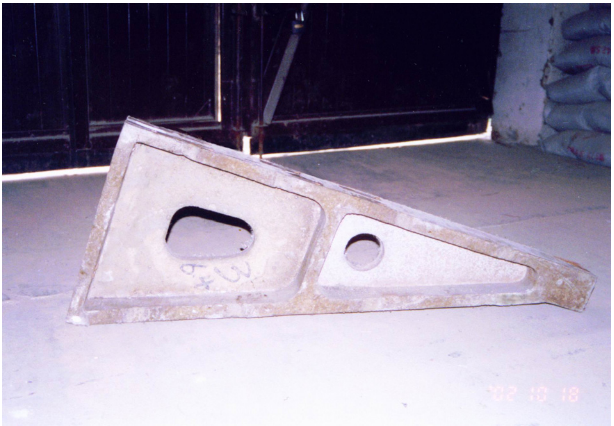

Fig. 1: Pre-cast bracket of RPC sidewalk system

5. Conclusion

The reactive powder concrete produced by routine concrete manufacture techniques has compressive strength above 160 MPa, bending strength above 20 MPa, fine frost resistance, and impermeability of chloride. The sidewalk flat system produced by the reactive powder concrete has light deadweight, low cost, and the littler workload, which makes it suitable for bridge and its subsidiary facilities on the Qinghai-Tibet plateau. Structural members have fine and steady quality and can satisfy the demand of practice production.

THE EFFECT OF FLY ASH ON THE FLUIDITY OF CEMENT PASTE, MORTAR, AND CONCRETE

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Abstract

The addition of ultra-fine fly ash (UFA) to cement paste, mortar and concrete can improve their fluidity, but some coarse fly ash can't reduce water. This paper investigates the effect of fineness and replacement levels of fly ash on the fluidity of cement paste, mortar, and concrete. The fly ash is collected by electro-static precipitators and airflow classing technology. Three different finenesses were chosen, and their replacement levels were 20%, 30%, and 40%, respectively. The experiment results show that particle size distribution, Zeta potential, density and particle morphologies of fly ash are the major factors affecting their fluidity.

1. Introduction

Currently, high-performance concrete (HPC) is widely used due to their technical and economical advantages. Such materials, so called the 21st century concrete, are characterized by improved mechanical and durability properties resulting from use of chemical and mineral admixtures as well as specialized production processes [1-4]. In the modern concrete, active mineral additives, such as fly ash, silica fume and slag, etc., have been the essential component that provides concrete with higher compressive strength, great fluidity, and higher durability. The use of fly ash is accepted in recent years primarily due to saving cement, consuming industrial waste and making durable materials, especially due to the improvement in the quality stabilization of fly ash. Because of these, more and more investigations have been made about their effects on concrete. A popular hypothesis put forward to explain the workability enhancement due to the use of certain fine mineral admixtures, especially fly ash or SF, is that the spherical particles easily roll over one another, reducing interparticle friction [5]. Sakai et al. [6] reported that a higher packing density was obtained with spherical particles as compared to crushed particles in a wet state. This resulted in lower water retention in the spherical case and subsequently lower water demand for a specific workability. A strong dependence of fluidity (defined as the inverse value of the viscosity) on the average particle size was reported with a pessimism value [6]. It was explained that, at an optimal particle size, the packing density was maximum, which helped to achieve maximum fluidity. Previous studies concentrated on the effect of fly ash on the fluidity of concrete [7-8]. In this study, the fly ash is collected by electro-static precipitators and airflow classing technology. The mechanisms are analyzed based on their characteristics such as particle morphology, particle size distribution, specific surface area and density.

2. Materials and Methods

2.1. Materials

The materials used in the presented research are described as the following:

- Cement: Shaofeng 42.5 grade ordinary portland cement made in Xiangxiang
- Fine aggregate: Xiangjiang river sand, fineness modulus 2.88
- Coarse aggregate: Qualified 5-20-mm broken gravel rushed from Xiangjiang river gravel, broken stone being 51%-53%, broken index being 7.7%-8.0%
- Superplasticizer: Naphthalene sulfonic acid-based superplasticizer.
- Ultra-fine fly ash: Collected by electro-static precipitators and airflow classing technology in Xiangtang power plant; Their chemical compositions and properties parameters are given in Tables 1and 2, respectively. Particle morphologies of the fly ashes are given in Fig. 1.

Table 1: Chemical composition of fly ashes used (wt %)

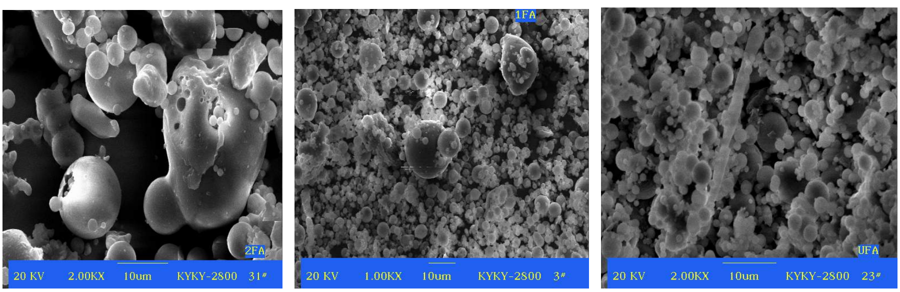
Sample ash	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Cl^-
A	51.7	26.8	4.39	3.4	0.95	1.28	0.65	0.31	0.009
B	49.5	28.6	4.98	3.6	1.02	1.26	0.7	0.27	0.008
C	48.2	30.31	5.57	3.85	1.05	1.34	0.60	0.30	0.009

2.2. Experiments methods

The tests of fluidity of cement paste fluidity of mortar and workability of concrete generally conform to Chinese National Standard GB/T 8077-1987, GB/T 2419-1994, and GBJ80-85 test methods, respectively. In this study, the mortars were prepared at a water-to-binder ratio of 0.30 and sand-to-binder ratio of 1.5, with 20%, 30%, and 40% equivalent replacement of cement by low-calcium fly ash A, B, and C, respectively. The concretes are prepared with three different finenesses fly ash A, B, and C and the equivalent replacement level is 20%, 30%, and 40%. The effect of the addition of FA is expressed by the changes in concrete slump, water demand, or water reducing rate in the concrete.

Table 2: Properties of fly ashes used

Properties		A fly ash	B fly ash	C fly ash
Specific gravity (g/cm^3)		2.111	2.256	2.258
Specific surface area (m^2/kg)	Blaine fineness	370	761	819
	BET	–	1560	2220
	Laser diffraction	1514	2819	3185
Mean particle size (μm)		27.16	9.31	6.05
Water demand ratio (%)		96	93	89
Zeta potential in de-ionized water (mV)		-27.35	-35.57	-80.67
Water reducing rate in concrete (%)		2.1	7.9	9.7



(a) A fly ash (b) B fly ash (c) C fly ash

Fig. 1: SEM of different fineness fly ash

3. Results and Discussion

3.1. Effect of UFA on cement setting time

The initial and final setting time of cement paste containing C fly ash is shown in Fig. 2. When the UFA replacement level is 20%, the initial and final set time of UFA-cement paste was about 9.56 and 11.25 hours, respectively. When the UFA replacement level increased to 40%, the initial and final setting tines of UFA-cement paste are prolonged to about 11.85 and 13.58 hours, respectively. In general, the set time of UFA-cement paste is prolonged with the increase of UFA. The outer surface of UFA particle increase with the increase of UFA, the amount of absorbed calcium ions increased. That inhibits calcium ions concentration build-up in fresh paste during early hydration, resulting in the setting time is prolonged, thus, the heat of hydration decreases.

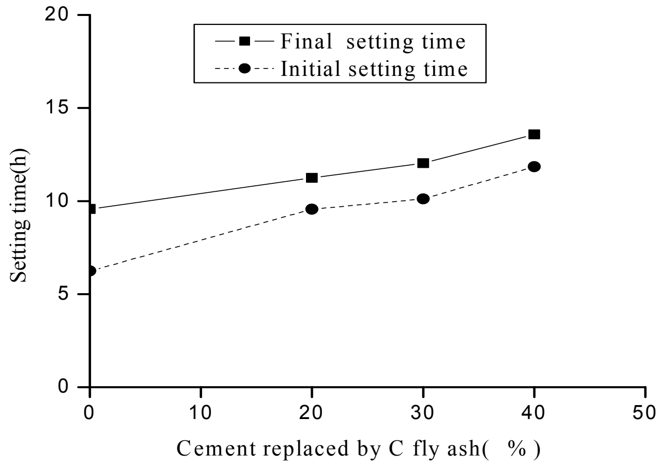


Fig. 2: Relation between the setting time and cement replacement

3.2. Effect of UFA on mortar fluidity

Fig. 3 shows the water demand of mortar containing different finenesses and replacement levels of FA for a given flow, where flow table tests were used. All water demand ratios of FA mortar are lower than 100%, that is, A, B, and C fly ashes all have water reducing function. When the replacement is equal, the water demand ratio of C fly ash is the lowest, B fly ash is the second, and A fly ash is the highest. In general, the finer the cementitious material, the larger surface area the material.

Thus, the more water will be absorbed by the material, that is the negative effect of UFA water reducing. At the same time, the finer fly ash, the more spherical-like fly ash particles morphology, the internal friction in fresh mortar reduce, the better "lubricant effect" fly ash has, on the other hand, the finer fly ash, the better close packing effect fly ash has when it partially replace cement, those are positive effect of UFA water reducing. The increase of positive effect is bigger than that of negative effect when the fineness of fly ash is increased in this study, Consequently the water demand ratio decrease with the increase of fly ash fineness. A fly ash is more porous than B and C fly ash, more water is adsorbed into FA pores. With the replacement level of A fly ash increasing, the water demand ratio decreases a little. When the replacement levels of B and C fly ash are increased from 0% to 30%, the water demand ratio reduce, but when the replacement is increased to 40%, the increase of negative effect of UFA water reducing surpass that of positive effect, the water demand ratio increase slightly. In order to obtain better fluidity, B and C fly ash cannot replace cement too much.

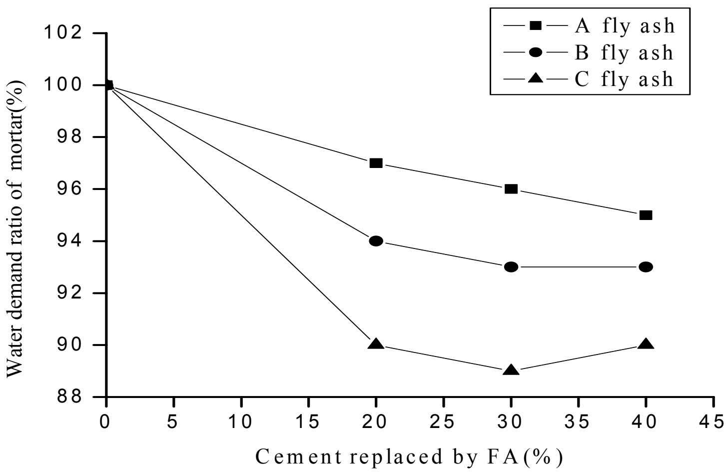


Fig. 3: Effect of FA replacement levels and fineness on water demand ratio of mortar

3.3. Effect of FA on concrete workability

High slump and low slump loss of fresh concrete were considered as an assurance for good concrete casting, vibrating and finishing. Generally, superplasticizer increases concrete slump, but causes high slump loss when compared with the plain concrete having the same initial slump. Because of a low water-to-binder ratio in HPC, when the same amount of water is lost through evaporation or by cement hydration, the slump loss was more significant.

Fig. 4 shows the water reducing rate of concrete containing different finenesses and replacement levels FA when the slump is equal. All fly ash have water reducing effects. When the replacement is 30%, the water rate of A, B, and C fly ash are 2.1%, 7.9%, and 9.7%, respectively. The water reducing rate increases with the level of fly ash replacement. The fly ashes actually function as a kind of mineral water reducers.

The test results of HPC containing C fly ash were presented in Table 3. As to plain concrete, the slump loss after 1 hour is 8.5%, 2 hours is 19.1%, and 3 hours is 36.2%, but the slump loss of concrete containing 30% UFA after 1 hour is 2%, 2 hours is 8.2%, and 3 hours is 10.2%. UFA could not only increase slump and spread, but also reduce the slump loss. First, because UFA can prolong the setting time, which result in decreasing slump loss of concrete, secondly UFA have huge specific surface area which can adsorb some superplasticizer, thirdly the Zeta potential of UFA is negative in de-ionized water.

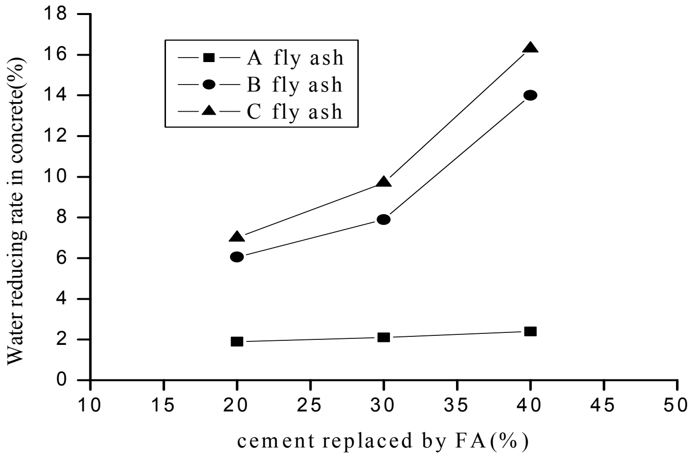


Fig. 4: Effect of FA replacement levels and fineness on water reducing rate

Table 3: Slump loss of concrete containing UFA

Specimen	Mix proportions (kg/m^3)			Slump (mm)			
	UFA	C	W	0h	1h	2h	3h
1	0	540	153	235	215	190	150
2	162	378	151	245	240	225	220
3	216	324	150	250	255	250	245

4. Conclusions

The fly ashes studied were collected by electro-static precipitators and airflow classing technology. Due to their spherical shape and smooth surface features, the fly ashes demonstrated improved water reduction effect with increased fineness. Based on the test results, the following conclusions can be drawn:

- The incorporation of ultra-fine C fly ash may increase the setting time of cement paste.
- The water demand ratio of UFA decrease with the increasing of fineness.
- The water reducing rate of 30% ultra-fine C fly ash reach 10%, ultra-fine C fly ash is a kind of good mineral water reducer.
- Ultra-fine C fly ash has significantly increased the slump and reduced the slump loss of concrete.

References

1. F. Neiqian. *High-Performance Concrete*. China Construction Industry Publishing House, Beijing, 1996.
2. W. Zhongwei. Green High-Performance Concrete: The Trend of Concrete Development. *China Concrete and Cement Products* 99(1), 1998, 3-6.
3. Aitcin P.-C., and Neville A.M. High-Performance Concrete Demystified. *Concrete International* 15(1), 1993, 21-26.
4. Forster Stephen W. High-Performance Concrete Stretching the Paradigm. *Concrete International* 16(10), 1994, 33-34.
5. V.S. Ramachandran. *Concrete Admixtures Handbook, Properties, Science and Technology*. Noyes Publications, Park Ridge, NJ, 1995.
6. E. Sakai, S. Hoshimo, Y. Ohba, and M. Daimon. The Fluidity of Cement Paste with Various Types of Inorganic Powders. *Proceedings of the10th International Congress on the Chemistry of Cement*, Sweden, 1997.
7. Liu Baoju et al. Influence of Ultrafine Fly Ash Composite on the Fluidity and Compressive Strength of Concrete. *Cement Concrete Research* 30, 2000, 1489-14893.
8. Chiara F. Ferraris, Karthik H. Obla, and Russell Hill. The Influence of Mineral Admixtures on the Rheology of Cement Paste and Concrete. *Cement Concrete Research* 31, 2001, 245-255.

RESEARCH OF HIGH FLY ASH CONTENT IN CONCRETE WITH DIPY CONSTRUCTION FORMWORK

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Abstract

This paper reports the research and application of high fly ash content concrete (HFCC) with Dipy construction formwork. Concrete construction using Dipy construction formwork can skip the processes of form stripping and concrete vibration. According to the research of the working principle of concrete with Dipy construction formwork, it can be found that cement paste composed of high fly ash content exudes out from the inner of the concrete wall. This process can reduce the air bubbles and then improve the compactibility of concrete. To improve the strength, durability, and carbonation resistance of the high fly ash content concrete, the DG-II fly ash activating agent has been developed and researched.

The test specimens are cored from nine concrete walls, which are different in mixing proportions. The research program consists of comparing the compactibility, compressive strength, and durability of concrete cores. Research program results show that, with the effect of DG-II fly ash activating agent, while the replacement of fly ash increase up to 50%, the strength of HFCC with Dipy construction formwork is at the same level as that of ordinary concrete. DG-II fly ash activated agent can improve the durability of HFCC with Dipy construction formwork to some extent.

1. Introduction

High fly ash content concrete (abbreviated as HFCC) is widely researched and applied recently in China. As to the concept of HFCC, it was advanced by Prof. Davis early in 1954. Owing to the invention of fly ash activator and the improvement of computation method of fly ash concrete proportion such as the method of fly ash cementitious coefficient, the early strength and carbonation resistance of HFCC has been enhanced a lot.

Concrete casting with Dipy construction formwork is also treated as a kind of new concrete construction technique. Dipy construction formwork is produced in factory and fixed at site. Fresh concrete can be poured into it directly and needn't to be vibrated. The formwork and the hardened concrete become an integral, which is called concrete with Dipy construction formwork. Although skipping the processes of form stripping and concrete vibration, it is easy to gain good concrete compactibility with relatively lower unit water consumption than other kinds of self-compaction concrete. This technique is wildly applied to external bearing wall of housing building in the northeast of China. The accomplished area of the build constructed with this technique has reached 50000 m^2 by now.

It has been found that several problems obstructed the progress of research and application of concrete with Dipy construction formwork. As a result of non-vibration and cement mortar filtration during the pouring course, concrete with Dipy construction formwork must have good workability and enough cement mortar as well. Considering the limitation of economic condition, it is obvious that the ordinary concrete couldn't match the above requirements. The results of this research program and the analysis of several engineering applications show that the high fly ash content in concrete with Dipy construction formwork has satisfying workability, mechanical property, and durability.

2. Research Program

2.1. Introduction to Dipy construction formwork

Dipy construction formwork (Fig. 1) is of space grid structure. The grid is composed of two pieces of expanded metal (or called snake-skin metal lath), which are fixed with zigzag loops and stiffening ribs by screws. If there's requirement of heat preservation, one side of the formworks of exterior wall shall be covered by insulating layers of foamed polystyrene plate (benzene plate) or rock wool plate (Fig. 2). Table 1 shows the technical characteristics of stiffening rib, expanded metal, and zigzag loop.

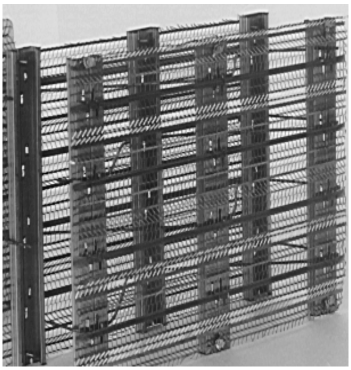


Fig. 1: Dipy construction formwork

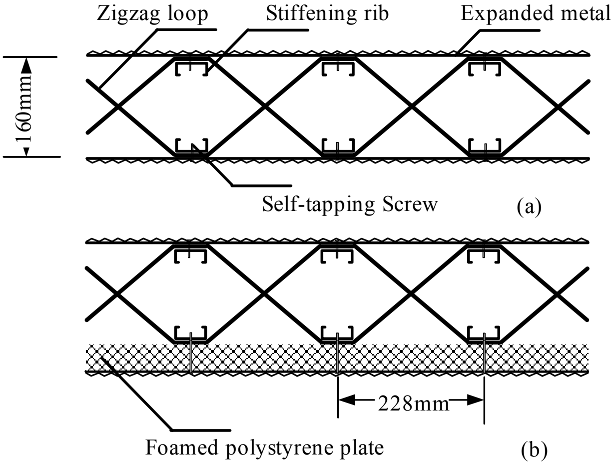


Fig. 2: Detail of Dipy construction formwork (a. standard; b. heat insulation)

Table 1: Technical characteristics of component

Component	Raw materials	Material standard	Tensile strength	Dimension
Stiffening rib	Hot-dip or cold-dip galvanized steel	GB700	≥320 Mpa	47.0 mm × 17.8 mm × 0.5 mm
Zigzag loop	φ6-mm galvanized low-carbon steel wire	GB3081	≥320 Mpa	–
Expanded metal	Cold rolled galvanized steel plate	GB700	–	–

2.2. Working principle of Dipy construction formwork

The main factor that leads to the microcosmic defects of concrete is much more water in freshly mixed concrete than the actually needed by cement hydration and the container effect caused by the formboards lateral pressure on the fresh mixed concrete. Owing to the structural particularity of Dipy construction formwork, especially the expanded metal with snake-skin meshes and the continuous w-shape zigzag hoops, concrete with Dipy construction formwork is obviously different from other kinds ordinary concrete. A great deal of experiments show that Dipy construction formwork has such effects as filtration effect, releasing of container effect, hoop effect and limitation of cracks. With the press from the concrete deadweight, plastic mortar flew out from the inner of the concrete wall to the external through the holes on the expanded metal. During this course, bubbles are sent out and concrete becomes self-compacting. Owing to the hoop effect that is provided by zigzag hoops and V-shape ribs on the mesh, the compressive strength and shear strength of the concrete with Dipy construction formwork increase remarkably. The two-sides snakeskin meshes of the construction formwork limit the shrinkage of the concrete inside, and this limitation could avoid the form of crack. At the same time, the mortar hardened on the outside of the mesh increases the bond strength of plaster.

2.3. Effect of high fly ash content on concrete with Dipy construction formwork

According to the working principle of concrete with Dipy construction formwork, the content of plastic mortar should be more than ordinary concrete, while the certain compactness of concrete is required. Only increasing sand percentage will lead the loss of slump of concrete and the overmuch cement mortar will raise the cost at the same time. Many experiment and research have testified that high fly ash content could replace part of cement and keep the content of cement mortar constant as well. The performance of concrete with Dipy construction formwork will be improved a lot by applying HFCC, properly raising the sand ratio and lowering the aggregate cementitious material ratio.

2.4 Materials and mix proportion

The cement used is portland cement P.O.32.5R, which is produced by Dalian Huaneng Onoda Cement Co. Ltd. The mechanical, physical properties and chemical composition of cement used are shown in Table 2 (Quality Standard GB175-99). The fly ash used is a kind levigated ash (Grade II), which is by-product of Dalian Beihaitou thermo-electric plant. The chemical composition of the fly ash is shown in Table 3. The admixture used is DG-II fly ash activated agent, which could improve the activity of fly ash and the workability of fresh concrete. The DG-II fly ash activated agent is a kind of composite agent, which has four different components respectively working as water-reducing agent, expansion agent, early-strength agent, and activated agent. Since there is no DG-II agent in the mix proportion of no.1, no.2, and no. 4, a kind of water-reducing agent NF is used for good workability. The used sand is river sand, which modulus of fineness is 2.8. The used gravel is crushed limestone, which particle diameter is in the range of 5-25 mm.

Nine concrete walls are made as test specimens, dimensions of which are all the same (1000×500×160 mm). The mix proportions of the concrete walls are shown in Table 4. The no.1 concrete wall is treated as reference specimen, which is made of ordinary concrete. In other concrete walls, fly ash replaces 10%-30%-50%-70% of cement.

Table 2: Physical properties and chemical composition of cement used

	Value for P.O 32.5R cement
Chemical composition	
Ignition loss (%)	4.5
MgO (%)	1.6
SO_3 (%)	1.9
Physical properties	
Fineness: Passing 80 µm (%)	4.5
Initial setting time (h-min)	3-10
Final setting time (h-min)	4-15
Compressive strength	
3-day (Mpa)	23.0
28-day (Mpa)	43.0

Table 3: Physical properties and chemical composition of fly ash used

		Value for fly ash
Specific gravity (g/cm^3)		2.23
Fineness: Passing 45 µm (%)		83.2
Water requirement, %		96.0
Pozzolanic activity index at 28 days (%)		79.9
Chemical composition (%)	SiO_2	52.28
	Al_2O_3	28.22
	Fe_2O_3	5.37
	MgO	0.93
	CaO	2.57
	Na_2O	0.38
	K_2O	1.82
	SO_3	1.38
	Others	3.58
	Ignition loss	3.42

Table 4: Mix proportion of concrete

	kg/m^3							FA/(C+FA) %	W/(C+FA)
	Cement	Water	Sand	Gravel	FA	DG-II	NF		
1	350	200	754	1038	0	0	4.2	0	0.57
2	315	200	740	1038	50	0	4.4	10	0.55
3	315	200	740	1038	50	28.1	/	10	0.51
4	245	200	712	1038	147	0	4.7	30	0.51
5	245	200	712	1038	147	30.18	/	30	0.51
6	174	207	676	1029	243	32.49	/	50	0.50
7	171	213	664	1011	239	54.12	/	50	0.52
8	103	212	634	1013	336	33.87	/	70	0.48
9	102	212	634	1013	335	57.68	/	70	0.48

2.5. Casting of test walls and curing

All the test concrete walls are cast within 2 hours. The concrete walls are cured for 28 days at curing room, the temperature in which always keeps at 20±2° and the humidity is over 90%.

2.6. Drilling test cores from walls

To research the strength and durability of high content fly ash concrete with Dipy construction formwork, cores are drilled out from the walls and submitted to compressive test, carbonation test and rapid freezing-thawing test. The diameter of cores drilled out from each test wall is 100 mm. The minimum distance from the upper-surface to the location of drilling is 300 mm. Cores are drilled out following the procedure described in ASTM C42. After cores are drilled out, the two ends of each test core are cut off, and the length of left part was more than 100 mm. The core specimens are cured in lime-saturated water at approximately 23° for at least 2 days prior to making the following serial tests.

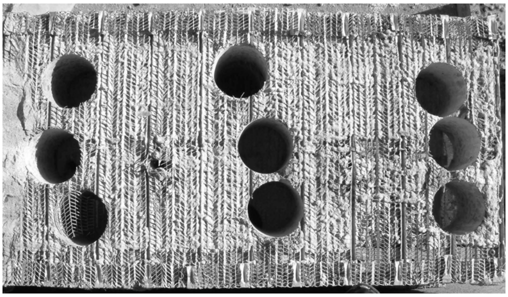


Fig. 3: Test concrete wall (after cores drilled)

3. Experiment Results and Discussion

3.1. Workability and compressive strength

The slump is measured three times. The average values of slump tests and 28-day compressive tests are shown in Table 5. The results of compressive tests show that the compressive strength decreases while the content of fly ash increasing. While the replacement of fly ash is 30%, compressive strength of HFCC is only 70% that of the reference ordinary concrete. After adding DG-II fly ash activated agent to HFCC, the data increase to 108%. Although the content of fly ash are the same, because of the effect of DG-II fly ash activated agent, the compressive strength of no. 3 specimens is 22% higher than that of no. 2 specimen, and the compressive strength of no. 4 specimens is 38% higher than that of no. 5specimen. It is obvious that DG-II fly ash activated agent is effective on raising the strength of HFCC with Dipy construction formwork. While the mass percent of replacing fly ash is over 50%, the increasing amount of DG-II agent effects on the strength little.

Table 5: Results of workability and compressive test

No.	Slump (mm)	Density of fresh concrete (kg/m^3)	28-day compressive strength (Mpa / %)	Density of hardened concrete (kg/m^3)
1	190	2420	32.0 / 100%	2390
2	195	2380	29.3 / 92%	2355
3	210	2375	36.4 / 114%	2350
4	195	2350	22.3 / 70%	2340
5	220	2372	34.5 / 108%	2355
6	215	2361	30.4 / 95%	2345
7	230	2352	28.2 / 88%	2330
8	220	2332	22.2 / 69%	2320
9	230	2310	24.5 / 76%	2310

3.2. Rapid freezing and thawing test

Rapid freezing and thawing test are carried out following the procedure described in GBJ82 and using the concrete rapid freezing and thawing box. One circle includes two hours freezing (-18°) and two hours thawing (20°). The test specimens are prism, which are cut from the lower part of the concrete walls. The dimensions are 100×100×400 mm. The test specimens cut from test concrete wall no. 1, no. 5 and no. 7, whose compressive strengths are satisfying and mix proportions are representative. The result of rapid freezing and thawing test are shown in Table 6. With the effect of DG-II fly ash activated agent, HFCC in which fly ash replaces 30% cement presents good durability, and the values of loss of weight and relative dynamic elasticity modulus are at the same level as ordinary concrete.

Table 6: Result of rapid freezing and thawing test

Cycle times	Loss of weight (%)						Relative dynamic elasticity modulus (%)					
	50	100	150	200	250	300	50	100	150	200	250	300
1	0	0	0.32	0.69	1.16	1.77	100	99	99	96	94	89
5	0	0.07	0.43	0.85	1.45	2.28	100	96	95	93	90	77
7	0	0.12	0.88	1.70	2.85	4.62	100	95	86	75	69	/

3.3. Accelerated carbonation test

Accelerated carbonation tests are carried out following the procedure described in GBJ82 and using chambers with 95% carbon dioxide and a relative humidity (RH) of approximately 60%, where 100 mm diameter cores are kept for 14 days. Test cores are split open and spray with phenolphthalein solution, enabling the measurement of the carbonation depths.

The results of accelerated carbonation tests are shown in Table 7. The results show that the carbonation resistance of HFCC decreases with the increasing of fly ash content. With the effect of DG-II fly ash activated agent, HFCC in which fly ash replaces 30% cement presents satisfying carbonation resistance. It is because that HFCC with Dipy construction formwork has better workability and thus is more compacting than that of ordinary concrete with Dipy construction formwork.

Table 7: Result of accelerated carbonation tests

No.	14-day carbonation depth (mm / %)
1	5.5
2	5.9
3	5.4
4	6.5
5	5.8
6	6.5
7	6.4
8	10.8
9	9.8

3.4 Engineering application

The 43-1/4 building of the Luanjin district of Dalian city is the first dwelling building in China that is adopted with HFCC concrete with Dipy construction formwork structure (see Fig. 4). The gross floor area of the building was about 2744 m^2. The building has been built and employed in 1999.

In this building, the design compressive strength of HFCC is 15 Mpa. The no. 6 mix proportion is used. 28 days after concrete casting, the average value of compressive strength of drilled cores is 18.7 Mpa.

Fig. 4: The 43-1/4 building of the Luanjin district

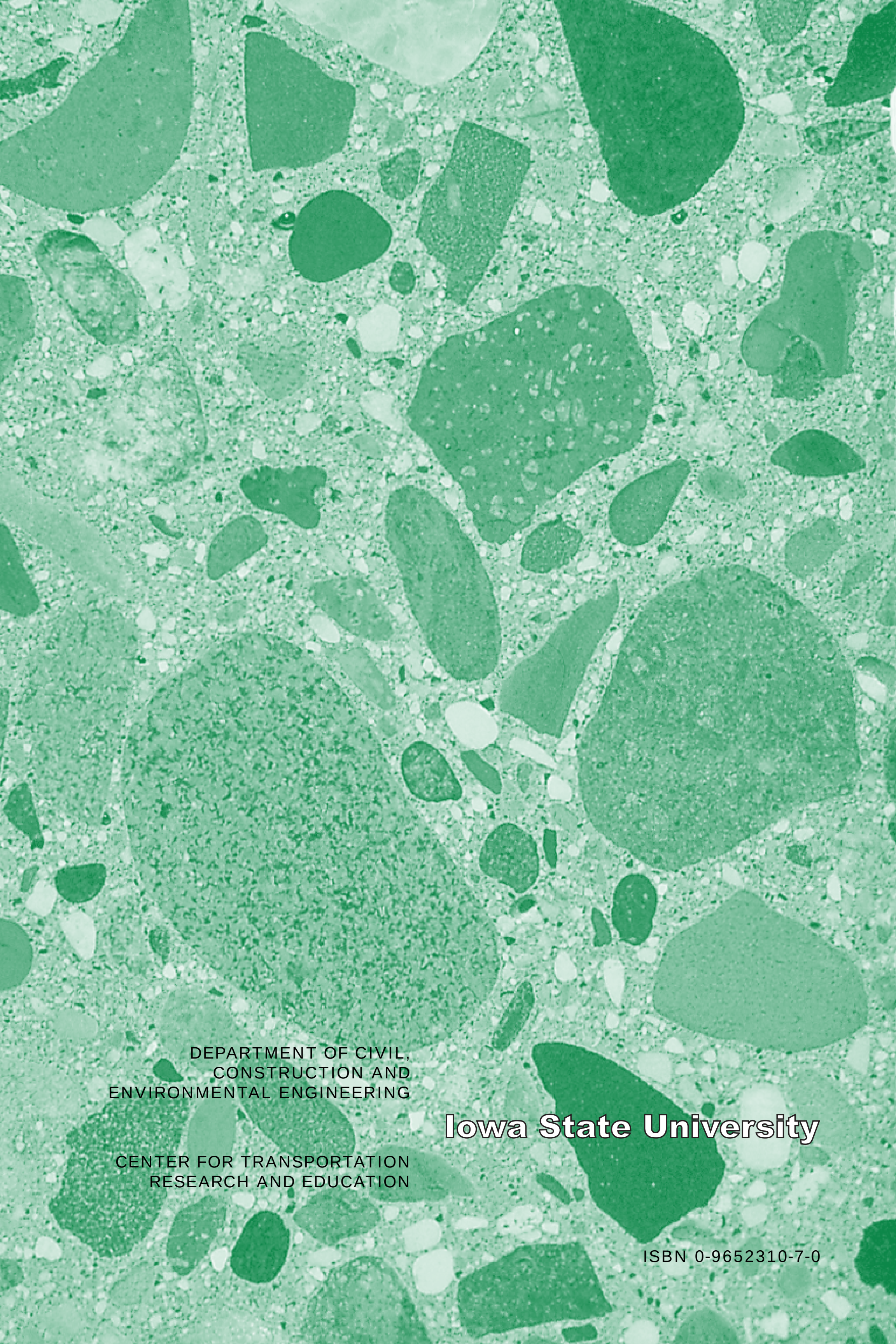
4. Conclusion

Application of high fly ash content can improve the workability and compacting of concrete with Dipy construction formwork. With the effect of DG-II fly ash activated agent, while the replacement of fly ash increase up to 50%, the strength of HFCC with Dipy construction formwork is at the same level as that of ordinary concrete. With the increasing of mass percentage of fly ash in concrete with Dipy construction formwork, the durability of concrete will decline. DG-II fly ash activated agent can improve the durability of HFCC with Dipy construction formwork to some extent. While the mass percentage of agent is over 7.7%, the increase of this agent in concrete could not bring great progress to the strength and durability of HFCC with Dipy construction formwork.

References

1. Murdock, L.J., K.M. Brook, and J.D. Dewar. *Concrete: Materials and Practice,* 6th ed. London: Edward Arnold, 1991.
2. Hurd, M.K. *Formwork for Concrete,* 6th ed. American Concrete Institute, 1995.
3. Chinese Regional Standards. Specification for Concrete Structures with Dipy Construction Formwork (DB21/1210). General Administration of Quality Supervision, Liaoning Province, 2001.
4. Chinese Standards. Hot-Dip or Cold-Dip Galvanized Steel Plates and Sheets (GB2518). General Administration of Quality Supervision, Inspection and Quarantine, Beijing, 1988.
5. Chinese Standards. Cold Rolling Ribbed Steel Wires and Bars (GBT/13788). General Administration of Quality Supervision, Inspection and Quarantine, Beijing, 1992.
6. ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, 1994.
7. Chinese Standards. Test Method for Long Term Properties and Durability of Concrete (GB82). General Administration of Quality Supervision, Inspection and Quarantine, Beijing, 1985.
8. Mehta, P. Kumar, and P.J.M. Monteiro. *Concrete: Structure, Properties, and Materials*. New York: McGraw-Hill Companies, Inc., 1993.
9. Lijiu, Wang, and Xianfu, Liu. "Dipy Construction Formwork." *House Materials and Applications* 4, 1999, pp. 22-22.
10. Lijiu, Wang, Mingli, Cao, Zhengyue, Ren, and Baomin, Wang. "Study and Application of High-efficiency Fly ash Activating Admixture." *Journal of Dalian University of Technology* 4, 2000, pp. 489-491.
11. Liu, Yan, Rong, Limin, and Wang, Laifu. "Application of Dipy Construction Formwork Mesh in Building Project of China." *Construction Technology* 8, 2001, pp. 29-30.
12. ASTM C42, Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete, 1994.

13. Joana Sousa Coutinho. "Effect of Controlled Permeability Formwork on White Concrete." *ACI Materials Journal*, March-April 2001, pp. 148-158.
14. Basheer, P.A.M., A.A. Sha'at, A.E. Long, and F.R. Montgomery. "Influence of Controlled Permeability Formwork on the Durability of Concrete." *Proceedings of the International Conference on Concrete*, E. & F.N., 1993, pp. 737-745.
15. Price, W.F., and S.J. Widdows. "Durability of Concrete in Hot Climates: Benefits from Permeable Formwork." *Proceedings of the International Conference on Concrete in Hot Climates*, E. & F.N., 1992, pp. 207-213.
16. Harrison, Tom. "Introducing Controlled Permeability Formwork. *Concrete Construction* 36(2), February 1991, pp. 198-200.



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