National Concrete Pavement Technology Center

The Use of

TERNARY MIXTURES IN CONCRETE

May 2014



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16. Abstract

This manual is a summary of the findings of a comprehensive study. Its purpose is to provide engineers with the information they need to make educated decisions on the use of ternary mixtures for constructing concrete structures. It discusses the effects of ternary mixtures on fresh and hardened mixture properties and on concrete sustainability; factors that need to be considered for both structural and mixture design; quality control issues; and three example mixtures from constructed projects.

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The Use of Ternary Mixtures in Concrete

May 2014

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INTRODUCTION

The purpose of this document is to provide engineers with the information they need to make educated decisions on the use of ternary mixtures for constructing concrete structures.

A ternary mixture is one that contains portland cement and two other materials in the binder, blended either at the cement plant or at the batch plant. The materials included may be interground limestone or supplementary cementitious materials (SCMs) such as slag cement, fly ash, silica fume, or metakaolin.

The information in this document is largely based on the findings of a significant research project conducted over the last seven years in three phases at Penn State, Utah University, and Iowa State University (Tikalsky 2007, 2011, Taylor 2012, respectively) along with published data. The first stage of work was to evaluate paste and mortar mixtures using an array of several portland cements and blended cements, mixed with supplementary cementitious materials. More than 120 different combinations were mixed and tested for properties such as setting time, flow, strength development, shrinkage, and sulfate resistance.

The second stage of the work was to select a more limited subset of materials tested in pastes and mortars and to conduct tests for a broader range of properties including bleeding, air content, alkali reactivity, electrical resistivity, and freeze-thaw resistance. A limited number of mixtures containing limestone as one of the components of the binder were included. Some of the testing included evaluating the effects of low or high temperature mixing and curing conditions.

An additional stage of work included field demonstrations in which bridge elements and one pavement were constructed in seven states around the country using ternary mixtures. Samples were taken at the time of construction, and the mixtures were evaluated. In addition, feedback was obtained from the contractors about their experiences with the mixtures. The information gathered indicated that there are few technical barriers to delivering ternary concrete mixtures with required performance parameters. In general, the effects of the mixtures could be predicted from a knowledge of the effects of the individual ingredients; i.e., there were few observed positive or negative synergies from interactions between the ingredients. As may be expected, increasing the amount of any given material may have desirable or beneficial effect(s), such as reduced heat of hydration, but other associated side effects, such as delayed setting, may require changes or close attention to construction practices. One of the benefits of using a ternary system is that a negative effect from one product may be balanced by the beneficial effect of another. In this way, reliable mixtures can be produced that contain relatively low amounts of cement clinker, which will improve sustainability both by reducing environmental impacts and by increasing the beneficial usage of a material that would have otherwise been considered a waste.

The following pages summarize the findings of the research, with supporting data from the literature. First, the effects of ternary mixtures on fresh and hardened properties of mixtures are discussed, followed by a discussion about sustainability. Factors that need to be considered by designers are discussed from the point of view of both structural design and mixture design. The final chapters discuss changes that may be needed in construction practice and quality management.

Fresh Properties

This section discusses how fresh properties of mixtures are affected by ternary systems. Properties discussed include workability, heat of hydration, setting time, and air entrainment. Fresh concrete properties are primarily important to a contractor because they affect the effort required to transport, place, finish, and cure the concrete.

While the owner typically is more concerned about the hardened properties of a mixture, there is an interest in monitoring fresh properties because they affect the ability of the contractor to deliver the final product to a required standard. Both owner and contractor are concerned about the uniformity of the mixture because variations between batches will impact both early and long-term performance.

Workability

Workability of a mixture influences the ease with which the concrete can be transported, placed, and finished. The greater the workability, the less effort required to consolidate the system without segregation, but for extruded systems such as slipformed pavements a stiffer mixture is needed to prevent edge slump. The correct workability is therefore required for the type of equipment being used.

Good workability provides indirect benefits to the hardened concrete, because full consolidation is easier to achieve and the volume of large voids in the concrete is reduced. Poor workability can make finishing difficult, increasing the risk of tearing of the surface or forcing the crew to overwork the surface to achieve a visually acceptable finish.

Workability also provides a measure of uniformity, indicating that something has changed from batch to batch, thus acting as a useful quality control tool. Rapid loss in workability may be an indication of materials incompatibility, as discussed in the section on Incompatibility. Historically, the workability of concrete has been measured using the slump test, but experience has shown that more information is required to describe workability fully. Rheological-based approaches are useful laboratory tools but have yet to find application in the field.

A significant change in concrete technology has been the widespread use of chemical admixtures to control workability. This means that variations in workability induced by the cementitious system can easily be adjusted for during mix proportioning.

According to Kosmatka et.al. (2011), SCMs generally improve the workability of concrete mixtures. Fly ash and slag cement have frequently been reported to improve concrete workability. Silica fume, however, will increase the water requirement and stickiness at dosages above five percent by mass of cement because of the high surface area. Less than five percent silica fume may improve workability because the silica fume particles tend to be spherical and assist with separating cement grains.

Data from Tikalsky (2007) have shown that flow values in mortar mixes did not vary significantly with changing combinations of SCMs.

In general workability

- Remained the same for mixtures with increasing Class C fly ash.
- Increased in mixes with increasing amounts of one Class F fly ash but decreased with a different Class F fly ash.
- Decreased or remained the same in mixtures with increasing slag cement.
- Decreased more rapidly in mixtures with increasing silica fume and metakaolin.

Data from the literature (Mala 2013, Elahi 2010, Hale 2008, Sharfuddin 2008, Bouzoubaâ 2004) indicate that trends are generally consistent with the properties of the ingredients. It may be expected that, in general, slag cement or fly ash should increase workability, but individual products or combinations may behave differently depending on the fineness and chemistry of the system.

Trial batches are strongly recommended.

Set Time

Setting is a measurement of when a fresh concrete mixture changes from a fluid to a solid. This is of interest because it will influence when finishing activities may be conducted. Initial set is formally defined as when a pressure of 500 psi is required to push a cylindrical plunger into a mortar sample extracted from the concrete, while final set is considered to have occurred at 4,000 psi.

Initial set can be explained physically as the stage when hydration products start to mesh with each other, reducing the ability of particles to move past each other. Final set may be thought of as when the concrete is hard enough to walk on, and may have been initially related to sulfate depletion in the hydration process. The 4,000 psi, however, seems to be an arbitrary number that has little correlation with compressive strength or hydration of modern mixtures.

As noted, setting time may be recorded by periodically pressing a plunger into a sample of mortar and plotting the pressure required. Alternative approaches finding acceptance are the use of temperature sensors and devices that monitor the speed of sound through a sample. The former approach is based on the fact that hydration is exothermic and a rise in temperature indicates chemical activity. This may be skewed because, although chemical reactions may have started, they may not have proceeded far enough to result in measurable physical change in the system. In concrete mixtures, however, this error is generally small enough to be acceptable.

Inclusion of fly ash and slag cement will generally retard the setting time of concrete depending on the water/cementitious materials (w/cm) ratio, the chemistry of the system, and the temperature of the concrete. Reducing w/cm ratio means that cement grains are closer together and so setting is slightly accelerated. Mixtures with increasing alkali contents and at higher temperatures will also tend to set sooner.

Results from mortar tests (Tikalsky 2007) show that setting times generally

- Increased with increasing Class C fly ash.
- Remained the same or slightly increased for mixtures with increasing Class F fly ash.
- Increased in mixes with increasing amounts of Grade 100 slag cement but remained the same for Grade 120.
- Decreased in mixtures with silica fume and metakaolin.

Hale (2008) reported that the effects of SCMs, including a ternary combination of slag cement and fly ash, varied depending on the cement.

Bleeding

Bleeding is the appearance of water at the surface of a concrete element between the times of placement and setting. It is caused by the settlement of solid particles (cement and aggregate) in the mixture and the simultaneous upward migration of water.

A small amount of bleeding is normal and expected in freshly placed concrete. Some bleeding may help control the development of plastic shrinkage cracking in slabs on grade. Excessive bleeding, however, reduces concrete strength and durability near the surface. The rising water can form channels through the matrix, significantly increasing permeability. If the surface has been troweled too early, the bleed water can be trapped at or below the surface, later resulting in a poor quality skin and/or blisters. Bleed water can also accumulate under large aggregate particles or reinforcing bars, causing reduced concrete strength and reduced paste-steel bond.

Excessive bleeding will delay the finishing and curing process, which should not proceed until bleed water has evaporated from the surface.

Bleeding is primarily reduced by increasing the amount of fine powder in the mixture, reducing workability and entraining air. Concrete containing fly ash generally exhibits a lower bleeding rate, but due to retarded setting times, the total bleed volume may be similar to or greater than portland cement–only concrete. Slag cements reportedly have little effect on bleeding rates. Silica fume can greatly reduce, or often stop, bleeding, largely because of the extreme fineness of the particles (Bouzoubaâ 2004).

In the work reported by Tikalski (2007) Class C fly ash had a mitigating effect on bleeding up to a point, but when more than 25 percent Class C fly ash was used in the mixture, bleeding increased. Class F fly ash also reduced bleeding but was not as effective as the C ash, and there was no pessimum effect observed with Class F fly ash. Bleeding was slightly increased in the mixtures containing slag cement, but decreased in the mixtures containing metakaolin. The high fineness of silica fume and large specific surface area greatly reduced the bleeding of the mixtures.

Air Void Structure

Air may be deliberately entrained in concrete primarily to improve freeze-thaw resistance. Other benefits include improved workability and increased yield. A difficulty is that control of air contents may be difficult as discussed below.

It is desirable to have a large number of small bubbles close together so that free water in a paste matrix is near a bubble. The spacing factor of bubbles should be less than approximately 0.20 mm, which is traditionally achieved by ensuring that there is about 5–6 percent total air in a mixture. This assumption may not be true for mixtures with newer admixture systems. Small bubbles are stabilized in a mixture by the use of so-called air entraining admixtures (AEA), but the amount of chemical required by a mixture can be strongly influenced by the chemistry of SCMs in the mixture and the workability of the mixture. Increasing loss-on-ignition (LOI) from unburned carbon in fly ash will significantly increase the amount of AEA required to achieve a given air content and likely reduce stability of the air voids. Increasing fineness of the powders (such as silica fume and metakaolin) in the system will also increase demand for AEA.

Data from tests conducted on mortars (Tikalsky 2007) confirm that a greater dosage of AEA is needed when incorporating a high LOI Class F fly ash. Increasing workability due to the presence of some SCMs may enhance the effectiveness of air entraining admixtures (Hale 2008).

Heat of Hydration

Cement hydration generates heat as the reaction proceeds. In addition, the warmer a mixture the faster will be the rate of reaction. In cool weather, a mixture that generates a lot of heat will accelerate itself, which may be desirable. On the other hand, in warm weather the lower the heat generated the lower the peak temperature and the better quality the concrete will be. Temperature differentials of concrete between that at the time of setting and the minimum in the first few days may lead to thermal cracking, again supporting the idea that lower heat gains may be generally preferred.

Supplementary cementitious materials will generally reduce the heat generated, depending on the alkali content and the fineness. Slag cements and Class F fly ashes are effective at reducing peak temperatures in mass-concrete systems, thus reducing the risk of thermally induced cracking.

The results of tests (Tikalsky 2007) were consistent with the literature, showing slag cement and fly ash reducing temperatures and silica fume increasing them. Finer ground slag cement generated more heat than the lower grade coarse ground product.

Incompatibility

Incompatibility is a phenomenon sometimes observed in which ingredients in a mixture under some conditions react with each other to result in undesirable and unpredictable behavior. The most commonly observed effect is rapid stiffening, sometimes accompanied by severely retarded set. The other effect may be instability of the air void system (Tikalsky 2007, Taylor 2006).

The stiffening is generally due to an imbalance of C_3A in the cementitious system and the required sulfates in solution to control C_3A hydration. Cements are normally manufactured to be in balance, but the addition of SCMs (typically Class C fly ash with a high calcium content) that contain additional C_3A may result in an uncontrolled reaction causing flash set. This effect is most often seen in systems at high temperatures (~90°F) and containing lignin based water reducers, both of which accelerate C_3A reaction. The risk is most commonly assessed by monitoring the shape of a heat of hydration plot measured using an isothermal or semi-adiabatic calorimeter.

It was observed by Tikalsky (2007) that a low-range water reducer showed significant reduction in time to set when used at a doubled dosage rate in mixtures containing Class C fly ash.

SCM Percentage

From the laboratory data (Tikalsky 2011) the only fresh parameter that appeared to be significantly affected by increasing SCM dosages, whether binary or ternary, was setting time; see Figure 1. As SCM dosage increased, the range of setting times increased significantly, meaning that at low or no dosage all mixtures set at about the same time while increased dosage meant that some mixtures were delayed while others were not, depending on other parameters in the mixture such as SCM type.

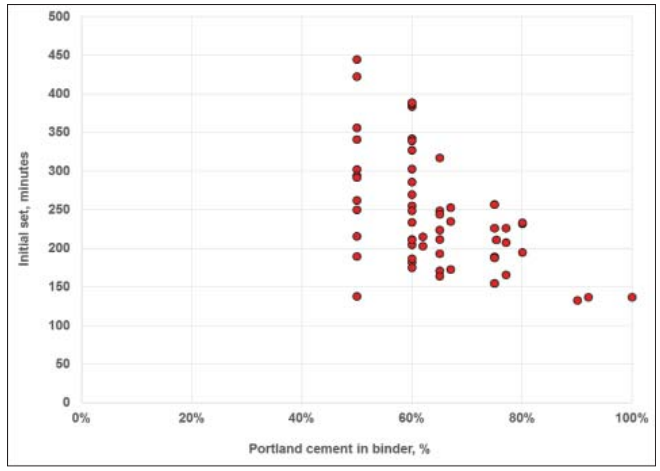

Figure 1. Initial setting time for mortar mixtures as a function of portland cement content in the binder

Hardened Properties

This section is focused on hardened properties of mixtures containing ternary systems. Properties discussed include strength, shrinkage, permeability, frost resistance, alkali silica reaction, and sulfate resistance, all of which can affect concrete durability.

Strength

Strength is a commonly measured property of concrete, largely because it is relatively simple to assess and because it is used to provide a fair analogue with other concrete properties. It is also critical to structural performance of elements. The age at which a given strength is required will vary depending on the need. Contractors may want early strength (rapid strength gain) in order to construct the next stage, while the owner may be interested only in the strength at a later age. The rate of strength development will also influence the risk of cracking. Concrete is generally strong in compression but weak in tension, and testing is normally in the form of compression tests on cylinders or cubes.

Strength increases as the w/cm ratio decreases because the capillary porosity decreases. This observation holds true for the entire range of curing conditions, ages, and types of cements available. There is a direct relationship between w/cm ratio and strength for a given set of cementitious materials, but the relationship will vary for different mixtures of cement and SCMs.

Concrete strength is influenced by the composition and fineness and, indirectly, the amount of the cement in the mixture. Finer cements hydrate faster than coarser cements due to their increased surface area and tend to have a limited later strength development because of a poorer quality paste microstructure.

The amount or rate of the contribution of SCMs will depend on the chemistry, fineness, and amount of the SCM. Generally, with Class F fly ash and slag cement, early strengths are lower than those of similar mixtures with portland cement only, and ultimate strengths are higher. The effect of Class C fly ash is less marked on early age strengths, depending on the specific fly ash used. Silica fume and metakaolin normally increase strengths at both early and later ages (Bouzoubaâ 2004). Ternary mixtures developed to achieve a given 28-day strength will tend to exhibit greater strengths than plain mixtures at greater ages (Chung 2012, Elahi 2010, Hale 2008).

Twenty-eight–day strengths can also be affected by the percentage of cement, particularly when it drops below 40 percent. Figure 2 shows data for ternary and binary mixtures containing Class C and Class F fly ash and slag cement prepared at a w/cm ratio of 0.45 (Shin 2012). It is notable that the ternary mixtures outperformed the binary mixtures. Similar trends were reported by Mala (2013).

From tests conducted on mortars (Tikalsky 2007) the following observations are made:

- Three-day strengths of all mixtures ranged from 1,200 to 4,800 psi.
- No clear trends in 3- or 28-day strengths were observed with increasing amounts of fly ash or slag cement.
- Increasing 3- and 28-day strengths were observed with increasing amounts of silica fume and metakaolin.

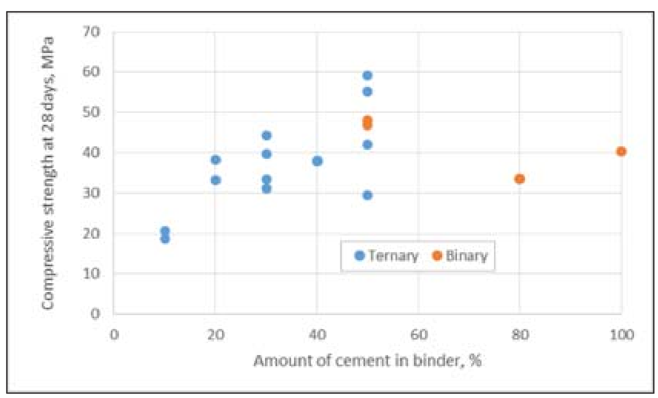

Figure 2. 28-day compressive strength as a function of cement in the binder (after Shin 2012)

From the concrete tests (Tikalsky 2011):

- Increasing amounts of one of the Class F fly ashes slightly reduced strength at 7 days, but no effect was seen at 28 days.
- Seven- and 28-day strengths were slightly increased with increasing silica fume dosage.
- The 28/7-day strength ratio was lowest for the plain mixture containing limestone (on the other hand, the strength ratio was highest for the mixtures containing Class F fly ash).

A clear increase in 3-day mortar strength was observed with increasing portland cement content, but the trend was less notable at 28 days as shown in Figure 3. No trend was observed in the concrete tests.

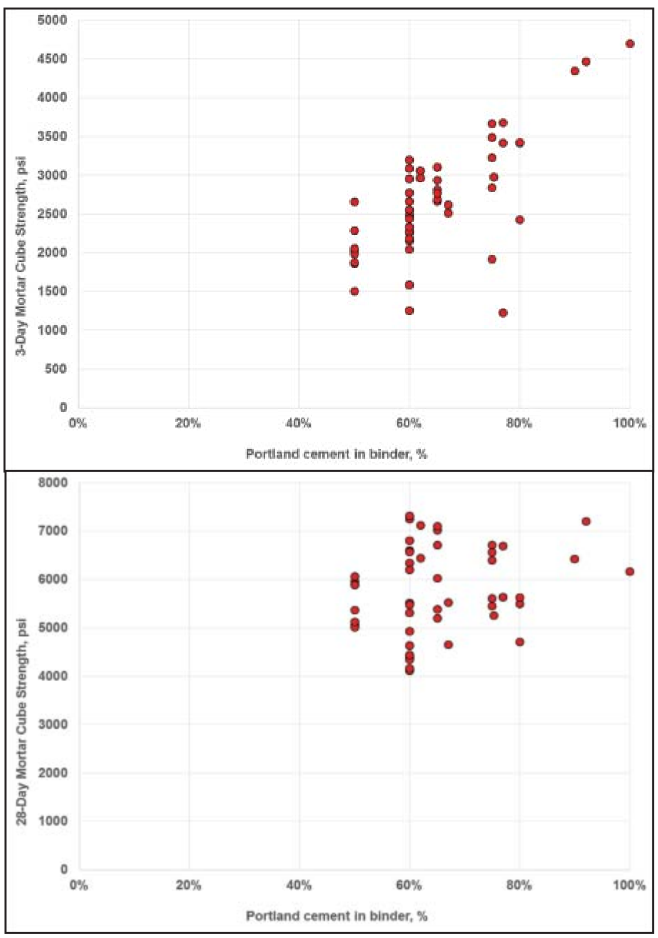

Figure 3. Compressive strength as a function of cement in the binder at 3 days (top) and 28 days (after Tikalsky 2007)

Shrinkage

Concrete shrinks due to several mechanisms that start soon after mixing and may continue for a long time. Because concrete shrinkage is generally restrained in some way, concrete almost always cracks. Uncontrolled cracks that form at early ages are likely to grow due to mechanical and environmental stresses.

A significant contributor to shrinkage is moisture lost from the system, largely due to evaporation. Plastic shrinkage occurs due to loss of moisture before the concrete sets that can result in plastic cracking at the surface. Drying shrinkage occurs after the concrete has set and results in random cracking. Total shrinkage can be minimized by keeping the water (or paste) content of concrete as low as possible.

Increasing cement fineness has been reported to increase shrinkage (Yang 2009). Supplementary cementitious materials usually have little direct effect on shrinkage (Tikalsky 2011, 101). The exception to this was the low moisture shrinkage observed in the control mixture containing interground limestone.

Permeability

Permeability is the ease with which fluids can penetrate concrete. Almost all durability-related distresses in concrete can be slowed or stopped by reducing its permeability because most durability-related distress mechanisms involve the transport of harmful substances into the concrete:

- Water that expands on freezing, leaches calcium hydroxide, and/or carries dissolved ions that attack the concrete
- Salts that crystallize on wetting and drying or exert osmotic pressure during freezing and thawing, causing surface damage
- Alkalis that release hydroxyls that react with alkali-reactive aggregates
- Sulfates that attack the aluminate compounds
- Carbon dioxide that reduces the alkalinity (pH)
- Oxygen and moisture that contribute to the corrosion of steel bars or reinforcement
- Chlorides that promote corrosion of steel bars

Permeability is primarily controlled by the paste system and the quality of the interfacial zone. If there are a large number of pores and they are connected (percolated), then the concrete will be permeable. Reducing the likelihood that pores will be connected is key to achieving low permeability. It is generally accepted that appropriate use of SCMs reduces permeability of concrete mixtures, particularly at later ages.

There are no practical tests to assess directly the permeability of a given concrete, but one approach is to use an analog such as the electrical conductivity. This has a logical basis because ionic charge is faster in fluids in the pore system than in the solids of the hydrated cement paste. The classic approach is the so-called rapid chloride penetrability test (ASTM C 1202). This test has been popular for some time despite its limitations and poor repeatability. An alternative is to use a resistivity approach such as the Wenner probe that measures resistivity between four probes a known distance apart.

Both approaches were used by Tikalsky (2011, 122) and a good correlation was found between the methods, but the resistivity test was far simpler to run.

In general, resistivity was increased (indicating improved permeability) with the increasing addition of SCMs except when more than 30 percent of the binder contained Class F fly ash (Tikalsky 2011, Bouzoubaâ 2004). Sorptivity has been shown to decrease with increasing age, particularly in ternary systems (Bai 2002, Elahi 2010).

Freeze Thaw and Scaling

Concrete that is exposed to cold weather can incur damage due to freeze-thaw damage and salt scaling among other mechanisms related to the use of deicing salts.

Freeze-thaw damage is due to pressures exerted by water attracted to the freezing front and expanding as it freezes. The damage is typically cyclic because, while saturation may be limited to a shallow depth, cracking at the surface will open up the system allowing further penetration of the water.

If a salt solution penetrates the microstructure, and then the water is removed either by freezing or by evaporation, the remaining salts may crystalize out and expand depending on the chemistry of the salt. Damage may also be due to osmotic pressures set up by differential salt concentrations between the pore solution at and remote from the freezing front. Surface scaling is also reportedly due to differential movements in the surface ice and the concrete at the surface causing shallow cracking.

Prevention is achieved by entraining small air bubbles close together that provide a place for expanding water to move into. Improving impermeability of the paste to limit the rate of water ingress is also beneficial.

Mixture factors that influence the risk of distress include the following:

- High LOI fly ash will require greater dosages of admixture to achieve the same air content.
- Variable LOI in a fly ash source may cause large variations in the concrete air content. Such a fly ash should be monitored using the foam index test with every delivery to prevent problems in the batch plant.
- Mixtures with finer cement and increasing cement content will require a higher dosage of admixture to achieve the same air content.
- There is a perception that increasing slag cement content in a mixture will reduce scaling resistance, particularly above 50 percent dosage (Tikalsky 2011).

All of the mixtures tested by Tikalsky et al. (2011) prepared with an adequate air void system performed satisfactorily in the ASTM C 666 test, regardless of the binder system.

Surface scaling was seen in all the mixtures tested. The addition of silica fume and metakaolin generally did not reduce the severity of the scaling. However, the addition of fly ash or GGBFS reduced the severity of the surface scaling. The presence of 10 percent limestone seemed to enhance the performance of Class F fly ash and slag cement.

Systems containing large amounts of SCMs can be more sensitive to poor curing (Radlinski 2008).

Alkali Silica Reaction

A chemical reaction can occur between certain types of siliceous aggregate, alkali hydroxides from the cement, and water that leads to the slow formation of a gel in and around the aggregates. This gel is expansive when it absorbs water and can lead to significant damage in a concrete system over a period of years. Ideally, the risk of such alkali silica reaction (ASR) can be mitigated by a number of actions or a combination thereof, as follows:

- Avoid use of reactive aggregates. This is not always possible when alternative aggregates are not available within a reasonable distance.
- Keep the concrete dry. Again, this is often not possible because, even in the desert, ground water will tend to collect under slabs on grade, elevating the relative humidity in the concrete above the levels needed to promote the reaction.
- Use appropriate dosages of SCMs. This is a common approach, although it is contingent on knowing how much SCM is needed for a given aggregate.
- Include lithium-based admixtures in the concrete, converting the gel to a non-expansive form.

The lower the calcium content of a fly ash, the lower the amount that is needed to control expansion. In some cases, an inadequate dosage of high calcium fly ash may exacerbate the problem.

Ternary mixtures containing silica fume and fly ash are reportedly effective at reducing ASR-related expansion by controlling pore solution alkalinity (Shehata 2002).

Tests were conducted (Tikalsky 2011) using the ASTM C 1567 mortar bar approach. Expansions were reduced in all mixtures containing SCMs. Class C fly ash used at less than 30 percent provided only a limited benefit, but significant reductions in expansion were noted in all mixtures containing one of the Class F fly ashes; the reduction was less marked with the other Class F fly ash. Increasing amounts of SCMs decreased expansions. Inclusion of limestone in ternary mixtures appeared to enhance the benefits of the other SCMs; see Figure 4.

Sulfate Attack

External sulfate attack comprises sulfates in solution reacting with C_3A and its hydration products, forming expansive compounds and decomposing the cement paste. This may be a significant issue for slabs in contact with sulfate-rich soils.

Mitigation is conventionally in the form of reducing permeability of the concrete using low C_3A cements and/or including low-calcium fly ash in the mixture.

Tests were conducted by Tikalsky (2011) in accordance with ASTM C 1012 on mortar bars. Expansions were evaluated at 12 months. Expansions were reduced in all mixtures containing SCMs. The benefit was limited and insufficient when using Class C fly ash at less than 30 percent but was very marked in all mixtures containing slag cement, Class F fly ash, and silica fume. These findings are similar to those reported by Dhole (2011).

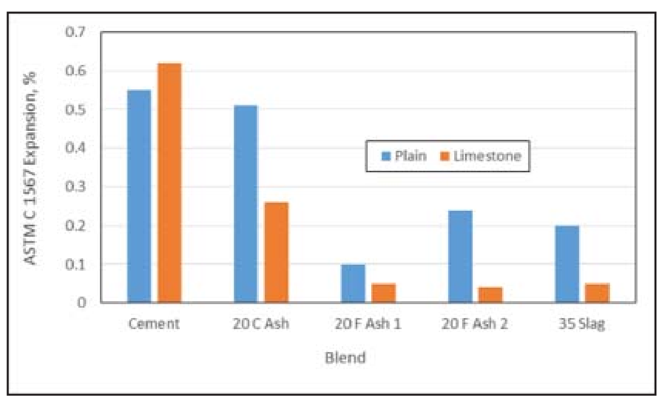

Figure 4. Sulfate expansion in mixtures with and without limestone (after Tikalsky 2011)

Sustainability

This section discusses how ternary mixtures can be used to improve sustainability of concrete mixtures and how these improvements can be quantified.

A basic definition of sustainability is the capacity to maintain a process or state of being into perpetuity, without exhausting the resources upon which it depends nor degrading the environment in which it operates. Typically, three general categories of sustainability are recognized: economic, environmental, and social. To be sustainable, any activity must comprise a workable balance between the three, sometimes competing, interests. Fundamental to the process is that engineering quality must not be compromised. Any approach to reducing, say, the carbon footprint cannot be allowed to impact safety and longevity of the system being built.

Balancing economic, environmental, and societal factors for construction projects requires

- Identifying applicable factors in each category.
- Collecting data for the factors to be evaluated.
- Applying tools to quantify the impact of each factor.
- Assessing the combined impact of the factors in relationship to one another.

Complicating the process is that factors must be identified and measured for all stages of a structure's life from conception through construction, use, and, eventually, removal. Therefore, assessment of the sustainability of a project will require the use of a robust life cycle assessment (LCA) approach.

Implementation of sustainable practices is largely being driven by the public's growing awareness that a more sustainable built environment is achievable. This requires civil engineers to examine alternative solutions that a few years ago might not have been considered. Agencies have begun to require that sustainability metrics be measured on construction projects, and such metrics may be used in the selection process for future projects.

Concrete suffers from a perception that it contributes a considerable amount of CO_2 to the atmosphere. This is partially due to the large quantities of concrete that are used to provide and maintain infrastructure worldwide. It should be noted that most of the CO_2 generated is from the manufacture of portland cement; therefore, activities that reduce the amount of portland cement in a structure will be beneficial. While cement manufacturers are developing and implementing more efficient systems, there is a limit to the reduction that can be achieved because about half of the CO_2 produced is a result of the decomposition of the limestone used to make the product.

Use of ternary mixtures provides a means to make better quality concrete while reducing economic, environmental, and social impacts as discussed below. The discussion in the preceding chapters have clearly shown that concrete mixtures can be developed using ternary mixtures that deliver both the fresh and hardened properties required for most applications.

Economic Impact

Engineers are used to providing a structure at minimum cost, largely because the low-bid system is built around that premise. Traditionally the focus has been on the initial cost, but some movement has been made toward considering life cycle costs when evaluating different solutions. Packages and models are available that assist practitioners in the process of accounting for future maintenance costs over the life of a structure. Such approaches are an integral part of sustainability.

When considering concrete mixtures containing SCMs it is normally assumed that such mixtures will be lower cost because these products are mostly byproducts from other industries. Other indirect reduction of costs may be found in various ways:

- Concrete with a given performance can be provided with a lower cement content.
- Some performance requirements, such as sulfate resistance or ultra-high strengths, may only be achieved with the use of SCMs.
- Lower water demands will lower admixture requirements or simplify handling constraints.

However, as the benefits of SCMs are recognized, prices tend to rise. Other factors that may negatively impact cost include the following:

- Transportation costs may dominate, depending on the distances to be covered and the availability of bulk handling facilities.
- Batch plants have to be modified to handle another material, unless it is purchased as a blended material from the cement manufacturer.
- The potential for errors goes up with increasing numbers of materials in a batch. Such errors include loading materials into the wrong silos, or switching proportions of SCM and portland cement.
- Testing and monitoring for quality assurance purposes will add to costs. This is exacerbated in materials that are byproducts because the source industry is concerned about its own product. The byproduct is therefore uncontrolled and consequently may be highly variable.
- Regulatory requirements on handling waste products may be significant, now and increasing into the future.
- Not all SCMs improve workability.
- Some SCMs, such as metakaolin, are finding more lucrative markets in other industries.
- Staff need to be educated about the products and their effects.

An exercise conducted in this project indicated that, in general, costs will be decreased with use of ternary systems because negative side effects of one material can be balanced with the benefits of another, while simultaneously reducing portland cement content.

Environmental Impact

When considering the environmental impact of any process, two aspects have to be considered: 1) the depletion of resources and 2) the generation of waste.

Sustainability has become a concern because people are becoming aware that availability of many resources on the planet is finite and that humankind is consuming them faster than they can be regenerated. This means that eventually we are going to run out of critical materials. The basic materials required to manufacture portland cement are limestone, shale, and energy. The first two components are still readily available, but there is concern about the future availability of carbon or hydrocarbons commonly used to heat cement kilns.

Of greater concern is the impact of waste materials and byproducts created during the processing of manufactured products. Life cycle analysis (LCA) models investigate a list of high impact indicators, including the following:

- Acidification
- Climate change
- Ecotoxicity
- Eutrophication
- Human-health effects
- Ozone layer depletion
- Smog

In the same way that LCCA models are desirable to assess the real financial cost of a plan, a rigorous LCA incorporating all of the above can account for all of the potential impacts over the life of the structure.

In the context of portland cement, it is the potential effects of CO_2 that is of greatest interest, with impacts of other factors being fairly limited. Supplementary cementitious materials, however, may be considered beneficial because if they were not used in concrete, they would have to be landfilled, adding to the environmental impact of their source industries. At the same time SCMs reduce the amount of portland cement required, thereby reducing the impact of a given amount of concrete.

Data from Tikalsky (2011) show a linear relationship between the amount of portland cement replaced and the reduction in CO_2 footprint; see Figure 5. Tied to this is that, in general, the mixtures tested still performed satisfactorily. At high replacement rates, some care may be required to ensure that side effects are acceptable. However, a given performance can be delivered with less impact than using a straight portland mixture because properties of the products can be utilized to balance each other.

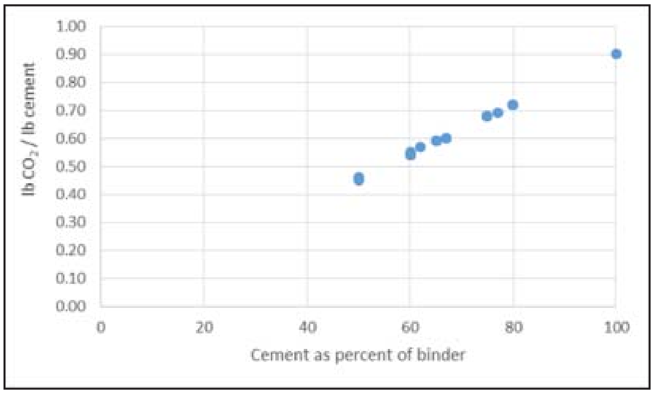

Figure 5. CO_2 footprint as a function of portland cement in the binder (after Tikalsky 2011)

Societal Impact

Civilization and our current lifestyle is utterly dependent on the functionality of the existing infrastructure:

- Transportation for mobility of food, water, medicines and people
- Communication to coordinate the movement of these
- Waste removal and treatment
- Heating and cooling in extreme climates

A significant portion of the physical infrastructure is built using concrete based systems.

Our charge as engineers is to continue to provide that needed infrastructure while reducing our impacts, as discussed above.

A societal benefit of using SCMs in ternary mixtures is that there will be a reduction in the amount of material that has to be stored in dumps or dams. This will have the direct benefit of reducing the risk that they will fail and so protecting the populations that live near or downstream of them.

Design

This section provides guidance on the factors a structural or pavement designer needs to be aware of when considering the use of ternary mixtures. Also in this section is guidance on selecting materials to be used in a ternary mixture and how to proportion them.

Structural Design

For the purposes of structural design, engineers are primarily concerned about the rate of concrete strength development. The data have shown that ternary mixtures can be provided that achieve almost any strength at a given age by modifying the w/cm ratio and the SCM types and dosages. Therefore, from a purely structural design point of view, designers simply need to state their requirements. This is true for all types of concrete elements including columns, beams, elevated slabs, and slabs on grade.

A complication develops, however, if the system is likely to be exposed to an aggressive environment, and measures have to be taken to ensure sufficient durability. Structural design codes (ACI 318) classify aggressive environments in terms of exposure to freezing and thawing, sulfates, corrosion, or aggressive fluids. The imposed requirements include limits on maximum w/cm ratio, air content, cement type, and chloride content in the mixture. Cements are addressed by reference to factory blended materials (ASTM C 595 or C 1157), but the only reference to the use of SCMs is to impose maximum dosages in systems exposed to freezing and thawing or sulfate exposure. The code is silent with respect to alkali silica reaction.

It is up to the designer, therefore, to be aware of the environment in which the system will be used and to require that the mixture comply with the stated requirements. This still leaves considerable flexibility for the effective use of ternary mixtures that can be proportioned to enhance potential durability.

Slabs on grade add a further level of complication because their high surface-to-volume ratio makes them sensitive to shrinkage and thermal affects and the related risk of random cracking. This may be addressed at the design stage by the careful detailing of sawn joints or provision of sufficient steel to distribute cracking. Ternary mixtures will likely have a beneficial effect on reducing temperature related stresses and little effect on drying, and may increase plastic shrinkage risk because of delayed setting. An approach may be to pass risk of cracking onto the contractors and allow them to proportion ternary mixtures in accordance with their practices and the weather.

Mixture Design

Language currently in use defines mixture design as the activity of selecting the performance requirements for a mixture while proportioning is the process of selecting the materials and amounts to achieve that performance. In some cases, minimum or maximum amounts of SCMs may be called for in order to achieve goals such as protection from ASR or minimization of salt scaling risk. Mixture design also takes into account the structural requirements of the system, as well as the needs of the contractor to place, finish, and cure the concrete, such as workability parameters. Proportioning should be the responsibility of the contractor, but mixture design has to be a collaboration of both the engineer and the contractor.

Parameters that should be considered in the mixture design process include the following:

- Workability for the construction process, including uniformity limits. This will be influenced by the type and dosage of SCMs but is primarily controlled by water content and admixture usage.
- Setting time. This is strongly affected by SCM type and dosage, as well as the weather. In general, increasing SCM dosage will increase setting time. This parameter is not commonly controlled but is monitored for its effects on construction activities such as finishing and sawing.

- Cracking risk. This topic involves a complex combination of setting time, moisture and thermal gradients, stiffness, and strength. While risks can be addressed at the design stage, workmanship effects such as curing and sawing largely have a greater influence.

- Strength. Long term strength needs are governed by the structural requirements, while the rate of development is often controlled by construction practices. It is primarily governed by the w/cm ratio and influenced by SCM type and dose, the use of admixtures, and the weather, with cooler weather slowing development. Typically, any system that has environmental durability requirements will deliver greater strength than required structurally.

- Stiffness and creep. These properties affect structural performance and the cracking risk of an element but are rarely controlled in the mix design.

- Permeability. This parameter is a fundamental requirement for harsh environments and is, again, primarily controlled by the w/cm ratio with a strong influence from SCM type, dose, and degree of hydration.

- Durability. Prevention of distress due to ASR and sulfate attack is often best achieved through the judicious use of sufficient SCMs in the mixture. Air entraining admixture dosages may have to be adjusted with some SCMs.

- Sustainability. If sustainability is called for in the contract, then this may be increased with the use of increasing amounts of SCMs in the mixture. This must be balanced with the need to control the side effects of their use, particularly at high dosages, such as delayed setting and slower hydration.

Research and practice have indicated that for most everyday applications

- The cement content should be above 40 percent.
- Silica fume content should be less than 10 percent.
- Class F fly ash content should be less than 30 percent.
- Class C fly ash content should be less than 40 percent.
- Slag cement content should be less than 50 percent.

Minimum contents of 15 percent are suggested for fly ash and slag cement because little benefit is normally observed below this level. These limits are only guides and can be exceeded for some applications if mixtures are carefully proportioned and workmanship is tuned to the expected side effects.

Factors such as cost are local issues because, while a given product may be technically desirable, the cost of obtaining and hauling it to the site may make its use impossible. Proportioning then, should be based on materials that are readily available.

Interactions

The side effects and interactions of SCMs are summarized in Table 1 (Tikalsky 2011). In general, the effects of multiple products in a mixture will be additive; therefore, accelerated strength gain with one product plus lower strength gain from another will likely result in a neutral overall affect if both products are incorporated.

It should be noted that these trends are very broad and may not be valid for a given material because of the chemistry of the product and the rest of the mixture. Appropriate testing using the planned materials is essential to ensure that a mixture will perform as required.

Table 1. Summary of Side Effects and Interactions of SCMs

Properties	Supplementary Cementitious Material					
	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume	Metakaolin	Limestone
Workability	Significantly improved	Improved	Neutral / Improved	Improved at low dose (<5%), decreased at high dose	Decreased	Slightly improved
Air void system	May be difficult to entrain air with high LOI	Neutral	Neutral	May be difficult to entrain air	May be difficult to entrain air	Neutral
Setting	Delayed	Slightly delayed	Slightly delayed	Accelerated	Neutral	Neutral
Incompatibility	Low risk	Some risk	Low risk	Low risk	Low risk	Low risk
Strength gain	Slower but continues longer	Slightly slower but continues longer	Slightly slower but continues longer	Accelerated initially	Accelerated initially	Neutral
Stiffness	(Related to strength)					
Heat generation	Lower	Slightly lower	Slightly lower	Higher	Slightly higher	Slightly lower
Shrinkage	Neutral	Reduced	Neutral	Increased	Increased	Neutral
Permeability	Improved over time	Improved over time	Improved over time	Improved	Improved	Neutral
ASR	Improved	Improved at sufficient dosage	Improved at high dosages	Slightly improved	Improved	Neutral
Sulfate attack	Improved	Improved at sufficient dosage	Improved at high dosages	Neutral	Neutral	May be worse at high dosages in very cold environments
Corrosion Resistance	Slightly improved	Slightly improved	Improved	Improved	Improved	Neutral

Constructibility

The focus of the discussion in this section is about the changes in construction practice that are necessary when using ternary mixtures. Field experience gathered by Taylor (2012) has demonstrated that ternary mixtures can be used successfully for construction. While ternary mixtures can be designed and proportioned to yield a wide range of hardened properties, there are some side effects that may affect construction practices. These are discussed in the following sections.

Form Removal

Setting times may be extended for some combinations of materials, particularly those mixtures containing high dosages of SCMs and those with low alkali and calcium contents. For structural elements, this may require a delay in form removal times, particularly in cold weather. It is recommended that maturity based approaches be used to monitor strength development (ASTM C 1074) to ensure that safety is not compromised when forms are removed.

Joint Sawing

For slabs on grade, a delayed set may require changes in sawing practice, especially in cold weather. In addition, the sawing window may become very short because the mixture is gaining strength slowly while still shrinking. Consideration may be given to the use of early entry saws in such a setting. A combination of a very low alkali cement with a high dosage of slow reacting SCMs can lead to a situation where cracking risk is significant. Computer models such as HIPERPAV may provide a useful means of assessing or adjusting for risk before construction starts.

Surface Finishing

Surface finishing should not be started until bleeding has stopped to prevent soft lenses forming below the surface of the slab. In drying conditions, this may be a challenge because the surface starts to stiffen before bleeding stops. Changes in bleeding behavior of the mixture with the use of SCMs add to the complication. There is no simple rule of thumb that can be applied here, because bleeding is primarily controlled by the powder content of the mixture and the rate of hydration, both of which will vary significantly with changing materials and weather. It can be stated that changing the SCM type and dosage will change bleeding. Finer materials will slow bleeding or, in the case of silica fume, prevent it. On the other hand, slower setting will mean that bleeding will continue longer. It is recommended that trial slabs be prepared when using a new combination of materials so that the timing for finishing can be assessed. Tests can be conducted on trial batches to determine when bleeding occurs and how much.

Overall field experience has shown that finishing crews have had little difficulty working with ternary mixtures.

Curing

Curing, the practice of keeping a mixture warm and wet to promote hydration, becomes more critical in slowly hydrating systems because premature cessation of hydration will leave the mixture in a state well short of its potential performance.

In drying conditions with high dosages of SCMs, there is an increased risk that plastic shrinkage cracking will occur because the mixture is still losing water to evaporation even though it has not yet set. Use of evaporation retarders or provision of fog sprays will assist in reducing the risk of cracking.

In cold weather, extra effort may be required to keep slowly hydrating systems warm so that hydration may continue until required performance is achieved (Taylor 2013).

Extreme Weather

Many of the issues related to the use of ternary mixtures have been addressed in the discussion above. Lab tests demonstrated that mixtures could be prepared and cured at 50°F and 100°F and still perform satisfactorily. Differences in performance were largely consistent with expectations based on the chemistry and dosage of the SCMs used.

Quality Assurance

This section provides recommendations on the factors that will need special attention in quality control (QC) and acceptance activities.

Quality Control

A significant concern for quality control processes is that the product being delivered complies with the specifications and that it is similar (enough) to the product used in trial batches. Approaches that may be adopted when cementitious materials are delivered to the site include the following:

- Ensure that the right product is loaded into the right storage. Color coding connectors or using different size devices may help reduce the risk of error.
- Monitor key parameters provided with delivery tickets where possible.
- Note changes in color.
- Conduct calorimetry on samples of the cementitious system on delivery and note changes in the shape of the curve.

Changes observed may not be definitive about potential problems, but they do provide an early flag that something has been changed and should be investigated.

Blending of materials can be conducted in a cement plant, in which case products should comply with ASTM C 595. In many ways, this is to be preferred because the manufacturer is then able to optimize sulfate contents and minimize the risk of incompatibilities. Factory blends also mean that fewer silos are required at the batch plant. It is not uncommon to have a binary material in one silo and another SCM in a second silo. The downside is that blends are limited to those offered by the manufacturer, which may not be those required at a given site.

Care should also be taken to ensure that blend proportions are within tolerances. This requires careful calibration and monitoring of blending and batching facilities. While some variation may be acceptable, if a minimum amount of SCM is required for a specific purpose such as ASR protection, then large errors may be catastrophic in the long term.

Issues related to the effects on construction practices are discussed in the section on construction. Setting times and bleeding rates should be carefully monitored to note changes that may affect cracking risk. In all other ways, QC requirements are the same as those for conventional concrete.

Acceptance

Key acceptance parameters for ingredient materials or blends should be based on published standards including the following:

- ASTM C 150, C 595, or C 1157 for cements and blended cements
- ASTM C 618, C 989, C 1240, C 1697 or C 1709 for SCMs

Acceptance will be based on both of the following:

- The proportions of the mixture, ensuring that the cementitious blend meets the requirements of the project
- Mixture performance, such as strength development and permeability.

As such, normal acceptance procedures should be sufficient.

Specifications

Specification language used in trial projects (Taylor 2012) did little more than permit the use of ternary mixtures, lay out the ranges of percentages of SCMs required, and refer to existing materials requirements. One state required the use of HIPERPAV during bidding to ensure that cracking risk was acceptable. This requirement eventually led to the reduction in the amount of one of the SCMs because it was having a strong effect on early hydration in laboratory tests.

Typical Examples

Following is a summary of three locations that were demonstration projects using ternary mixtures (Taylor 2012).

Iowa Pavement

A ternary mixture was placed on an interstate pavement in Iowa. The cementitious system comprised a Type 1P cement (25 percent fly ash) blended with 15 percent Class C fly ash. Project facts include the following:

- Location: Monona County, Iowa
- Contractor: McCarthy Improvement Co.
- Rigid pavement improvement (southbound of Interstate 29 in Iowa) (Figure 6)

Figure 6. Interstate 29 in Iowa (southbound)

The following observations were made:

- Slab dimensions were 11 inches by 26 feet for the mainline and 7 inches by 6 or 8 feet for shoulders, which were tied to the mainline by #4 bars.
- The concrete was supplied from a central batch plant and was delivered to the job site in dump trucks. The plant had a 90-second mix time. Once in the truck, the mix had to be placed on the ground within 60 minutes without segregation.
- Workability and coarseness factors were 34.5 and 64.9, respectively. The combined aggregate gradation fell in the well graded region. Similarly, the combined percent retained curve indicated a well graded system.
- The relative humidity ranged between 21 percent and 89 percent. The ambient temperature ranged from 48°F to 88°F. The wind speed varied from 3 mph to 20 mph.
- The slump was 2.0 inches. The unit weight was 135.6 lb/ft^3. The water/cm ratio was 0.35.
- The air content was 8.75 percent from the one test conducted at the batch plant, which was slightly higher than the specified minimum, 6 percent..
- The initial setting time of the mix was at 2.32 hours.
- Properties of the hardened concrete are shown in Table 2.
- The visual rating of the mixture after 50 freeze thaw cycles (ASTM C 672) was "4."
- No difficulties were reported in placing the mixture.

Table 2. Properties of Hardened Concrete

Tests	Results		
7-day compressive strength, psi	4,860		
28-day compressive strength, psi	5,960		
Rapid chloride permeability, coulombs	Sample 1	Sample 2	Average
	980	1,413	1,197
Strength development 28/7 day fc ratio	1.23		
Shrinkage microstrain @ 28 days, in/in	183.30		
Average stress rate by restrained ring test, psi/day	28.21		

Pennsylvania Bridge Deck

A ternary mixture was placed on a bridge deck on State Road 36, section 20, in Pennsylvania. The cementitious system comprised 60 percent Type I/II cement, 30 percent Grade 100 slag cement, and 15 percent Class F fly ash. Project information includes the following:

- Location: Roaring Spring, Blair County, New07A42&07B42
- Contractor: Plum Contracting
- State Route 36, section 20
- Bridge deck placement (1 span—structural steel girders with concrete deck) (Figure 7)

The following observations were made:

- All concrete came from a fixed batch plant and was delivered to the job site in transit mix trucks. The concrete was placed using a conveyor belt.
- Contractors used form riding bridge deck paver. The bridge deck was 8 inches deep with a 2½-inch cover on the top layer of reinforcement and a 1-inch cover on the bottom layer of reinforcement.
- Cementitious materials included Type I/II portland cement (Holcim-Hagerstown, Maryland), Grade 100 slag cement (GranCem-Camden, New Jersey), and Class F fly ash (Headwaters-Sammis Plant). Dolomitic limestone coarse aggregate was used, and the fine aggregate was sandstone. An MBVR air entraining agent, Glenium 3030 water reducer, and 100XR retarder were used as chemical admixtures.
- The relative humidity ranged from 70 percent to 82 percent; the ambient temperature ranged from 69°F to 77.4°F; the wind speed varied from 0 mph to 7 mph; and the concrete temperature ranged from 73°F to 80.4°F during the recorded period.
- Slump varied from 3.0 inches to 6.5 inches. Unit weight was 147.3 lb/ft^3. The w/cm ratios obtained from microwave water-cementitious ratio tests were 0.50 and 0.46. The design value was 0.41.
- The air content varied from 5.0 percent to 7.1 percent, with an average value of 6.0 percent based on eight sets of testing. The specified minimum was 6 percent.
- Setting time of the mix was determined as a single measurement: initial set occurred at 3.63 hours and the final set was achieved at 10.96 hours.
- Hardened properties are shown in Table 3.
- The visual rating of the mixture after 50 freeze thaw cycles (ASTM C 672) was “2.”
- No difficulties were reported by the contractor. The DOT has indicated that it will permit future construction using ternary systems.

Figure 7. State Route 36, section 20, bridge deck in Pennsylvania

Table 3. Properties of Hardened Concrete

Tests	Results		
7-day compressive strength, psi	4,240		
28-day compressive strength, psi	4,700		
Rapid chloride permeability, coulombs	Sample 1	Sample 2	Average
	1,860	1,731	1,796
Strength development 28/7-day fc ratio	1.11		
Shrinkage microstrain @ 28 days, in/in	612.50		
Average stress rate by restrained ring test, psi/day	55.35		

New York Bridge Structure

A ternary mixture was placed on the I-86 bridge structure in Coopers Plains, New York (Figure 8). The cementitious system comprised a binary Type 1P cement (6 percent silica fume) blended with 20 percent Class F fly ash. The project information includes the following:

- High performance concrete project on I-86 at exit #42 (D261576, Steuben County)
- Contractor: Cold Spring Construction Co.
- Mix ID: C042911015
- I-86, Exit 42 rehabilitation (Meads Creek Road Reconstruction; pavement, drainage, signs, pavement markings and guiderail, and box culvert replacement) and bridge replacement (three composite girders), Town of Campbell (Figure 8)

Figure 8. I-86 Coopers Plains bridge abutment stem structure in New York

The following observations were made:

- The concrete was mixed at a central mix plant (Cold Spring Construction Co.) and transported to the construction site by ready-mix trucks (Hanson Heidelberg Cement Group).
- A blend of Type 1P, which contains 6 percent silica fume by mass (Whitehall, PA), and 20 percent Class F fly ash (Headwaters Resources) was used. The coarse and fine aggregates, crushed gravel and river sand, respectively, were obtained from Dalrymple Gravel & Contracting Co., Erwin, New York.
- Setting time of the mix was determined as a single measurement: initial and final sets occurred at 5.76 hours and 6.72 hours, respectively.
- The slump results were 3.75 inches and 4.00 inches; unit weights of concrete were determined as 138.2 lb/ft^3 and 138.0 lb/ft^3; w/cm ratios were found to be 0.46 and 0.47; and the air content were 6.5 percent and 7.3 percent, respectively. The design value for w/cm ratio was 0.40, and target air content was 6.5 percent.
- Hardened properties are shown in Table 4.
- The visual rating of the mixture after 50 freeze thaw cycles (ASTM C 672) was "2."
- No difficulties were reported by the contractor.

Table 4. Properties of Hardened Concrete

Tests	Results		
7-day compressive strength, psi	3,160		
28-day compressive strength, psi	3,970		
Rapid chloride permeability, coulombs	Sample 1	Sample 2	Average
	1,100	1,256	1,178
Strength development 28/7-day fc ratio	1.26		
Shrinkage μ-strain @ 28 days	693.00		
Porosity by boil test, %	5.90		

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