GGREGATE TESTS RELATED TO PERFORMANCE OF PORTLAND CEMENT CONCRETE PAVEMENT

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Introduction

Aggregate sources for use in concrete are changing in many areas of the country due to depletion of existing sources and the difficulty of opening new quarries and sand and gravel sources. Reasons for this include environmental and zoning regulations and the increased value of properties for development instead of mining. Aggregates are being transported longer distances; and, in the future, will have to be transported even further, adding to their effective cost, unless convenient water or rail transportation of aggregates into an area is available. The net result is that highway agencies will be asked to evaluate and approve a greater variety of aggregate sources for use in concrete.

A recent FHWA Publication on "Early Distress in Concrete Pavements" (Gress, 1997) and an interim guidance document on minimizing potential distress in concrete pavements provide recommendations for interim measures and research needs. (FHWA, 1997) A number of the topics discussed address the use of aggregates in PCCP for better performance related to alkali-aggregate reaction (AAR), workability, segregation, permeability, volume change, and freeze-thaw resistance. Aggregates are critical in PCCP.

Individual aggregate particle expansion, shrinkage, or deterioration is likely to cause a response or, if excessive, a problem in a stiff, brittle material, such as portland cement concrete. In a granular aggregate base or even asphaltic concrete, aggregate volume change and some aggregate breakdown can be accommodated in the flexible pavement system. However, in a rigid concrete, volume changes from aggregate distress will generally cause cracking or popouts. Cracks and void spaces created do not normally heal, and they accumulate moisture and salt solutions that continue the deterioration process.

The objective of this work is to provide a more efficient and accurate series of tests and techniques to assure, with good confidence, the selection of aggregates for concrete. An improved suite of tests and procedures should help to keep costs down while assuring quality. Cost saving should result if local materials can be used to the extent that performance is good. The challenge will be to identify the applications and environments where an aggregate will perform; and just as important where it will not perform. Techniques and methods will need to go beyond just the physical and mechanical tests that are normally used by civil engineers. Aggregates must also be evaluated by petrographic and chemical tests that will involve methods used by geologists, mineralogists, and physical chemists.

With aggregates moving longer distances -- across state and national boundaries in many cases -- savings will result if the tests and evaluation tools are more uniform from agency to agency so that each can understand and rely on testing by others when out-of state aggregates are proposed or required. Sand and gravel in the past has been a mainstay for concrete production; however, with depletion of local supplies much more use is now being made of crushed stone for both coarse and fine aggregate in concrete. This has implications in both the ordinary commercial and highway concrete in the 35 MPa to 50 MPa (3500 psi to 7000 psi) compressive strength range, but also to the new high performance concrete (HPC) applications that will demand high strength concrete along with optimized properties for the particular application.

For concrete pavement we may be looking toward the use of a wider range of strength levels -- perhaps from 25 MPa to 100 MPa (3500 to 15,000 psi) compressive strengths depending on the applications and materials available. While aggregate for HPC is considered outside the scope of this study, it should be considered for the validation of proposed aggregate testing protocols to expand the range of properties included in the research on the relation of existing and innovative tests to performance of PCCP. Core strength levels in some existing pavements have been reported as high as 8,000 to 10,000 psi, and several agencies are considering researching the use of higher strength for PCCP.

A better understanding of carbonate aggregates for use in concrete is needed. This goes the full range from dense, non-absorptive limestones and dolomites to the porous carbonate materials that are available in the southeast and in many areas in the great middle part of the country. Full understanding of the performance of both coarse and fine carbonate aggregates in concrete is needed. More manufactured carbonate fine aggregates are being used with success in concrete. However, there are sometimes workability and mixing water limitations. Many gravels in the mid-west are predominately carbonate, while the sands mined with them contain mostly harder siliceous minerals. Concrete research has shown that many of the weaker, absorptive carbonates perform better than might be expected both in strength and durability, but there are some notable exceptions. What is the effect of chemical reactions or bonds between cement paste and carbonate aggregates that usually gives higher strengths than would be expected for the W/C or W/C+P ratios? Why are many durable even when they have significant absorption values, and some are not?

Another issue with the use of carbonate fine aggregates in concrete is the resulting wet weather frictional properties of the concrete pavement. Means are needed to specify and insure the use of enough of the harder, non-polishing, minerals in aggregates to control the frictional properties of PCCP surfaces for a reasonable period of time, before an overlay or other type of surface rejuvenation is needed.

This NCHRP 4-20A report builds on the Interim Report submitted under NCHRP 4-20 (Fowler et al, 1996), with independent evaluation, additional literature research, and contacts with the 4-20 panel and others in agencies to determine what research could be done to develop a proposed set of aggregate tests and evaluations that are related to the performance of PCCP.

A laboratory study is proposed to evaluate selected aggregate tests and to verify the relationship between the selected aggregate tests and concrete performance. Then, the next step is to validate the set of tests and performance relationships with laboratory concrete research and PCCP performance in the field.

Chapter 1

Performance Parameters of Portland Cement Concrete Pavements (PCCP) Affected by Properties of the Aggregates

1.1 -- Introduction

1.1.1 -- Portland cement concrete performance parameters (of both fresh and hardened concrete) can be affected or influenced by the properties of the aggregates used in the concrete. Good performance, serviceability, and longevity of portland cement concrete pavement (PCCP) is not possible without concrete that performs as intended both during construction and after the pavement has been placed in service. An example is spalls at joints and cracks where placing and finishing characteristics related to aggregate grading and particle shape may build in weakened areas and areas with too much mortar. These areas may tend to spall when subjected to stress concentrations, shear forces, and more severe moisture and weathering conditions near a joint or crack. Aggregates can also contribute to spalls through direct aggregate freeze-thaw or alkali silica reactivity (ASR) deterioration of the concrete. Aggregates are certainly one of the basic building blocks of good PCCP, and in many cases it is not possible to overcome a performance problem related to aggregates by adjustments in other materials, changes in proportions, or changes in construction practices. In other cases such as ASR it may well be possible and economical to use alternative cementitious materials or pozzolans with the aggregate to prevent an expansive reaction.

1.1.2 -- Performance parameters of concrete that may be affected by aggregate properties are discussed here for jointed (plain and reinforced) concrete pavement (JCP), for continuously reinforced concrete pavement (CRCP), and also to some extent for PCCP overlays over concrete or asphalt pavement. However, this discussion is not intended to cover very thin overlays or specialized PCCP such as prestressed pavement, fiber reinforced concrete, or pervious (no-fines) concrete pavement designed to be permeable to water. High performance concrete (HPC), which for pavement may be a high strength or optimized concrete tailored to the service conditions expected, is discussed briefly but not considered fully in this report. HPC should be considered for inclusion in any validation research, although few PCC pavements have been built with design compressive strengths over 50 MPa (7000 psi). The boundaries of future experiments and data needs to be stretched so that the performance of optimized higher strength (and presumably much stiffer) pavements can be better understood, along with the effects of aggregates in those HPCs.

1.1.3 -- For the purpose of this discussion concrete performance parameters for JCP and CRCP are examined for the possible influence of aggregate properties in new construction on the performance and long term serviceability of the pavement. With respect to PCCP overlays, an overlay over existing asphalt pavement would be very similar to a new pavement over a stabilized firm base, assuming that deterioration and irregularities in the underlying asphalt pavement have been repaired. Issues that may be exceptions are the reflection of existing transverse cracks from the asphalt pavement through the concrete overlay, bonding of the concrete to the asphalt, drainage issues, and widening or offsets of the new pavement where it may span across the edge of the old pavement on to newly placed base material with different characteristics and movement than the abutting older pavement. The use of a coarse interlayer may be desirable to isolate the overlay from the layers below, but some of the inherent strength of the system may be lost. Addition of drainage layers and/or shoulder drains may also be necessary. For bonded PCCP overlays over PCCP recommendations have been published, but certainly aggregate effects on drying shrinkage and thermal properties should be considered, as well as, accommodation of underlying transverse joints and cracks. (DeLatte, et al, 1996)

1.1.4 – Overview -- Performance parameters affected by aggregates are identified and discussed in the sections below in two categories (Critical "C" and Lesser "L"), along with some of the intermediate factors ("F") which aggregates affect and which play an important role in the aggregates influence on these performance parameters:

a. Parameters of critical importance to concrete performance in PCCP. The selected parameters are listed here and in Table 1 at the end of this chapter. The reasons for these selections and relationships to aggregate properties are discussed in the following sections. These performance parameters are illustrated in the SHRP Distress Identification Manual (Strategic Highway Research Program, SHRP-P-338, 1993). The reader is directed to the diagrams and photographs on the pages in that manual for illustration and description of the distress modes. Note that the manual has separate sections for the two principal concrete pavement types – JCP and CRCP.

Critical PCCP Performance Parameters:
Joint and Crack Related:
    C1 – Transverse Cracking
    C2 -- Faulting of Joints and Cracks
    C3 -- Punchouts in CRCP

Consolidation, Workability Related
    C4 -- Spalling at Joints and Cracks

Freezing and Thawing Related
    C5 -- D-Cracking (Durability Cracking)

Alkali Aggregate Reaction (AAR) Related
    C6 – Map Cracking

Four of the above critical parameters tend to increase moisture availability in localized areas in cracks and depressions in and around the defect (C1,2,3, and 4), and the other two are exacerbated by the increased moisture (C5 and 6), and which in advanced stages allow greater access of moisture to the concrete through the cracks formed. Elevation difference and surface depressions will hold water on the concrete longer allowing susceptible aggregates to take on more moisture in the area of the joint or crack. A rougher pavement surface texture also will tend to hold water on the concrete longer, as well. Moisture damage to the subbase is generally needed for faulting to become serious.

b. Parameters generally of lesser importance to concrete performance in PCCP

<u>Lesser PCCP Performance Parameters:</u>

L1 -- Friction of Pavement Surface (Low Friction in Wet Weather)
L2 -- Longitudinal Cracking
L3 -- Popouts
L4 -- Wear and Abrasion of Pavement Surface
L5 -- Joint Staining

Two of these parameters of lesser importance also tend to increase moisture in localized areas (L2 and L3), while joint staining is probably an indicator that increases in moisture is, or has, occurred in the concrete adjacent to the joint or crack.

c. Below are several intermediate factors (that can be influenced by aggregate properties) that are related to the selected performance parameters:

<u>Intermediate Factors or Steps in Relating Properties to Performance:</u>

F1 -- Joint and Crack Movement (Crack Opening, Blow-ups)
F2 -- Fresh Concrete Workability
F3 -- Hardened Concrete (Strength and Toughness)
F4 -- Sawing Joints (Timing for Aggregate Hardness and Concrete Strength Development)
F5 -- Permeability of Uncracked Concrete
F6 -- Change in Air Entrainment in Fresh Concrete

These intermediate factors will be included under the discussion of the parameters and aggregate properties and tests where appropriate.

d. Other parameters that are necessary to the validation that aggregate properties and tests are related to performance of PCCP include:

-- Service Records of Specific Aggregate Sources and Types in PCCP
-- Performance of High Performance Concrete (HPC) in PCCP. (High Strength and/or Optimized Concrete)

1.2 -- <u>Performance Parameters of Critical Importance</u>. Each of these six parameters are considered of equal importance because poor performance in any of these areas can greatly decrease the service life of a PCCP and require premature maintenance, overlays, and/or reconstruction. Performance with respect to all of these critical parameters can be influenced by or related to aggregate properties.

1.2.1 -- **Transverse Cracking – C1**. Some type of transverse strain relief is required in all types of PCCP to accommodate the longitudinal movements due to thermal and moisture cycling, and the drying shrinkage of the concrete. Aggregate minerals and mineral grain structure in aggregate particles can influence concrete properties and volume change tendencies due to these factors. Certain aggregates will increase the magnitude of these movements. While typical designs generally assume uniform strains due to these non-load related volume-change factors over the cross section of the pavement, the truth is that non uniformity of temperature, moisture, and drying shrinkage with depth in the pavement causes slab warping (curling) tendencies, particularly in JCP, which decreases the spacing of transverse cracks or increases the severity of pumping and/or corner breaks, as loads pass over the pavement, because of loss of support under the pavement.

With JCP the spacing of joints is intended to be close enough to preclude major transverse cracks from opening. With reinforced JCP any transverse crack should be tight with differential movement minimized by intact steel reinforcing and aggregate interlock. In plain JCP a shorter joint spacing (30 feet or less) is generally used to try to eliminate transverse cracks and maintain aggregate interlock. (Childes, 1973) Aggregate effects on concrete volume change and linear movement due to thermal, moisture, and shrinkage properties of the concrete should be considered, along with the environment, pavement dimensions, and drag friction, in selecting joint spacing. When volume change is large enough there is a loss of aggregate interlock at the crack allowing more slab deflection and movement and impact forces on any reinforcing or remaining aggregate contact. This can cause rupture of the steel, spalling, faulting, and pumping.

For CRCP, transverse cracks are expected; and their spacing and tightness is dependent on many factors of geometry, environment, amount and details of steel placement, as well as the properties of the concrete as affected by aggregates. It is generally felt that more closely spaced, clustered transverse cracks are more harmful, lead to a more flexible CRCP pavement structure, and are more apt to degenerate into punchouts (discussed later). However, as stated by one FHWA pavement engineer interviewed and in several references (Burke,1979; Childs, 1973; and Tayabji, 1995) -- crack width governs the performance of CRCP -- if the distance between transverse cracks is too great they will open more, reducing aggregate interlock, and increasing the probability of rupture of the steel causing major transverse cracks, spalls, and punchouts.

In any PCCP, once a transverse crack has opened up and differential movements are permitted because of loss of aggregate interlock, and yielding or breaking of the steel (if any), the transverse crack begins to function as a joint and is subject to the same or worse problems since it will lack the proper load transfer devices normally included in jointed pavements receiving heavy traffic. This was documented in the report for the Ohio Test Road in Vermilion, Ohio (Stark, 1991) where the incidence of transverse cracking increased when the maximum size of the aggregate was decreased, and severe faulting occurred on most transverse cracks. Little or no faulting occurred on doweled transverse joints. Open cracks will increase the availability of moisture and soluble salts to the concrete nearby. In colder climates where deicing chemicals are used open cracks can promote localized corrosion of steel in reinforced pavement.

For PCCP overlays the concrete's thermal coefficient as well as its moisture shrinkage and swelling factors will affect transverse cracking of the overlay. The closer the matching of thermal properties between the new and old concrete, the better. (Hutchinson, 1982)

Other concrete properties such as tensile strength and strain capacity or creep before cracking may play an important role in determining how much strain can be accommodated before a crack forms, and these properties also play a role in the spacing of those cracks. Aggregates have an influence on tensile strength and stress-strain relationships, as well.

1.2.2 -- **Faulting of Joints and Cracks – C2 --** are serious progressive performance problems that are caused by loss of load transfer at the joint or crack. Certainly aggregate size, strength, bond, and toughness play a role in aggregate interlock at cracks and joints, and as indicated previously, any aggregate contribution to more thermal and moisture induced length change, or warping (curling) can increase the tendency for faulting. Corner cracks can result as well since aggregate interlock is lost in the portion of the slab near an edge or joint.

Roughness and ride quality is an associated performance parameter that is affected by several of the parameters selected for discussion in this chapter. Increases in transverse cracks, faulting of joints and cracks, and punchouts in CRCP, along with curling actions resulting from thermal and moisture gradients, will increase roughness. Because these more specific parameters are included as separate factors in PCCP performance, the more general parameter of rideability is not included as one of the listed performance parameters.

Aggregate will affect the modulus of elasticity (E) of the concrete -- another factor determining deflection under load, as it affects tendency to fault or tendency for corner breaks. For concrete of otherwise the same thickness and properties a stiff concrete with a higher E would not deflect as much under load, perhaps reducing pumping and forces on dowels, tie bars, and aggregate particles in the interlock zone of joints and cracks. A lower E would allow more deflection-related damage. However, with respect to corner breaks a lower E may allow more deflection without actually breaking.

Research has shown that consolidation of the concrete properly during placement is very important (proper density, minimized voids, and minimizing of segregation in the joint area). Any voids or weakened areas can lead to increased faulting and joint deterioration. (Hossain and Wojakowski, 1996) (Newlon, 1977) Also, once faulting has occurred the portion of the slab just beyond the joint in the direction of travel is lower and will tend to retain moisture and chlorides on that part of the pavement and channel additional moisture into the joint and any spalls or microcracks near it.

1.2.3 -- **Punchouts in CRCP – C3 --** are where concrete due to fatigue and loss of support breaks out a generally rectangular section of concrete between transverse cracks, usually in a wheel path near the pavement edge. The concrete section drops down or rocks to one side as it is pounded by wheel loads, creating a pothole that has to be repaired. Since the punchout area is lower than the surrounding pavement it tends to hold moisture and deicing salts and increase its availability to the surrounding concrete through cracks. A number of factors play a role, but aggregates effect on crack spacing and width, as well as their influence on shear resistance at cracks through aggregate interlock need to be investigated.

Flexing and fatigue of CRCP under wheel loads undoubtedly forms microcracks at the paste-aggregate interface. Tayabji, et al, in 1995 reported that CRCP pavements were subject to more flexing and curling at the outside edge where the steel could be overstressed allowing cracks to open too much. Many punchouts start in the wheelpath near the outside edge of the truck lane. How tenacious the aggregate bond is will have an effect on the reduction in strength and stiffness of the concrete in that area and the number of repetitions before a through crack is formed. Once a crack is formed the toughness and bond of the coarse aggregate in the interface zone will determine its resistance to punching through.

1.2.4 – **Spalling at Joints and Cracks -- C4 --** of PCCP generally occurs at transverse joints or cracks or at longitudinal joints or cracks. Occasionally spalls caused by corrosion of reinforcing steel may occur in uncracked areas away from joints. Spalling can progress into a very serious problem in a concrete pavement. Initially cracks develop around a potential spall area. Sometimes these incipient spall areas can be seen after a rain as the surface of the concrete is drying. They may tend to retain moisture longer or be surrounded by fine cracks that remain wet longer. These cracks allow moisture access to the concrete and with time a chunk of concrete is lost creating a void which allows water and debris to accumulate. These cause the surrounding concrete to stay moist longer following precipitation. It may be the beginning of a pothole that will have to be patched later. In areas where deicing salts are used, the cracks and hole allow chlorides to penetrate to and begin corrosion of steel reinforcing, tie bars, dowels, and any appurtenances imbedded in the concrete. Corrosion of steel causes corrosion products which are greater in volume that cause pressure to initiate new cracks and spalls.

Concrete properties that contribute to spall crack patterns at joints and cracks can be associated with aggregates and the effects of the aggregate on properties of both fresh and hardened concrete. For fresh concrete good concrete workability is necessary to assure proper consolidation of concrete against form surfaces and around steel embedments in the concrete. Voids, honeycombing, and weak areas may be the nucleus of a spall.

In addition, for hardened concrete, strength, integrity, and toughness is needed to resist forces at edges and joints which tend to knock off edges and corners. Impact from external forces such as snowplows or heavy trucks, or internal forces from pavement expansion and contraction, can cause spalls. Aggregate size, distribution, and bond plays a role in assuring these properties. Lack of bond with an aggregate surface and or expansion of a porous aggregate during freezing can help initiate a spall. Spalls may also progress from popouts near edges, joints, and cracks.

As indicated before, thermal and moisture length changes that lead to more joint and crack movement as well as lack of support due to pumping and curling, or the like, can be a factor in creating spalls.

Many spalls are associated with joint hardware and problems with its functioning. Impact, bearing, and shear loads are present in a working joint or crack. Properly controlled, strong, durable concrete is needed to provide aggregate interlock, and to provide strong, tough concrete encasing the joint hardware. This will help minimize the incidence of spalls.

Other forms of aggregate related distress (D-cracking and ASR) as they progress tend to form cracks parallel to edges of joints and cracks. As these cracks open, they may eventually break off creating a spall.

1.2.5 -- **D-Cracking, C5.** (a Gradual Freezing and Thawing Deterioration of Coarse Carbonate Aggregate Particles). D-Cracking (also called Durability Cracking) in concrete pavements is generally recognized and described as a coarse aggregate durability problem of some carbonate crushed stones and gravels. Occasionally a D-cracking-like pattern may be caused by inadequate air-void parameters in the mortar or deterioration of other fine grained rock in coarse aggregate such as a siltstone or shale of intermediate quality -- not porous enough to contribute to early popouts and localized cracking.

Larger maximum size of aggregate are more prone to D-cracking problems, and it is generally recognized that fine aggregate does not play a significant role in freeze-thaw deterioration. (Klieger, 1974 and 1978; and Gaynor, 1967)

D-Cracking develops over some time period, usually 5 to 15 years, depending on the pore properties of the aggregate and the freezing and moisture exposure of the pavement. Cross sections of affected PCCP show cracking in the coarse aggregate, often in a closely spaced parallel pattern, which begins near concrete surfaces exposed to higher moisture levels -- at joints, cracks, edges, and the underside of the slab. D-cracking pavements can give good service for many years, but eventually the deterioration along cracks, joints, and edges begins to cause spalling, opening of larger cracks, and general loss of integrity, which exposes additional aggregate particles to more moisture.

Once D-cracking is recognized, and it has begun in a pavement, the only action that might retard its progression is an improvement of drainage of water from the pavement. This can be done by providing better sealing of joints and cracks and/or providing edge drains to remove excess water from the subbase as rapidly as possible, and perhaps increasing the slope of shoulder. (Stark, 1991; and also the Clare Test Road in Michigan)

1.2.6 -- **Map Cracking, C6.** (Sometimes called random or pattern cracking.) Map cracking is a series of cracks generally only in the upper surface of the concrete in the pavement. The larger of these cracks may tend to be oriented in the longitudinal direction, is an indication that the interior (more moist) portion of the concrete has expanded causing the surface crack pattern. Very early surface cracking or crazing may be an indication of lack of curing or rapid drying of the surface. However, when the map cracking develops over an extended period, and tends to get worse with time, it is an indication of a gradual growth of the concrete in the PCCP. This groeth may be caused by a general pervasive alkali-aggregate reaction (AAR) in the interior concrete which is causing it to increase in volume. Cracking may start as parallel longitudinal cracks because of the restraint. As the map cracking develops, "larger cracks are oriented in the longitudinal direction of the pavement and are interconnected by finer transverse or random cracks." (SHRP P 338, 1993) The two types of AAR – (1) alkali silica reaction (ASR) and (2) alkali carbonate reaction (ACR) – are treated in detail in ACI 221R.X, 1997. If ASR is causing the expansion, petrographic examination of the concrete usually shows a gel reaction product in aggregates or surrounding the aggregate particles that are reacting with cement alkalis. The gel reaction product takes on water, expands and causes growth and cracking of the concrete. Cracks may radiate from the sites or particles where expansion is taking place. The reactivity and expansion is more rapid with higher temperature and moisture. Expansion and microcracking of the interior (more moist) concrete may also be caused by freezing and thawing deterioration of the mortar or coarse aggregate.

Note that other reactions not involving the aggregate may also cause internal expansion and map cracking, with the presence of ettringite in cracks and voids. Work is ongoing on this so-called delayed ettringite formation (DEF). This mechanism is considered beyond the scope of this report since it has not been conclusively related to aggregate properties.

1.3 -- Parameters generally of lesser importance to concrete performance in PCCP. Many of these performance parameters do not require major rehabilitation or reconstruction of a PCCP when problems occur. They may be controlled by job QC adjustments, milling or sawing grooves in the pavement surface, or perhaps an overlay during the life of the pavement.

1.3.1 – **Friction of Pavement Surfaces** Wet weather pavement friction on concrete surfaces is initially dependent on texture and the presence of hard minerals in the fine aggregate. (Meyer and Goodwin, 1972) It is only after much wear that the properties of the coarse aggregate come into play. If friction is not adequate there are surface treatments, grooving, and thin overlays that can be applied. Regular pavement management practices using skid trailer data normally can identify problem areas and type of aggregates that polish faster in service. Most agencies do not allow pure limestone to be used as 100 percent of the fine aggregate in a PCCP traffic surface because of its tendency to polish more rapidly.

Fine Aggregate Hardness and Polish Resistance. After initial cement paste texture wears from a PCCP surface, the fine aggregate minerals exposed at the surface are an important factor in the mico-texture of the surface and its wet-weather Friction Properties. Presence of hard (non-polishing) minerals is the most desirable or a mix of minerals that polish or deteriorate at different rates. This helps prevent the uniform polishing of like minerals on the surface. Specification control for fine aggregate is usually by source approval through the use of ASTM D 3042 Test for Acid Insoluble Residue in Carbonate Aggregates, petrographic analysis, and/or relation to past performance. The performance measurement for this property is skid trailer data, generally using AASHTO T 242, the full-scale friction trailer test, from the state's pavement management system. The field data can be used to rank fine aggregates once the initial texture has worn down. Some states rely on the acid insoluble test. It is only after major surface wear that coarse aggregate would play a role in the skid trailer data.

Polishing Tests of Coarse Aggregate -- Laboratory tests are used to qualify coarse aggregates with respect to wet weather **friction properties** and polishing. The coarse aggregate performance is much more important to asphalt pavements than to concrete. For this reason it is not recommended that this property of the coarse aggregate be given major emphasis for PCCP.

In the survey reported in the NCHRP 4-20, Phase I Report (Fowler, et al, 1996) 11 agencies reported that they had tests related to friction performance of PCCP surfaces. The two aggregate properties tested were insoluble residue and polish properties of aggregate.

1.3.2 -- **Longitudinal Cracking** normally can be tolerated in a PCCP; however, additional maintenance would be required to seal the crack and to fill any spalls that develop. It is not as critical a parameter as transverse cracks. Aggregate effects on the tendency to crack longitudinally are related to its effect on sawing timing in relation to the hardness of the aggregate and the rate of strength development of the concrete, and its effect on the magnitude of the warping stresses and movement. (Birle, 1987 and Okamoto, 1994) Reducing and eliminated early longitudinal cracking is more properly addressed through construction, and the timing and equipment used for sawing, than through control of aggregates. Aggregates that reduced the tensile strength of the concrete may also contribute to more frequent longitudinal cracking. Serious ASR or ACR or fatigue of PCCP from heavy repeated loading can also induce longitudinal cracking. Generally, measures to help control transverse cracking will also serve to reduce longitudinal cracking. These are the steps to reduce volume change due to drying shrinkage and thermal factors.

1.3.3 -- **Popouts** are not normally a serious problem in a PCC pavement as long as the frequency is low and they are not associated with a developing, deep seated freeze-thaw deterioration of the coarse aggregate or a developing alkali silica reactivity problem. Most coarse aggregate specifications allow a very small percentage of deleterious materials that may produce an occasional popout due to freeze-thaw or ASR. In the survey reported in the NCHRP 4-20, Phase I Report (Fowler, et al, 1996) 18 agencies reported that they had tests for the prediction of popout performance. The reported aggregate properties tested related to popouts were unsound aggregates, freeze-thaw, and chemical reactivity. It can be unsightly and occasionally popouts near an edge, joint, or crack will lead to a spall.

ASTM Specification C 33 for concrete aggregates has a limit of 5 percent chert particles in coarse aggregate with a specific gravity less than 2.40; Masters and Evans,1987, reported that in Illinois gravel concrete freeze-thaw research that the most expansive rock types included chert below 2.35 specific gravity, ironstones, silty dolomites, and weathered carbonates. Expansive chert pebbles near the surface of a freeze-thaw beam can cause a popout without causing expansion of the beam, but those in a critical position deep within the specimen core may contribute strongly to expansion of the specimen without causing a popout.

Freeze-thaw beams are more sensitive to positioning of expansive particles, and show more variability due to the size effect, than the larger pavement section. (Gaynor, 1967) Incidence of popouts in the surface of a PCCP will decrease for a particular source as the MSA is decreased. (Stark, 1991) Popouts, per se, as a performance parameter is not discussed further in this report. Of course, susceptible particles if present in larger percentages is potentially a more serious problem. These aggregates may cause D-cracking and such aggregates should be identified by the D-cracking related aggregate properties.

1.3.4 -- **Wear and Abrasion of Pavement Surface** is most severe in those areas where studded tires and chains are used and where these traction devices can cause rapid wearing of the mortar from the surface, exposing the coarse aggregate. Some of the highways leading to mountain pass and ski areas in the west often show this kind of wear. In those cases where the coarse aggregate is not hard and abrasion resistant, or with time even for hard aggregates, troughs will wear in the wheel paths. These troughs will puddle water creating a hydroplaning hazard, and increase moisture availability to the concrete. Ultimately an overlay or milling would be needed to restore proper drainage for the pavement. In areas with only normal tire traffic, surface wear is slow and polishing, loss of surface friction, will be the more important parameter.

In the survey reported in the NCHRP 4-20, Phase I Report (Fowler, et al, 1996) 11 agencies reported that they had tests related to abrasion and wear performance of PCCP surfaces. The aggregate properties listed were abrasion, wear, and hardness. It is presumed that most were referencing the LA abrasion test.

1.3.5 -- **Joint Staining** is sometimes a precursor of D-cracking; however, there are many pavements with stained joints, and some in non-freeze-thaw areas, that do not develop D-cracking. At this point there is no known relationship between the staining and aggregate performance, but more porous or absorptive aggregates may play a role in the movement of moisture or solutions containing dissolved solids in the region adjacent to cracks and joints. Also, the interface zone around aggregates may play a role as well. This parameter is not considered serious enough to warrant further consideration.

1.4 – Intermediate Factors

1.4.1 -- **Joint and Crack Movement.** Shortening and lengthening of concrete in PCCP slabs due to drying shrinkage, moisture, and temperature causes cyclic opening and closing of joints. As explained before, gradients of moisture and temperature can also cause warping (curling). To the extent that particular aggregates cause greater movements due to moisture and temperature changes in the concrete it makes it more difficult to properly seal joints and cracks and can lead to transverse cracks opening more. Increased opening reduces aggregate interlock and can promote faulting, particularly at undowled joints and open transverse cracks.

If incompressible materials or loose aggregate particles are allowed to restrain joint movements, localized spalls or more general blowups of transverse joints and cracks may result. Blowups can also be caused by deterioration of the PCCP that causes gradual growth in pavement slabs. In JCP when aggregates or other factors increase volume change movements, a close joint spacing should be used to reduce typical joint movement. More joints of course will increase costs and potential problems if other joint related deficiencies occur.

In CRCP, aggregates, which cause more potential volume change, will affect anticipated stress levels in the concrete perhaps requiring different percentage of steel to control transverse crack spacing

1.4.2 -- **Fresh Concrete Workability**. For proper placement of concrete in pavements a low slump, but workable, concrete is necessary. A number of aggregate properties can contribute or detract from a workable, placeable mixture:

-- Maximum Size
-- Grading
-- Particle Shape, Angularity, and Surface Texture
-- Minus No. 200 Fines
-- Generation of Fines in Handling, Mixing, and Placing

The grading and compatibility of all the particulate material in the mix influences strength. It has been said that we need to get away from recipe specifications. (Cole and Hall, 1997) Not only the design grading, but the consistency of grading expected in a well controlled project, is needed to minimize segregation and reduce the real variation of the concrete in the pavement. (Teng, 1997) Changes in grading or fines content also affects entrained air levels, which in turn affects workability as well. If the mixture is not workable, too much water may be added; and hand finished repairs will be needed in placing the pavement. Water additions or sprinkling will raise w/c, lower strength, and also increase the variability of strength within the pavement. In this scenario the weaker concrete would be at the surface, edges, and joints. Hand finishing repairs needed during placement can also lead to weak, over mortared material near the surface at edges and joints, as well as other defects. These are the very areas of the pavement facing the most severe environmental exposures and, in many cases, traffic-related impact loading as well.

Defects in PCCP from workability problems include the following:

-- Voids
-- Incomplete Consolidation
-- Bleeding Channels and Pockets
-- Edge Slump
-- Poor Rideability
-- Poor and Variable Texture
-- Difficulty Controlling Entrained Air
-- Over-Vibration that Results in Low Air Content

Several of these defects often play a role in the previously discussed six critical PCCP performance parameters, particularly spalling and joint and crack related performance.

Workability of paving concrete is difficult to measure and judge. Research to develop or adapt a workability measuring procedure for low slump concrete would be a real help in both the design and QC stages. Research by Kansas and the Corps of Engineers for the Air Force have pointed to the problems resulting from poor workability, incomplete consolidation, and variability in the material placed, particularly in the joint areas. (Hossain and Wojakowski, 1996) (Newlon, 1977) (Rollings, 1997) (LaFrenz, 1997). NCHRP 1-31 as summarized in Eye on ERES newsletter (1997) in the feature article on "The Long-Term Effects of Initial Pavement Smoothness" showed a 9 percent increase in pavement life correlated with concrete pavements that were built smoother to begin with. Work on developing a practical workability test for low-slump concrete is proceeding at the Corps of engineers.

1.4.3 – **Hardened Concrete (Strength and Toughness)**

Aggregates are an important factor in concrete strength and toughness. A number of the critical performance parameters – transverse cracking, faulting, punchouts, and spalling – are all affected by these hardened concrete properties. In many ways improvements in these areas through better selection and use of aggregates will improve PCCP performance. In research to validate the predictive effect of aggregate properties or tests on PCCP performance for these parameters, testing of the aggregate's effect on strength and toughness under both sustained and rapidly applied load could be used as a screening test. With respect to D-cracking and map cracking performance no evidence exists that increases in the mechanical properties of the concrete will be of benefit.

1.4.4 -- **Sawing Joints** with aggregates of different hardness will affect timing and equipment needed for sawing. (Birle, 1987; Okamoto, 1994, and The Concrete Sawing Committee of The Industrial Diamond Association) A very hard aggregate such as a quartzite or hard chert gravel may cause sawing to be slowed or delayed to minimize raveling. That may lead to drying shrinkage or thermal warping in a wide pavement that could cause cracking during the early strength gain stage. In extreme cases a difficult aggregate to saw may contribute to incipient spall sites. Performance problems related to joint construction and related longitudinal and transverse cracking may be reduced by proper construction and sawing techniques, equipment, and control.

1.4.5 -- **Permeability of Uncracked Concrete** may be important if steel reinforcing does not have sufficient cover or when corrosion of dowels, tie bars, or other joint hardware is a potential problem. More permeable concrete will become saturated faster in wet weather and exacerbate any tendency toward freeze-thaw durability problems. In areas where chlorides are applied for deicing purposes they can work their way to the embedded steel and cause corrosion, expansion, and spalling in the joint region. Aggregates that are more porous and those with poor bond can increase the concrete's permeability. Deicing salts in concrete and aggregates pores and cracks will tend to attract moisture and increase the degree of saturation. (Hudec and Achampong) Some aggregates and other ingredients in the mixture may have sufficient chlorides to initiate corrosion without an outside source of chlorides. Increase in permeability with time, and cyclic loading, may be an indicator of loss of bond of paste with aggregate surfaces allowing flow of liquid or gas through aggregate interface and zone micro-cracks. (Newlon, 1977) (Bentz, 1992) (Graves, 1992) (K. A. Snyder, undated)

1.4.6 -- **Change (Variation) in Air Entrainment in Fresh Concrete.** Variation in aggregate grading and minus No. 200 fines content can cause changes in the needed air-entraining admixture dosage to provide specified air contents. It is assumed that this problem will be picked up during QC tests and necessary adjustments in AE admixture dosage made. If it is not there can be variations in both workability and freeze-thaw resistance of the concrete in the pavement. Aggregates that tend to generate fines during handling, mixing, and placing operations can cause troublesome problems in the control of air. Also, segregation and variation of workability in stiff paving mixtures can make it difficult to entrain and control proper air levels. For the purposes of this report this performance parameter will be considered with fresh concrete workability and grading of the aggregate since proper workability and reduction in variability of grading should improve the consistency and control of entrained air in PCCP.

1.5 – Validation - Parameters critical to future design and understanding of performance of PCCP. These are issues that need to be addressed if concrete performance is going to be taken to a new level. More must be understood about the actual mechanisms of deterioration by examining concrete and aggregates in service. Also research and evaluation involving high performance concrete is needed to expand the scope of our data bases and design models.

1.5.1 -- **Service Records** of Specific Aggregate Sources and Types in PCCP. A standardized method needs to be developed to investigate and report the long-term performance of aggregates in concrete. This type of data is needed not only for the continued use of aggregates which do give good performance but which do not meet all of the specified criteria, but also to provide the factual basis for changes in specifications and test procedures. Service is a true performance parameter of the concrete and the aggregate in the concrete. Much information can be obtained by examining petrographically both the aggregate in service in concrete -- and the aggregate from the same or similar source. In many cases failure mechanisms in the concrete related to the aggregate should be apparent and the considerations necessary to avoid those problems can be incorporated specifically in the new project or more generally in the specifications for PCCP.

1.5.2 -- **Performance of High Performance Concrete (HPC) in PCCP**. More understanding is needed of how pavement will perform if the strength is, say, doubled and the stiffness increased a great deal as well. Would attributes such as less deflection (higher E), better aggregate bond (and better aggregate interlock at joints and cracks), and a harder surface translate into improved pavement performance? Most of the PCCPs in the US are not above 7000 psi compressive strength. Some in Europe are higher strength, and I understand that in the Seattle, WA area aggregates are such that 10,000 psi compressive strength in concrete pavements are achieved at normal cement contents. Going to a much higher strength level is now possible. It needs to be studied to see if the extra effort and expense would pay off in longer service life and lower life cycle cost. Other types of HPC may not involve great increases in strength, but the optimizing of other properties to improve PCCP performance.

1.6 – Summary of Important PCCP Performance Parameters Affected by Aggregates.

1.6.1 – Listed here and in Table 1 are the six critical performance parameters deemed to be most important to the selection and use of aggregates. Four of these – transverse cracking, spalling, D-cracking, and map cracking) were included on the survey reported in the NCHRP 4-20, Phase I Report (Fowler, et al, 1996). Many respondents had tests that were related to D-cracking [chemical reactivity (12) and freeze-thaw (3)] and map cracking [freeze-thaw (12), absorption (4), and pore size distribution (2)]. None identified any tests to address transverse cracking. No agencies indicated that they had tried any tests of aggregate related to thermal or drying shrinkage properties. Several agencies identified property tests that they tried to correlate with spalling of PCC [chemical reactivity (6) and aggregate-mortar bond (1)]. It is not known what bond test was used.

Joint and Crack Related

C1 -- Transverse Cracking
C2 -- Faulting of Joints and Cracks
C3 -- Punchouts in CRCP

Consolidation, Workability, Grading Related

C4 -- Spalling at Joints and Cracks

Freezing and Thawing Related

C5 -- D-Cracking

Alkali Aggregate Reaction (AAR) (Includes ASR and ACR) Related

C6 -- Map Cracking

Three other parameters (*) that were in the lesser importance category; however, they were cited in the 4-20 survey by several respondents as being related to aggregate tests. (These parameters are frictional resistance, popouts, and wear/abrasion.) They are included below.

Table--1 Selected PCCP Performance Parameters

Critical Performance Parameters --

- C1 Transverse Cracking
- C2 Faulting of Joints and Cracks
- C3 Punchouts in CRCP
- C4 Spalling at Joints and Cracks
- C5 D-Cracking (Durability Cracking)
- C6 MapCracking

Lesser Performance Parameters --

- L1 Friction of Pavement Surface
- L2 Longitudinal Cracking
- L3 Popouts
- L4 Wear and Abrasion of Pavement Surface
- L5 Joint Staining

the fines materials to judge its effect on drying shrinkage. These tests might take six months, but may be worth doing on a source approval basis.

2.2.3 -- **Fine Aggregate Particle Shape and Angularity**

Related to Critical Performance Parameters:
C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

Flat, elongated, and more angular particles in fine aggregates, particularly some crushed manufactured fine aggregate, impacts on the workability of the fresh concrete and generally requires more mixing water in the concrete. It is known that using an all crushed harsh manufactured fine aggregate makes it more difficult to place concrete with slip forming to achieve satisfactory rideability and tolerable edge slump. Poor workability can contribute to incomplete consolidation in the joint area, which is a cause of **spalling**. Higher mixing water will generally require higher cement contents and result in more drying shrinkage, and consequently more **transverse cracking**. Increases in drying shrinkage will, as stated above, cause cracks and joints to open more, thus decreasing aggregate interlock and increasing tendency for **faulting** and **punchouts**. It also puts more stress on the remaining aggregate interlock regions and allows larger incompressible particles to fall into joints and cracks. Both of these factors can increase **spalling**.

Often concrete paving contractors under those conditions opt for a 50-50 blend of manufactured and natural sand. It helps overcome the workability issue from both particle shape and grading problems. Manufactured sands tend to have more of the coarser and very fine sizes – whereas natural sands are generally plentiful in the middle No 16 to No 100 sizes.

2.2.4 -- **Coarse Aggregate Particle Shape and Angularity**

Related to Critical Performance Parameters:
C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

Coarse aggregate particle shape if spherical or cubical in nature and without severe angularity does not have a major effect on workability or other PCCP performance parameters, except perhaps bond if the particles are very rounded and have a smooth surface texture. However, an abundance of flat and/or elongated particles will harm workability and placeability thus contributing to **spalling** and other deterioration related to voids and incomplete consolidation. Poor workability leads to higher mortar contents in the mixture, which will increase drying shrinkage and frequency of **transverse cracking**, all other factors being equal. Also flat and elongated particles may initially contribute to good interlock at joints or cracks, but eventually thin particles will be easier to break causing increasing **faulting** in JCP and **punchouts** in CRCP.

Bond of cement paste with coarse aggregate surfaces is important to strength, durability, and aggregate interlock at joints and cracks. Rounded smooth aggregates will not bond as well as more angular particles with texture. Therefore, very spherical rounded particles may contribute to more **faulting**. Good quality limestones develop better bond. (Hsu and Slate)

From a performance standpoint the extremes of either very spherical and rounded or very flat, elongated, and angular are problematic. Particle shape between these extremes yields better performance. The new AASHTO Proposed Provisional Test by 4 -19 on Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading) may be a test of interest to identify the extremes without having to do detailed petrographic evaluations of particle shape and angularity using visual methods.

2.2.5 -- **Absorption, Porosity, and Specific Gravity**

Related to Critical Performance Parameters:
C5 – D-Cracking

These aggregate properties -- Absorption, Porosity, and Specific Gravity -- are generally interrelated for a given rock type; and, depending on the test method and specification approach taken, can be used interchangeably with appropriate limits. Koubaa, et al (1997) reported a high level of correlation between absorption and specific gravity. Some favor specific gravity, but that approach is confounded when different rock types are used with different mineral specific gravities. It is the total porosity and water holding capacity that is the property more directly related. For that reason absorption to water will be used in this discussion to represent all three. From a performance standpoint it is understood that a very low absorption aggregate is dense with little porosity to cause breakdown or durability problems in freezing and thawing that might cause **D-cracking**, popouts, or related map cracking in the concrete. Coarse aggregates having medium or higher absorption values may or may not contribute to **D-cracking** durability problems and further information and tests are needed to describe the link between higher absorption and durability. Several agencies specify a maximum absorption of coarse aggregate as a control to prevent the use of some freeze-thaw susceptible materials.

With respect to fine aggregate higher absorption usually does not lead to freeze-thaw breakdown of the concrete because of the small particle sizes. However, often it has been noted that higher absorption fine aggregates are related to degradation of the fine aggregate during mixing of the concrete and correlation may be possible between absorption, sulfate soundness, and attrition tests. (Meininger ASTM STP 169B)

2.2.6 – **Pore Properties: Pore Size Distribution, Surface Area, Pore Volume**

Related to Critical Performance Parameters:
C5 – D-Cracking

Total pore volume is generally related to water absorption; however, the method of soaking or saturation can give different results. Also it does not distinguish between size of pores and their distribution. Pore size distribution by mercury intrusion has shown that it is the small to intermediate pore sizes that are related to low durability. The sizes that are able to attract water by capillarity and fill enough of the pore space to create expansion and fracture upon freezing, causing **D-cracking** and sometimes popouts. Pore surface area can also be determined, but it is unduly influenced by the small pores. Water in extremely small pores either does not freeze or it occupies too small a volume to cause damage. Large pores in aggregates generally do not fill completely with water. In heterogeneous gravel materials these properties may vary substantially from particle to particle. In some carbonate aggregates deicing salts may initiate a chemical reaction or contribute to quicker saturation of coarse aggregates by the greater attraction of moisture to cracks and voids.

Pore systems that have a higher internal surface area and/or which are able to absorb water at a higher rate are generally related to non-durable coarse aggregates. In a study of Minnesota dolomite coarse aggregates the aggregates with a fine grain structure tended to perform poorer than those aggregates with a coarse grain structure. (Koubaa and Snyder)

2.2.7 – **Coarse Aggregate Durability and Soundness**

Related to Critical Performance Parameters:
C5 – D-Cracking

This property concerns the ability of aggregates to resist weathering actions so that the aggregate will not deteriorate or break down into smaller particles both before mixing into the concrete or, more importantly, after the concrete has been manufactured and placed into service in a weathering environment. (This property does not include breakdown due to wet or dry attrition or impact during movement, handling, batching, or mixing of concrete. Those properties are considered in subsequent sections.) In colder climate areas durability and soundness are usually considered to be resistance of aggregate to freezing and thawing exposure while moist or wet, resistance to **D-Cracking**. In areas not experiencing significant freezing, the action of wetting, drying, heating, cooling, and exposure to salts which can cause osmotic forces or exert pressure due to crystal growth when drying or swelling when rehydrating continue to be important considerations. Some rocks and minerals have seams of clays or other planes of weakness that can cause breakdown when exposed to weathering. Tests, discussed in the next chapter, either involve exposure of the aggregate to a freezing and thawing regime or a procedure intended to simulate cyclic pressures and volume change from freezing and thawing, heating and cooling, and/or wetting and drying, sometimes in the presence of a salt or other chemical solution.

Weathering of aggregate before mixing in concrete is not normally a problem. Aggregate products are generally processed to remove unsound materials, although small amounts may remain and are the subject of specification limits. Aggregate breakdown while exposed to weathering in stockpiles, bins, or while in transit can be detected in QC/QA testing. If this occurs red flags are raised to recheck the aggregate source for a change in properties, incomplete processing, or unsuitability for use in PCCP.

For aggregate in concrete subject to weathering research (Gaynor, 1967) has shown that it is the coarse aggregate durability and soundness properties have a much greater impact on the long term durability properties of concrete than the properties of the fine aggregate.

Lab Freeze-Thaw of Unconfined Aggregate -- Many states have used variations of this test as a quality and soundness indicator for coarse aggregate. Recent experience by several states point to a better relationship to durability performance in the field (**D-cracking, map cracking, and popouts**) when a salt or brine solution is used in the test. It appears that aggregates (particularly carbonate aggregates) are more susceptible to deterioration in concrete with the presence of deicing salts along with freeze-thaw cycles. The salts tend to attract moisture to cracks and voids keeping the concrete more moist, and the salts may play a role in additional chemical or physical deterioration reactions that may add to damage from freezing and thawing.

2.2.8 -- Thermal Coefficient of Aggregate

Related to Critical Performance Parameters:

- C1 – Transverse Cracking
- C2 – Faulting of Joints and Cracks
- C3 – Punchouts in CRCP
- C4 – Spalling at Joints and Cracks

– Thermal properties of concrete are influenced to a large extent by the thermal coefficient of the aggregates and the volume percentage that the aggregates occupy in the concrete mixture. As a general rule limestone and dolomite aggregates have a significantly lower thermal coefficient than siliceous aggregates. (Gaynor, Ytterberg, Carlson) Thermal expansion and contraction is a major factor in Joint Movements, Blow-ups, **Faulting, Punchouts, Spalling, Transverse Cracking, and Longitudinal Cracking.** Day-night diurnal temperature cycling is a contributing factor in warping and curling of slabs. Also, stresses and movement within slabs as they undergo seasonal changes – fully contracted in the coldest part of winter and subsequent expansion in summer -- influence how much cracks and joints open, whether aggregate interlock will be lost, and if opportunity for incompressables to enter and foul the joint movement process, contributing to **spalls** and blow-ups.

Even when dowels, reinforcing and tie bars are used, higher stresses and movement due to thermal and drying shrinkage of the concrete will create shear stresses near joints and cracks as the steel restrains forces due to expansion, contraction, warping, and curling. Any weak areas or durability related cracks in these areas could result in **spalls** and other forms of joint degradation. The more movement there is the more important is the proper installation and alignment of dowels. Aggregates can have a significant impact on both thermal movement and drying shrinkage. It is entirely possible that aggregates can cause a doubling of the volume change due to each of these factors.

2.2.9 – **Coarse Aggregate Drying Shrinkage**

Related to Critical Performance Parameters:

C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

Aggregate restrains the shrinkage of cement paste, which occurs upon drying after the moist curing period. The mineral make-up and crystal texture of some aggregate materials actually allows the particles to shrink and swell with changes in moisture. These aggregates do not restrain concrete shrinkage as well and can, in extreme cases, result in long-term drying shrinkage values twice or three times that with a more stable rock. Also, the presence of certain clay minerals as fines in the aggregate can mix with the cement paste increasing its drying shrinkage.

Although drying shrinkage results in only a contraction in the pavement on a long term basis, it, like thermal movements, contributes to Joint Movement, **Faulting, Punchouts, Spalling, Transverse Cracking, and Longitudinal Cracking**. Gradients in drying shrinkage and temperature in the pavement from top to bottom set up warping (curling) stresses that can tend to lift the slab off the base support creating the potential for cracks from overloading the section. (Ytterberg)

2.3 -- Mechanical Properties of Aggregates

2.3.1 – **Fine Aggregate Breakdown and Slaking in Wet Attrition**

Related to Critical Performance Parameters:

C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

It has long been felt that coarse and/or fine aggregate when subjected to attrition action in the presence of water – where both the action of the water as well as the rubbing together of the particles – creates a testing approach related to weathering and degradation of construction aggregates in handling and mixing, and in some cases in service. The Micro Deval test of CA and FA and the ASTM C 1137 fine aggregate attrition test, for example, has been related to performance of material in fresh concrete where generation of excess fines has caused workability problems with loss of slump, as well as problems controlling air entraining admixture dosage. Creation of fines will increase shrinkage and mixing water requirements. Resulting volume change can increase **transverse cracking,** as well as **faulting, and punchouts.** Decrease in workability causes problems in placing and finishing leading to **spalling.** Strength has also been affected when additional water has had to be added for workability. This type of breakdown is often not otherwise detected by routine laboratory methods.

2.3.2 -- **Coarse Aggregate Breakdown and Slaking in Wet Attrition**

Related to Critical Performance Parameters:

C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

Breakdown of coarse aggregate in a wet environment during mixing will cause similar effects as breakdown of fine aggregate above and affect fresh concrete workability and hardened concrete volume change properties, which in turn increase tendency for **Faulting, Punchouts, Spalling, and Transverse Cracking.** Since CA has less surface area than FA the creation of fines from the coarser materials is usually not as serious a problem. (Meininger, 1978;and Bureau of Reclamation)

2.3.3 -- **Coarse Aggregate Breakdown in Dry Impact, Attrition, and Abrasion**

Related to Critical Performance Parameters:

C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

Breakdown of coarse aggregate in a dry environment during handling and batching will usually cause degradation into larger, less harmful particles compared to the effects of breakdown of fine aggregate and coarse aggregate in a wet environment. Any increase in finer material and decrease in larger particles will affect fresh concrete workability and hardened concrete volume change properties, which in turn increase tendency for **Faulting, Punchouts, Spalling, and Transverse Cracking.** Since CA has less surface area than FA the creation of fines from the coarser materials is usually not as serious a problem.

2.3.4 – **Coarse Aggregate-Mortar Bond**

Related to Critical Performance Parameters:

C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

Bond properties are dependent on a number of factors, including:

- -- Aggregate surface texture
- -- Aggregate Angularity
- -- Surface Chemistry at the Interface (TTI surface energy work)

Many researchers have identified the interface zone of cement paste with aggregate as very important to the durability, strength, and corrosion resistance of concrete. Any lack of bond with CA will increase tendency for **transverse cracking**, and the inability of CA to create strength and interlocking in resisting **faulting, punchouts, and spalling**. A good way needs to be found to assess the quality and competency of the bond and the character of the interface zone. Often obtaining higher strength and lower permeability for High Performance Concrete is dependent on improving the bond and reducing weaker crystals (such as CaOH) and voids at the boundary. Silica fume used in concrete has been shown to improve bond and reduce permeability greatly. Cubical, textured crushed aggregate also has better bond and performance in high strength mixtures. References (Graves, K. A. Snyder, and Bentz)

Methods of assessing this bond might be mechanical tests of concrete, of aggregate surfaces with attached paste or mortar, permeability tests, or microscopic evaluations by observing the aggregate-paste interface or observing the effect of a dye or stain used in a thin section of the bonding zone. Hsu and Slate showed both the significance of the aggregate surface to bond strength, and the difficulty of getting consistent results from mechanical bond tests. Limestone had a higher tensile bond than granite or sandstone. Polished aggregate surfaces gave the lowest bond. No practical test for a direct measurement of bond of mortar with CA has been identified.

2.3.5 – **Stress - Strain Response of CA, Modulus of Elasticity, Creep, Impact**

Related to Critical Performance Parameters:

- C1 – Transverse Cracking
- C2 – Faulting of Joints and Cracks
- C3 – Punchouts in CRCP
- C4 – Spalling at Joints and Cracks

The modulus of elasticity of the rock material in the aggregate coupled with its bond to the paste or mortar will influence the overall modulus of elasticity of the concrete. The most direct approach to obtaining better estimates of the E of the concrete as affected by aggregate type, minerals, grading, and proportions is to measure E of the concrete mixture proposed in the laboratory or from core or cylinder specimens taken from concrete for the PCCP. In the evaluation of performance related to deflection and warping a good value of E will improve the accuracy of load related stress and deflection calculations and improve the understanding of performance parameters such as **transverse and longitudinal cracks** as well as Joint Movement, **faulting, punchouts, and spalling.**

Creep, Strain Capacity of Concrete Containing Aggregate -- Some concretes are able to give more and stretch more in tension before they crack; and, short of using fibers to improve this extensibility, there is merit in determining what properties of aggregates contribute to this desirable performance. The Corps of Engineers has done research and developed a test method on strain capacity of concrete. Some of the questions that need to be asked include whether an increase in concrete strength consequently dictates that the concrete will be stiffer and more brittle in its cracking tendencies.

Modulus of elasticity of concrete in tension, as affected by aggregate, may have an influence on the spacing of **Transverse Cracks**. For HPC the effect of the interface zone on micro-cracking and developing full strength of the aggregate influences the E that can be obtained.

2.3.6 -- **Strength of Coarse Aggregate**

Related to Critical Performance Parameters:
- C1 – Transverse Cracking
- C2 – Faulting of Joints and Cracks
- C3 – Punchouts in CRCP
- C4 – Spalling at Joints and Cracks

Normally the strength of the rock material in the aggregate is not measured. Instead the effect of the aggregate on concrete strength is tested through comparative tests of aggregates in concrete by flexure and/or compressive strength.. Actual strength or modulus of elasticity of aggregate materials might be measured by non destructive means, by extracting small cores from an aggregate for testing, or by crushing a collection of particles in a confining ring such as in the British Crushing Value test.

Strength of aggregate is one of the factors in the load transfer through aggregate interlock at cracks and joints and will have an influence on **Faulting** and **Punchouts** as performance parameters. A test on a collection of particles such as the British Crushing Value may be a valid test of the toughness of aggregates in joints and cracks when subjected to shear and impact under loading. Strength of aggregate also helps concrete resist **transverse cracking and spalling.**

2.4 – Petrographic/Chemical Properties of Aggregates

2.4.1 – **Mineral Structure of Coarse and Fine Aggregate**

Related to Critical Performance Parameters:
- C1 – Transverse Cracking
- C2 – Faulting of Joints and Cracks
- C3 – Punchouts in CRCP
- C4 – Spalling at Joints and Cracks
- C5 – D-Cracking
- C6 – Map Cracking

The use of basic and advanced petrographic methods by a trained geologist or mineralogist is essential to the proper description of aggregate materials and an understanding of the performance of these materials in concrete. Petrography can provide an early evaluation of the attributes of an aggregate, such as a **D-Cracking** limestone for example, and an identification of potential problems which should be investigated further such as the presence of shale, potential ASR causing **Map Cracking**, porous chert particles causing Popouts, impurities of other types, or the presence of mica in fine aggregates affecting Workability.

Petrography is also very important in establishing Service Records for aggregates. An accurate petrographic description of the aggregate source will help in evaluating, later, the performance of the aggregate in PCCP.

2.4.2 – **Elements Present in Aggregates**

Related to Critical Performance Parameters:
C5 – D-Cracking

Methods are available to determine the quantity of different element in aggregate samples and from these quantities calculate the theoretical percentages of the different principle oxides. Recent research in Iowa and Minnesota using more sophisticated chemical and physical evaluation tools in research relating these properties of carbonate aggregates to performance both with respect to **D-Cracking** of pavements subjected to deicing salts and suspected reactivity in some cases which may be related to **D-Cracking and Map Cracking**. If further research is proposed for carbonate aggregates, work with these techniques is recommended to better understand the performance of limestone and dolomite aggregates in concrete. These types of aggregates are major national aggregate sources, and more work in developing techniques to better classify and understand the performance related properties of the full range of carbonate aggregates for use in different climate areas would be valuable information for highway agencies and to aggregate producers, as well, in selecting sources of aggregates for concrete.

2.4.3 – **Compounds Present in Aggregates**

Related to Critical Performance Parameters:
C5 – D-Cracking

Also, the recent research in Iowa and Minnesota used sophisticated thermal evaluation tools in research relating compound properties of carbonate aggregates to performance with respect to **D-Cracking** of pavements subjected to deicing salts. Again, if further research is proposed for carbonate aggregates, work with these techniques is recommended to better understand the performance of limestone and dolomite aggregates in concrete.

2.4.4 – **Fine Aggregate Mica Content.**

Related to Critical Performance Parameters:

C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

As reported by ACI Committee 221 (ACI 221, 1996) small amounts of mica in fine aggregate are not harmful, but as the amount rises it increases mixing water requirement and bleeding tendency of concrete and can reduce workability and strength of concrete. These actions can increase **transverse cracking ,faulting, punchouts, and spalling**

2.4.5 – **Organic Impurities.**

Related to Critical Performance Parameters:

C1 – Transverse Cracking
C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

Substantial organic material in the aggregate is a rare problem that is probably not worth further discussion and research. If the problem is found, it is normally corrected rapidly by a change in processing or source. Organics can affect strength of concrete and can have an effect on setting time and air-entrainment of the fresh concrete. Lower strength will increase transverse cracking, **faulting, punchouts, and spalling**

2.4.6 – **Chlorides in Aggregates**

Related to Critical Performance Parameters:

C2 – Faulting of Joints and Cracks
C3 – Punchouts in CRCP
C4 – Spalling at Joints and Cracks

Chlorides in aggregates is not a property that is normally looked at with respect to PCCP. However, if **spalling** or other deterioration around joint hardware or reinforcing steel is a problem, corrosion of steel may be a contributor to this type of long-term performance problem. Severe corrosion of reinforcing steel may cause rupture and **faulting** at cracks or **punchouts** in CRCP. Restrictions on the chloride in the ingredients, as well as, mixtures which are more impermeable to the movement of chlorides are approaches used to solve the problem.

From an aggregate perspective there are some carbonate aggregates that test high in chlorides when the material is ground to a fine powder and the chlorides are extracted with an acid. Another test (the Soxhlet Extraction using pieces of aggregate) is probably related more to the actual availability of chlorides in concrete, and it can be used for aggregates as a referee test if those aggregates otherwise test high in chlorides. ACI Committee 222 on corrosion of steel in concrete has published a recommended test and limits.

Many good performing carbonate aggregates have high chloride contents which do not appear to be available for deleterious corrosion of steel in concrete.

2.4.7 – **Reactivity with Alkalis in Concrete.**

2.4.7.1 -- **ASR Reactivity**

Related to Critical Performance Parameters:
C6 – Map Cracking

Recently much attention has been given to aggregate reactivity in concrete. A new report has just been completed on the subject by ACI Committee 221 on aggregates. Confirmed expansion due to alkali silica reactivity (ASR) will result in **map cracking** and in advanced stages longitudinal cracking. Petrographic and laboratory techniques are available to identify potentially reactive minerals. One of the problems is that these procedures often identify many aggregates which have not shown any significant ASR in service, and if all aggregates so identified are excluded from use in concrete, the impact on aggregate and transportation costs for concrete materials could be substantial in many areas. Technology for the use of pozzolans and blended cements to prevent ASR is improving rapidly and research efforts are on-going. One of the critical problems now in the mid-west is the proper identification of ASR as the agent causing deterioration as opposed to other chemical factors not related to the aggregate. Research by others is being done on this and it appears outside of the scope of the 4-20 study.

2.4.7.1 -- **ACR Reactivity**

Related to Critical Performance Parameters:
C6 – Map Cracking

Alkali carbonate reactivity (ACR) is a more limited problem known to exist in certain geographical areas and carbonate rock ledges. This mechanism is covered in some detail in the new ACI 221 report on alkali-aggregate reactivity. Damaging ACR expansion will cause **map cracking** and, in extreme cases, significant expansion. Petrographic and laboratory methods are available to identify carbonate rocks with the potential problem. Because of the limited extent geographically of ACR, national research is not recommended.

Table–2a Linkage Between Aggregate Tests, Aggregate Properties, and Performance Parameters
12/31/97

Performance Parameter – **No. C1 Transverse Cracking**
Below Properties Influence Volume Change and Warping/Curling Tendencies
Except CA Bond with Mortar Which Influences PCC Tensile Strength

Aggregate Property	Aggregate Test	Technique or Modif.	Rank	Validation Approach
Physical —				
Gradation, CA&FA	Sieve Analy.& -75µm	T 27 & T 11	_1	Accepted Test
	Comb.Grading&MSA	By Calculation	_1	Accepted Test
Fines Charac. -75µm	(none)	Mech. Size Dist.	_2	Compare These Test Results with Concrete Shrinkage and Mix Water Requirements
▪	Sand Equiv.	T 176	_3	
▪	Methylene Blue	TP___ (From 4-19)	_1	
	Minerals, Clay	XRD of Fines	_4	
FA Particle Shape	Uncompacted Voids	T 304	_1	Compare These Tests To Mix Water Demand; Visual Too Tedious
	Particle Index	ASTM D 3398	_3	
	Proposed CAR Test	Proposed	_2	
	Petrographic, Visual	C 295	_4	
CA Particle Shape	Uncompacted Voids	TP___ (From 4-19)	_1	Compare These Tests To Workability and Strength in Concrete and to Bond of CA in Concrete
	Particle Index	ASTM D 3398	_2	
	Computer Image	Developmental	_3	
	Crushed Faces	D 5821	_5	
	Petrographic, Visual	C 295	_6	
	Flat & Elongated	D 4791	_4	
Thermal Coef.CA&FA	Dilatometer	Aggr. in Liquid-TAMU	_2	New Proposed
	Dilatometer	ASTM Dilatometer	_1	Adapt an Existing Meth.
	Petrographic	Assume Fr. Minerals	_3	(Conpare to TCE of Concrete)
	Rock Core/Particle	Direct Measurement	_4	
CA Drying Shrinkage	(none)	Particle Measurment	_1	Compare to Drying Shrinkage of the Concrete
	(none)	Dilatometer Wet-Dry+	_3	
	Petrographic	Mineral&Rock Prop.	_2	
Mechanical —				
CA Breakdown in Wet Attrition, Slaking:				
	Duribility Index	T 210	_2	Compare to Worability and Shrinkage of Concrete
	Micro Deval of CA	Ontario LS-618	_1	
FA Breakdown in Wet Attrition, Slaking:				
	Micro Deval of FA	CSA A23.2-23A	_1	Compare to Worability and Shrinkage of Concrete
	Vane Attrition	ASTM C 1137	_3	
	Duribility Index	T 210	_2	
CA Breakdown in Dry Attrition, Abrasion, Impact:				
	LA Abrasion Test	T 96	_1	Accepted Test
CA-Mortar Bond	Surface Energy	Texas A&M Method	_1	Compare to Strength and to Evaluation of Mortar to CA Bond
	(none)	Petrographic, Surface	_2	
	(none)	Meas. Surf. Texture	_3	
	Cleanness Value-CV	Caltrans Test 227	_4	
CA Stress-Strain	Sustained (none)	Rock Core	_2 Cr. St.	Compare to Strength and Fatigue
	Impact (none)	Rock Core, Dyn E	_1	
CA Strength	British Crush Value	BS ____	_1	Compare to Strength and Fatigue
	Rock Core	ASTM D 2938	_2	
	British Impact Value	BS ____	_3	
Petrographic/Chemical —				
Agg Mineral Structure	Petrographic Eval.	C 294/C 295	_1	
	XRD		_2	
FA Mica Content	Petrographic Eval.	C 295, Point Count	_1	
	XRD		_2	
Fines Charac. -75µm	XRD (See Above for Same Property Listing Under Physical Properties, Next to Other Options)			
Organic Impurities	Colorimetric FA, CA	C 40 or C 40 Modif.		
	Petrographic Eval.	C 294, Wood, Coal ...		
	Heavy Liquid, C 123	Wood, Coal, Lignite ...		

Table–2b Linkage Between Aggregate Tests, Aggregate Properties, and Performance Parameters

Performance Parameter – **No. C2 Faulting of Joints and Cracks**
For Aggr. Interlock – Grading, MSA, and CA Shape, Angularity, Strength, Bond
For Joint/Crack Movement – Grading, MSA, Shape, Thermal, Dry Shr., Fines Charac.

Aggregate Property	Aggregate Test	Technique or Modif.	Rank	Validation Approach
Physical —				
Gradation, CA&FA	Sieve Analy.& -75µm	T 27 & T 11	_1	Accepted Test
	Comb.Grading&MSA	By Calculation	_1	Accepted Test
Fines Charac. -75µm	(none)	Mech. Size Dist.	_2	Compare These Test Results with Concrete Shrinkage and Mix Water Requirements
	Sand Equiv.	T 176	_3	
	Methylene Blue	TP___ (From 4-19)	_1	
	Minerals, Clay	XRD of Fines	_4	
FA Particle Shape	Uncompacted Voids	T 304	_1	Compare These Tests To Mix Water Demand; Visual Too Tedious
	Particle Index	ASTM D 3398	_3	
	Proposed CAR Test	Proposed	_2	
	Petrographic, Visual	C 295	_4	
CA Particle Shape	Uncompacted Voids	TP___ (From 4-19)	_1	Compare These Tests To Workability and Strength in Concrete and to Bond of CA in Concrete
	Particle Index	ASTM D 3398	_2	
	Computer Image	Developmental	_3	
	Crushed Faces	D 5821	_5	
	Petrographic, Visual	C 295	_6	
	Flat & Elongated	D 4791	_4	
Thermal Coef.CA&FA	Dilatometer	Aggr. in Liquid-TAMU	_2	New Proposed Adapt an Existing Meth. (Compare to TCE of Concrete)
	Dilatometer	ASTM Dilatometer	_1	
	Petrographic	Assume Fr. Minerals	_3	
	Rock Core/Particle	Direct Measurement	_4	
CA Drying Shrinkage	(none)	Particle Measurment	_1	Compare to Drying Shrinkage of the Concrete
	(none)	Dilatometer Wet-Dry+l	_3	
	Petrographic	Mineral&Rock Prop.	_2	
Mechanical —				
CA Breakdown in Wet Attrition, Slaking:				
	Duribility Index	T 210	_2	Compare to Worability and Shrinkage of Concrete
	Micro Deval of CA	Ontario LS-618	_1	
FA Breakdown in Wet Attrition, Slaking:				
	Micro Deval of FA	CSA A23.2-23A	_1	Compare to Worability and Shrinkage of Concrete
	Vane Attrition	ASTM C 1137	_3	
	Duribility Index	T 210	_2	
CA Breakdown in Dry Attrition, Abrasion, Impact:				
	LA Abrasion Test	T 96	_1	Accepted Test
CA-Mortar Bond	Surface Energy	Texas A&M Method	_1	Compare to Strength and to Evaluation of Mortar to CA Bond
	(none)	Petrographic, Surface	_2	
	(none)	Meas. Surf. Texture	_3	
	Cleanness Value-CV	Caltrans Test 227	_4	
CA Stress-Strain	Sustained (none)	Rock Core	_2 Cr. St.	Compare to Strength and Fatigue
	Impact (none)	Rock Core, Dyn E	_1	
CA Strength	British Crush Value	BS ____	_1	Compare to Strength and Fatigue
	Rock Core	ASTM D 2938	_2	
	British Impact Value	BS ____	_3	
Petrographic/Chemical —				
Agg Mineral Structure	Petrographic Eval.	C 294/C 295	_1	
	XRD		_2	
FA Mica Content	Petrographic Eval.	C 295, Point Count	_1	
	XRD		_2	
Fines Charac. -75µm	XRD (See Above for Same Property Listing Under Physical Properties, Next to Other Options)			
Organic Impurities	Colorimetric FA, CA	C 40 or C 40 Modif.		
	Petrographic Eval.	C 294, Wood, Coal …		
	Heavy Liquid, C 123	Wood, Coal, Lignite …		
Cl in Aggregate	Chem Analysis for Cl	Acid Sol. C 1152	_1	
		Water Sol. C 1218	_2	
		Soxhlet Extr. ACI 222.	_3	

Table–2c Linkage Between Aggregate Tests, Aggregate Properties, and Performance Parameters

Performance Parameter – **No. C3 Punchouts In CRCP**
For Aggr. Interlock – Grading, MSA, and CA Shape, Angularity, Strength, Bond
For Crack Movement – Grading, MSA, Shape, Thermal, Dry Shr., Fines Charac.

Aggregate Property	Aggregate Test	Technique or Modif.	Rank	Validation Approach
Physical —				
Gradation, CA&FA	Sieve Analy.& -75µm	T 27 & T 11	_1	Accepted Test
	Comb.Grading&MSA	By Calculation	_1	Accepted Test
Fines Charac. -75µm	(none)	Mech. Size Dist.	_2	Compare These Test Results with Concrete Shrinkage and Mix Water Requirements
▪	Sand Equiv.	T 176	_3	
▪	Methylene Blue	TP___ (From 4-19)	_1	
	Minerals, Clay	XRD of Fines	_4	
FA Particle Shape	Uncompacted Voids	T 304	_1	Compare These Tests To Mix Water Demand; Visual Too Tedious
	Particle Index	ASTM D 3398	_3	
	Proposed CAR Test	Proposed	_2	
	Petrographic, Visual	C 295	_4	
CA Particle Shape	Uncompacted Voids	TP___ (From 4-19)	_1	Compare These Tests To Workability and Strength in Concrete and to Bond of CA in Concrete
	Particle Index	ASTM D 3398	_2	
	Computer Image	Developmental	_3	
	Crushed Faces	D 5821	_5	
	Petrographic, Visual	C 295	_6	
	Flat & Elongated	D 4791	_4	
Thermal Coef.CA&FA	Dilatometer	Aggr. in Liquid-TAMU	_2	New Proposed
	Dilatometer	ASTM Dilatometer	_1	Adapt an Existing Meth. (Conpare to TCE of Concrete)
	Petrographic	Assume Fr. Minerals	_3	
	Rock Core/Particle	Direct Measurement	_4	
CA Drying Shrinkage	(none)	Particle Measurment	_1	Compare to Drying Shrinkage of the Concrete
	(none)	Dilatometer Wet-Dry+E	_3	
	Petrographic	Mineral&Rock Prop.	_2	
Mechanical —				
CA Breakdown in Wet Attrition, Slaking:				
	Duribility Index	T 210	_2	Compare to Worability and Shrinkage of Concrete
	Micro Deval of CA	Ontario LS-618	_1	
FA Breakdown in Wet Attrition, Slaking:				
	Micro Deval of FA	CSA A23.2-23A	_1	Compare to Worability and Shrinkage of Concrete
	Vane Attrition	ASTM C 1137	_3	
	Duribility Index	T 210	_2	
CA Breakdown in Dry Attrition, Abrasion, Impact:				
	LA Abrasion Test	T 96	_1	Accepted Test
CA-Mortar Bond	Surface Energy	Texas A&M Method	_1	Compare to Strength and to Evaluation of Mortar to CA Bond
	(none)	Petrographic, Surface	_2	
	(none)	Meas. Surf. Texture	_3	
	Cleanness Value-CV	Caltrans Test 227	_4	
CA Stress-Strain	Sustained (none)	Rock Core	_2 Cr. St.	Compare to Strength and Fatigue
	Impact (none)	Rock Core, Dyn E	_1	
CA Strength	British Crush Value	BS ___	_1	Compare to Strength and Fatigue
	Rock Core	ASTM D 2938	_2	
	British Impact Value	BS ___	_3	
Petrographic/Chemical —				
Agg Mineral Structure	Petrographic Eval.	C 294/C 295	_1	
	XRD		_2	
FA Mica Content	Petrographic Eval.	C 295, Point Count	_1	
	XRD		_2	
Fines Charac. -75µm	XRD (See Above for Same Property Listing Under Physical Properties, Next to Other Options)			
Organic Impurities	Colorimetric FA, CA	C 40 or C 40 Modif.		
	Petrographic Eval.	C 294, Wood, Coal ...		
	Heavy Liquid, C 123	Wood, Coal, Lignite ...		
Cl in Aggregate	Chem Analysis for Cl	Acid Sol. C 1152	_1	
		Water Sol. C 1218	_2	
		Soxhlet Extr. ACI 222.1	_3	

Table--2d Linkage Between Aggregate Tests, Aggregate Properties, and Performance Parameters

Performance Parameter -- **No. C4 Spalling at Joints and Cracks**
Lack of Workable Concrete That Can Be Consolidated and Finished Properly
Strength, Toughness Under Impact Loading

Aggregate Property	Aggregate Test	Technique or Modif.	Rank	Validation Approach
Physical --				
Gradation, CA&FA	Sieve Analy.& -75µm	T 27 & T 11	_1	Accepted Test
	Comb.Grading&MSA	By Calculation	_1	Accepted Test
Fines Charac. -75µm	(none)	Mech. Size Dist.	_2	Compare These Test Results with Concrete Shrinkage and Mix Water Requirements
	Sand Equiv.	T 176	_3	
	Methylene Blue	TP___ (From 4-19)	_1	
	Minerals, Clay	XRD of Fines	_4	
FA Particle Shape	Uncompacted Voids	T 304	_1	Compare These Tests To Mix Water Demand; Visual Too Tedious
	Particle Index	ASTM D 3398	_3	
	Proposed CAR Test	Proposed	_2	
	Petrographic, Visual	C 295	_4	
CA Particle Shape	Uncompacted Voids	TP___ (From 4-19)	_1	Compare These Tests To Workability and Strength in Concrete and to Bond of CA in Concrete
	Particle Index	ASTM D 3398	_2	
	Computer Image	Developmental	_3	
	Crushed Faces	D 5821	_5	
	Petrographic, Visual	C 295	_6	
	Flat & Elongated	D 4791	_4	
Thermal Coef.CA&FA	Dilatometer	Aggr. in Liquid-TAMU	_2	New Proposed
	Dilatometer	ASTM Dilatometer	_1	Adapt an Existing Meth.
	Petrographic	Assume Fr. Minerals	_3	(Conpare to TCE of Concrete)
	Rock Core/Particle	Direct Measurement	_4	
CA Drying Shrinkage	(none)	Particle Measurment	_1	Compare to Drying Shrinkage of the Concrete
	(none)	Dilatometer Wet-Dry+E	_3	
	Petrographic	Mineral&Rock Prop.	_2	
Mechanical --				
CA Breakdown in Wet Attrition, Slaking:				
	Duribility Index	T 210	_2	Compare to Worability and Shrinkage of Concrete
	Micro Deval of CA	Ontario LS-618	_1	
FA Breakdown in Wet Attrition, Slaking:				
	Micro Deval of FA	CSA A23.2-23A	_1	Compare to Worability and Shrinkage of Concrete
	Vane Attrition	ASTM C 1137	_3	
	Duribility Index	T 210	_2	
CA Breakdown in Dry Attrition, Abrasion, Impact:				
	LA Abrasion Test	T 96	_1	Accepted Test
CA-Mortar Bond	Surface Energy	Texas A&M Method	_1	Compare to Strength and to Evaluation of Mortar to CA Bond
	(none)	Petrographic, Surface	_2	
	(none)	Meas. Surf. Texture	_3	
	Cleanness Value-CV	Caltrans Test 227	_4	
CA Stress-Strain	Sustained (none)	Rock Core	_2 Cr. St.	Compare to Strength and Fatigue
	Impact (none)	Rock Core, Dyn E	_1	
CA Strength	British Crush Value	BS ____	_1	Compare to Strength and Fatigue
	Rock Core	ASTM D 2938	_2	
	British Impact Value	BS ____	_3	
Petrographic/Chemical --				
Agg Mineral Structure	Petrographic Eval.	C 294/C 295	_1	
	XRD		_2	
FA Mica Content	Petrographic Eval.	C 295, Point Count	_1	
	XRD		_2	
Fines Charac. -75µm	XRD (See Above for Same Property Listing Under Physical Properties, Next to Other Options)			
Organic Impurities	Colorimetric FA, CA	C 40 or C 40 Modif.		
	Petrographic Eval.	C 294, Wood, Coal ...		
	Heavy Liquid, C 123	Wood, Coal, Lignite ...		
Cl in Aggregate	Chem Analysis for Cl	Acid Sol. C 1152	_1	
		Water Sol. C 1218	_2	
		Soxhlet Extr ACI 222.1	_3	

Table--2e Linkage Between Aggregate Tests, Aggregate Properties, and Performance Parameters

Performance Parameter -- **No. 5 D-Cracking (Durability Cracking)**
Freeze Thaw Durability of Coarse Aggregate -- Particularly Carbonates and Low Sp. Gr. Chert
Related to Maximum Size of Aggregate (MSA)

Aggregate Property	Aggregate Test	Technique or Modif.	Rank	Validation Approach
Physical ---				
Gradation, CA&FA	Sieve Analysis	T 27		
	Comb.Grading&MSA	By Calculation	_1	Accepted Test for MSA
				(Simulative Tests)
CA Absorption	Absorption, Sp. Gr.,	T 85 -- 15 Hr. Soak	_2	Modified C 666
(Index Tests)	Absorption, Sp. Gr.,	C 127 -- 24 Hr. Soak	_1	Method C with Aggr.
	Absorption, Sp. Gr.,	Vac. Saturated	_3	Soaked in NaCl Soln.
	Absorption, Sp. Gr.,	Water Aspirator	_4	
CA Pore Properties	Mercury Intrusion		_2	Modified C 666
(Index Tests)	Iowa Pore Index		_1	Method C with Aggr.
	Pore Surface Area	N, H2O Vapor Adsorp	_3	Soaked in NaCl Soln.
CA Durability & Soundness				
(Index Tests)	Sulfate Soundness	T 104 Mg SO4	_2	Modified C 666
		T 104 Na SO4	_5	Method C with Aggr.
				Soaked in NaCl Soln.
	Hydraulic Fracture	TP 12	_3	
	Unconf. Freeze Thaw	T103 A-50 Cyc Soakd	_7	
		T103 B-16 Cyc Alcohl	_4	Modified C 666
		T103 C-25 Cyc V. Sat	_6	Method C with Aggr.
		CSA, NY Cyc. Na Cl	_1	Soaked in NaCl Soln.
Mechanical ---				
CA-Mortar Bond	Surface Energy	Texas A&M Method	_1	(Examine the Fz-Tw
	(none)	Petrographic, Surface	_2	Interface Zone)
	(none)	Meas. Surf. Texture	_3	
	Cleanness Value-CV	Caltrans Test 227	_4	
Petrographic/Chemical ---				
CA Mineral Structure	Petrographic Eval.	C 294/C 295		
	XRD			Modified C 666
				Method C with Aggr.
Elements	XRF			Soaked in NaCl Soln.
Compound Structure	TGA			

Table--2f Linkage Between Aggregate Tests, Aggregate Properties, and Performance Parameters

Performance Parameter -- **No. C6 Map Cracking**
ASR -- Alkali-Silica Reactivity
ACR -- Alkali-Carbonate Reactivity

Aggregate Property	Aggregate Test	Technique or Modif.	Rank	Validation Approach
Physical ---				
Mechanical ---				
Petrographic/Chemical ---				
CA&FA Mineral Struct.	Petrographic Eval.	C 294/C 295 for:		
		ASR React. Minerals	_1 ASR	ASR Concrete Prism (C 1293)
		ACR React. Minerals	_1 ACR	ACR Concrete Prism (C 1105)
ASR Reactivity Test	ASR Mortar	C 227	_2 ASR	ASR Concrete Prism
	ASR Mortar	TP 14, C 1260	_4 ASR	(C 1293) and
	ASR Acc. Mort. Modif	Stark/Nelson	_3 ASR	ASR C 441 Min Admix
	ASR Quick Chem	C 289	_5 ASR	Effectiveness
ACR Reactivity Test	ACR Rock Cylinder	C 586	_2 ACR	ACR Concrete Prism (C 1105)

Chapter 3

Test Procedures for Measuring Properties of Aggregates for PCCP

3.1 – Introduction

What are the best test procedures for measuring critical aggregate properties that are related to performance? Test methods need to be practical and cost effective, without requiring extensive time for results. Tests must also be accurate, safe, and provide acceptable between-laboratory precision. Of most importance are methods that can generate the confidence of users by a demonstrated relationship to performance of the concrete in the laboratory and ultimately to the PCCP in the field.

3.1.1 – Two approaches were taken to help identify and rank the appropriate test procedures for measuring aggregate properties found to be related to the performance of PCCP – (1) Survey from 4-20 Phase I which is reported below in the next section ,and (2) the literature related to research and experience with tests for measuring the properties related to performance. The results of this review of tests are reported and ranked together in section 3.3 for each of the selected aggregate properties.

3.2 -- Information Gathering – Survey Results

In the Interim Report for NCHRP 4-20 (Chapter 3) an analysis of the survey of transportation agencies is given along with results of the literature search and agency contacts. As a follow-on, in 4-20A additional literature was reviewed and panel and agency contacts were made to discuss state and regional trends and experience with the performance of aggregates in PCCP. While the survey results cannot be relied on as the determination of properties or tests related to PCCP performance it does provide a sampling of the experience and practice of the highway agencies. For that reason the more significant survey results are reviewed here prior to discussion, selection, and ranking of tests related to performance later, based on the literature and past research and experience.

3.2.1 -- Survey Results – For Aggregate Properties and Tests Related to Performance

The higher level of responses – at least 4 responses – indicating correlation between a distress mechanism for PCCP and an aggregate property or test that was able to predict performance are reviewed below:

3.2.1.1 -- Hardened Concrete Properties (Number of responses given in parentheses.)

-- D-Cracking performance related to coarse aggregate (CA) freeze-thaw tests (12) and related to CA absorption (6). (It is not known whether the freeze-thaw tests were of aggregate or of aggregate in concrete, both types are used by agencies for source approval.)

-- Random/Map Cracking performance related to chemical reactivity tests of aggregates (12). Alkali-Aggregate Reactivity (AAR) in concrete by Alkali-Silica Reactivity (ASR) or Alkali-Carbonate Reactivity (ACR)

-- Popout performance related to unsound aggregates (10). Presumably this is a petrographic count, a percentage of unsound particles, and/or a soundness test of unconfined aggregates, since only five (5) of the respondents related popouts to freeze-thaw tests.

-- Low Friction performance related to aggregate acid insoluble residue test (7) and related to polishing tests in the laboratory (4).

-- Abrasion and Wear performance related to aggregate abrasion (6) and wear (4). It is not known what tests are being referenced here, but some may be relating to LA abrasion.

-- Spalling performance related to aggregate chemical reactivity (6) respondents. (In advanced stages ASR, for example, leads to spalling of concrete between wider surface cracks.)

3.2.1.2 -- Fresh Concrete

-- Slump (slump is not a distress or performance property, per se; workability and placeability would be more appropriate. A workability test is needed for the evaluation of low-slump paving mixtures.) Nine respondents (9) related slump (workability performance ?) to aggregate grading and (8) to absorption. Absorption must be a reference to the use of dry CA where rapid absorption of mixing water during placement can cause slump loss problems. Of course this problem can be averted by having the CA thoroughly wet at time of batching. This has the added advantage of providing better early curing when a porous aggregate is moist, and better bond according to Hsu and Slate.

-- Segregation of the concrete is another performance category related by (4) respondents to grading.

3.2.1.3 – Needed New Tests

Another section of the survey asked agencies whether new tests are needed for the aggregate properties given below. There appeared to be most interest in developing tests for Aggregate-Mortar Bond and Aggregate Strength:

-- Aggregate-Mortar Bond test method (17 of 43). It is thought to be related to fatigue, spalling, cracking, concrete strength (compression and flexure), aggregate pull-out (interlock); and it is a property required for high performance concrete (HPC). Since no good direct bond test (mortar or paste bond to aggregate surfaces) has been developed (Hsu and Slate, 1963), it appears that a new test for aggregate bond properties is needed with the best approach for validation an evaluation procedure of the CA interface zone in concrete using microscopy or permeability measurements. In some research of aggregate durability, the deterioration appears to start in the interface zone, and it will be of critical importance in HPC. (NIST)

-- Aggregate Strength test method (14 of 43). It is thought to be related to all of the above for aggregate bond, but also has a relationship to shear distress at pavement crack interfaces. This may refer to aggregate interlock at joints and cracks or to the actual shear strength of the concrete in resisting cracking or spalling due to forces from dowels, ties, or aggregate particles during load transfer due to aggregate interlock.

-- A much lower level of interest was expressed in a test for aggregate modulus of elasticity (E). Options include measuring E on the concrete containing the aggregate, and for sound rock material E might be related to that of the parent rock measured by core test or nondestructive technique.

Other tests mentioned were aggregate cleanliness, ASR, and water demand.

3.2.1.4 – Surveyed Opinions of Current Tests

Another survey section asked agencies about the popularity of current test methods (AASHTO, ASTM). Most of the basic tests listed from that survey are the normal specification and QC tests of aggregates used every day by highway agencies. They are not listed here since most agencies use them; and, with the exception of grading, the tests appear to be universally recognized as performing the indented purpose.

-- Grading -- For grading about (6) of the respondents said their agencies have examples of poor performance of aggregates that passed the test, and also of aggregates with good performance that did not pass the test

-- Absorption -- . For the T 85 absorption test of CA (5) indicated experience with aggregates that pass the test but do not perform well in the field. However this is in contrast to the durability section below where a dozen agencies use it satisfactorily for durability.

-- Petrographic Evaluation -- Another important fact is that only (10 of 43) agencies use Petrographic Evaluation; and of the ten the great majority appear to be satisfied with the procedure. This is an area where substantial improvement might be made. Particularly the use of petrographic methods to develop service record evaluations of aggregates to improve use in the future and to help in aggregate applications in high performance concrete.

-- Sulfate Soundness -- Most agencies use the sulfate soundness test of fine aggregate (FA) and coarse aggregate (CA). Less than half a dozen (6) indicate any dissatisfaction in the relationship of these tests to performance.

-- LA Abrasion Test of CA -- Less than half a dozen (6) indicate any dissatisfaction in the relationship of this test to performance.

-- Organic Impurities Test of FA-- Less than half a dozen (6) indicate any dissatisfaction in the relationship of this test to performance.

-- Durability -- Other current tests used by about a dozen (12) agencies include AASHTO T 161 Freezing and Thawing of CA in concrete and/or T 85 for CA Absorption as durability indicators in concrete. For all but 2 respondents these are reported to be well related to performance. Two indicated, that for T 161, aggregates that pass the test sometimes do not perform well in the field.

-- Other Tests -- Also about a dozen (12) agencies use ASTM C 227 for ASR (with apparent satisfaction) and use AASHTO T 242 (skid trailer) and ASTM D 4791 (flat and elongated) with general satisfaction. Another group of tests are only used by about a half a dozen (6) agencies, including: ASTM C 157 and C 490 for dimensional changes of concrete or mortar containing aggregates; ASTM C 289 (Quick Chemical Test for ASR); and C 295 (Petrographic) for ASR and CSR. In general these agencies indicated satisfaction.

3.2.1.5 – Additional Recommendations from the Survey

In the final section of the survey of U.S. agencies the following tests were recommended for research by more than one respondent:

-- ASR testing in general, and the Canadian concrete prism test (which is now ASTM standard C 1293), in particular.

-- Sand Equivalent (AASHTO T 176, ASTM D 2419) and Cleanness Value (Calif. Test Method 227)

-- Freeze-Thaw Testing of Aggregates using Brine (unconfined or salt treatment of aggregates used in concrete) -- Iowa Test Method 209, NY State Method, CSA, and others may use unconfined freeze-thaw tests in brine. The newer approach of salt-treating the aggregate before freezing and thawing in concrete appears to have promise.

-- Washington Hydraulic Fracture Test (AASHTO TP 12) now under study by CTL for the FHWA through several state highway agencies and the National Aggregates Association laboratory.

3.2.2 – Summary of Survey Results Regarding Tests and Properties

Current Tests. The following tests and evaluation procedures were identified as suitable and related to aggregate performance by the agencies responding (Note – see the discussion in the sections to follow on why certain tests were selected for use in the proposed research):

Soundness of Aggregates, Including Sulfate Soundness (Selected Mg SO4)
Petrographic Approval and Limits on Deleterious Particles (Selected C 295)

Grading of Aggregate and its Relation to Workability (Selected T 27 & T11)
Absorption of Coarse Aggregate (CA) (Selected Absorption by 15 & 24 Hr. Soak and Vacuum Saturation)

LA Abrasion of CA (Selected T 96)
Freeze-Thaw Durability of CA in Concrete in the Lab (For Validation)
Acid Insoluble and Polishing Tests for Aggregate Friction
(Acid Insoluble Selected for Carbonate Aggregates Only.)
Aggregate Reactivity in Mortar Bar Tests (Selected TP 14 and C 227)

Needed New Tests and Research From the Survey

Test for Aggregate Bond to Mortar (No Test Available)
Test for Aggregate Strength (Selected British Crushing Value for All Aggregates and Rock Core Compressive Strength for Carbonates)

More Research On:
- ASR Tests Using Concrete Prisms (For Validation)
- Sand Equivalent of FA (Selected)
- Cleanness Value of CA (Not Selected)
- Unconfined Freeze-Thaw of CA in Salt Solution (Selected CSA, NY Test)
- Freeze-Thaw of Salt Treated CA in Concrete (For Validation)
- Development of the New Hydraulic Fracture CA Test (Selected)

These opinions were considered in the selection and ranking of aggregate tests and validation of these tests in research discussed in the remainder of the Chapter 3 and in Chapter 4.

3.3 – Discussion and Ranking of Tests for Each of the Selected Aggregate Properties.

The tests for each aggregate property are listed and ranked in Table 2, at the end of Chapter 2. The tests selected for further evaluation have been drawn from independent research and discussions with other researchers, as well as from the information reported in the NCHRP 4-20, Phase I Report. The consolidated list of recommended tests to be selected for further research in relation to performance in PCCP are given in Table 3 at the end of this chapter.

-- Physical Properties of Aggregates

3.3.1 -- **Gradation and Minus 75µm (No. 200) Determination (Including Calculation of Combined Grading and Maximum Size Aggregate in Concrete)** – Maximum size and amount of fines influences volume change through drying shrinkage and moisture cycles; and in turn, increased volume change is an important factor that can increase **transverse cracking, faulting, punchouts, and spalling**. These accepted tests and calculations for grading are selected to characterize aggregates to be used in the research and will be one of the major variables in a study on aggregate effects on the workability of paving concrete, which is a factor in the **spalling** performance of PCCP.

3.3.2 – **Characteristics of Minus 75μm (No. 200) Material** –

Character of fines influences volume change through drying shrinkage and moisture cycles (Meininger, 1966 Report on Drying Shrinkage Data from the NAA-NRMCA Laboratory); and in turn, increased volume change is an important factor that can increase **transverse cracking, faulting, punchouts, and spalling**. With increased interest in using more fines in concrete a characterization standard is needed to tell the good from the bad.

Several methods of evaluation of clay minerals are: size analysis of fines (hydrometer or new mechanized methods); mineral identification by microscope or XRD; engineering procedures (such as PI and sand equivalent), or the methyl blue techniques being tried on aggregates for asphalt. Because of the advances in new equipment it is recommended for research into minus 75μm fines size analysis on recovered fines from fine aggregate and only from coarse aggregate if it has high fines or tends to generate significant fines in handling. (Micromeritics, 1997; Kandhal and Frazier, 1997) Also the availability of XRD equipment is such that it is practical to evaluate the fines for clay mineral types and relative quantities in principally the fine aggregates. For manufactured fine aggregates the amount of desirable minerals (rock flour) from the parent stone can be determined. Sand Equivalent and Methylene Blue are tests that are being recommended for aggregates for asphalt. The Methylene Blue test identifies harmful smectite clays. The dye is added to a sample until adsorption of the dye ceases, as evidenced by a permanent blue halo is observed on filter paper.

These are practical, not expensive, and are not time consuming. They are recommended for research. The PI test is not selected. It is not being used widely outside soil and base course technology, and it also would bring up the issue of whether it should be run on minus No. 40 or Minus No. 200 material.

3.3.3 -- **Fine Aggregate (FA) Particle Shape and Angularity** – Increase in flat and elongated pieces and angularity and texture in FA is known to cause increased mixing water requirements to maintain slump in concrete. Also, to maintain workability and strength more cementitious material and less CA may be used, increasing volume change tendencies. Volume change and a decrease in the quantity or size of the CA is an important factor that can increase **transverse cracking, faulting, punchouts, and spalling**.

AASHTO T 304 Uncompacted Void Content of Fine Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading) The uncompacted void test of FA is now required for Superpave and most all agency labs have the equipment and have begun testing. The test was originally developed for concrete and research has related it to mixing water demand in concrete (Wills, Gaynor). It is a simple, quick test which can be run from the results of a typical FA sieve analysis. It is selected for the research. Particle Index of fine aggregate is not selected because it is not practical and it was found to be highly correlated with T 304. (Kandhal and Frazier, 1997) A visual petrographic method (C 295 or Corps of Engineers Method) is not selected for the same reason; it is not practical. It is too tedious for routine testing. A proposed new "CAR" test is being researched for possible use in asphalt technology. It uses an as-received graded FA sample, and shear resistance is measured in a modified Marshall flow test. This test is not selected for research at this time, pending results form the asphalt related studies.

Along with the selection of T 304, it is recommended that during the petrographic analysis of fine aggregates used in the study that a count be made of mica particles in several size fractions. The methodology along with some references are included in ACI 221R-96 and in Gaynor's ACI Concrete International paper on fine aggregates for concrete. The count should only be made on fine aggregates with more than a trace of mica. This will provide an indication of whether mica will influence concrete mixing water demand, workability, and strength beyond its effect on the T 304 test results.

3.3.4 -- **Coarse Aggregate (CA) Particle Shape and Angularity** -- Increase in flat and elongated pieces and angularity and texture in CA is known to cause some increase in mixing water requirements to maintain slump in concrete. Also, to maintain workability less CA may be used, increasing volume change tendencies. Volume change and a decrease in the quantity or size of the CA are important factors that can increase **transverse cracking, faulting, punchouts, and spalling**. Concrete is not affected as much by CA particle shape properties as it is affected by fine aggregate. The principle problems with CA in concrete are at the extremes. When very flat, and angular CA is used it will not only hurt workability, but its weaker thin sections will not be as good at preventing **transverse cracking** or providing the need strength in the particle interlock zone to resist, **faulting and punchouts.** On the other hand very spherical rounded CA particles will not bond well with mortar and will be less effective in aggregate interlock at joints and cracks. The new CA uncompacted voids test used by Kandhal and Frazier, 1997 in NCHRP 4-19, and previously researched at the NAA-NRMCA Lab, is selected for the research. It provides a promising new technique for identifying CA at the extremes of shape and angularity. It is the new AASHTO Proposed Provisional Test on Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading). It has the advantage of not having to do detailed petrographic evaluations of particle shape and angularity using visual methods or counting crushed faces (C 5821), or measuring individual particle length, width, and thickness (D 4791). D 4791 is also selected since it is a test that will be run routinely for Superpave. While there is currently confusion as to how it will be used in Superpave, those issues should be settled in the next year. The method does have the ability of identifying aggregates with a very large portion of flat and elongated particles. It will not identify spherical, rounded, smooth CA particles. C 5821 is not selected since it only applies to gravels.

Two other tests are also selected for evaluation in the research: (1) The Particle Index Test (D 3398) for use on CA, where it is much simpler to run than the FA portion of the test. It is also based on void content and should correlate with the above AASHTO provisional test and provide measurement of the extremes in particle characteristics. (2) The use of a computerized technique for scanning a CA by image methods and allowing the computer analysis to produce a factor related to shape and angularity. Several methods have been used, but the most practical at this point in terms of a developed system is the French device being used in research at the FHWA Laboratories.

3.3.5 -- **Absorption, Porosity, and Specific Gravity** – CA Absorption and Specific Gravity are routine QC tests that have been reported to be generally related to CA Durability in freezing and thawing and factors that have been related to **D-cracking** and to popouts. However, the relationship does not extend to all types of aggregates. Absorption is the weight percent of water absorbed in the pores, and porosity in terms of percent by volume can be calculated as absorption times bulk dry specific gravity. Absorption is generally the measurement that is used because it is calculated directly from the mass of the water in the pores of the aggregate and it does not require measurement of specific gravity on the sample. FA absorption and specific gravity is also used in QC activities and mixture calculations, but it has not been found to be related to any of the performance factors, with the possible exception of fine aggregate breakdown or slaking in wet attrition. It is the higher absorption fine aggregates that may have weaker particles with a loose bond between mineral grains in the particles. FA specific gravity is needed for T 304, the uncompacted voids test for shape and angularity.

There are several ways to soak or saturate CA for absorption:

15 Hr. Soak for AASHTO T 85
24 Hr. Soak for ASTM C127
Vacuum Saturation (C 830 is an example) It has been used by a number of researchers to saturate as much pore volume as possible. (Meininger, 1964; Vogler, 1989; Walker, et al, 1970)

It is proposed that all three of these methods be selected and used in the research. For agencies, such as Minnesota (Koubaa, et al, 1997), which use absorption as a specification limit for CA it needs to be clarified if a modest difference in soaking time is significant, and whether the vacuum saturation approach, if standardized, would be a more precise measure, although it gives higher values.

There is another issue concerning soaking or saturation of the CA which is to be mixed in to concrete for concrete freeze-thaw tests. Vacuum saturation can cause an early failure for any coarse aggregate that has a medium to high absorption, and therefore be an overly severe test. CA in concrete is rarely saturated to that degree. It is an issue that must be addressed in the validation phase. Perhaps the use of salt saturated aggregate is a middle ground, in that the salt may tend to attract more moisture into the pores for fine pore structures, but not totally saturate the pore system.

3.3.6 -- **Pore Size Distribution, Surface Area, and Pore Volume** – In **D-cracking** deterioration, forces due to freezing of water in CA pores and in some cases perhaps osmotic pressures are what cause the damage. The size distribution of pores, the surface area of pore walls, and the overall pore volume are important factors about the aggregate to be researched. Size distribution can be obtained with the mercury intrusion (Winslow, et al, 1982 and Meininger, 1964), and also using gas adsorption methods, such as nitrogen adsorption. Gas adsorption give a better measure of pore wall surface area. Total pore volume is of course estimated by vacuum saturated absorption, above; but it does not distinguish anything about the volume in different sizes of pores.

Iowa Pore Index -- Iowa Pore Index test provides a measure of the volume of the smaller micro-pores (secondary load) which is a measure of water, under pressure, penetrating into an aggregate sample over a 14 minute period after the initial one minute (primary load) where water flows into larger macropores. The Iowa pore index secondary load is thought to be related to freeze susceptible pore volume in carbonate aggregates, but yet is not well related to performance, **D-cracking** and map cracking in Iowa pavements indicating to researchers that other mechanisms (perhaps reactivity) were also involved, and that laboratory freeze-thaw methods were more severe than the field exposure. Currently Iowa uses the primary and secondary load as an indicator of potential chemical reactivity. A higher penetration of water indicates a pore system susceptible to reactivity potential. (Marks, 1997; and Dubberke, 1994) In Illinois (Schwartz, NCHRP Synthesis 134) found a relationship of the Iowa Pore Index with field performance of carbonate crushed stone aggregates but no trend for gravels. In Ontario (Rogers) feels that the Iowa Pore Index is related to the performance of carbonate aggregates there. The Iowa pore index test is practical, quick, and inexpensive. It also uses a large sample than the following two methods. This test is selected for further research.

Mercury Intrusion – gives more information about the CA pore structure, but it uses a small sample, requires multiple tests to represent a heterogeneous CA, and involves the handling and disposal of mercury. More automated equipment is available, but it is expensive. It could provide results within about a day on a research basis, but it is not very practical for routine testing. This would be an interesting test to include in the research, but because of its lack of practicality has not been selected

Gas Adsorption – This method may be more practical in terms of sample size, as well as the ability to give measurements of both CA pore surface area and an indication of pore size distribution. It is recommended that in the research this technique be explored to see what types of equipment and gases might be used for aggregates, particularly carbonate aggregates, and to determine if it can be a practical test. If so it should be included as a selected test in the research. Both nitrogen and water vapor adsorption have been used to research the pore properties of aggregates.

3.3.7 – **Coarse Aggregate Durability and Soundness** As indicated in the previous chapter tests for this property subject aggregate to a freezing and thawing regime or a procedure intended to simulate cyclic pressures and volume change from freezing and thawing, heating and cooling, and/or wetting and drying, sometimes in the presence of a salt or other chemical solution. Agencies do use these types of unconfined aggregate cycling tests as a general quality test for aggregates in PCCP, and some report correlation with D-cracking for some materials containing carbonate aggregates and not others. (Paxton, 1979)

Sulfate Soundness -- Using either magnesium or sodium sulfate is the most widely specified durability test for aggregates. However, its results are not generally correlated with performance in the field when viewed from a North American perspective for all types of aggregates. Some agencies feel they do have success with the test when limited to use on certain types of aggregate in one well controlled laboratory. Individual states using central laboratories with well controlled sulfate soundness test facilities have related sulfate soundness to the durability of certain types of materials in their state. However, because of the wide variety of material types nationally, and the poor precision of the more popular sodium sulfate soundness test, it has not been recognized nationally as having good relationship with performance. One of the problems is the poor precision of the sodium sulfate test between laboratories (AMRL supplied precision on statement in ASTM C 88). The magnesium sulfate soundness has better precision in the AMRL reference sample program, and has just been recognized by NCAT as one of the better tests in a study of the relationship of aggregate properties to the performance of hot mix asphalt in the field. It is recommended that the magnesium sulfate soundness be selected for the research in spite of the fact that more agencies used the sodium test rather than the magnesium procedure.

Hydraulic Fracture – This is a test developed under SHRP to detect aggregates which cause **D-Cracking** and which is now being evaluated through the efforts of FHWA technology applications for both precision between laboratories and its relation to performance of aggregates in pavements in freeze-thaw exposure. Reports of these activities from FHWA contractor CTL have not been studied yet. Several states have indicated that there is not a general relationship between hydraulic fracture deterioration of aggregate and its performance in concrete exposed to freezing and thawing. Minnesota researchers have included it in one phase of their recommended protocol for the testing and approval of coarse aggregates for concrete. (Koubaa, et al, 1997) Since FHWA is continuing work on the investigation of this property and its relation to performance, the selection of the test should be made pending a recommendation on how it might best be applied.

Unconfined CA Freeze-Thaw Tests – ASSHTO T 103, as well as other agency tests of a similar nature involve, cyclic freezing and thawing of unconfined aggregate pieces in water, an alcohol solution, or in a solution of NaCl. Some literature (Rogers and Senior; and Paxton) have reported better correlation with **D-cracking** by using freezing and thawing in a salt solution than using pure water. The test options include:

AASHTO T 103 Soundness of Aggregates by Freezing and Thawing

Method A -- Total Immersion in Water, 50 Cycles, after 24 hr soak
Method B -- Partial Immersion in Alcohol Solution, 16 Cycles after Vacuum Saturation with the alcohol solution
Method C -- Partial Immersion in Water, 25 Cycles, Vacuum Saturation with Water
Method NY -- Using a Na Cl Brine Solution, 25 Cycles
CSA A23.2-24A -- Freeze-Thaw of Aggregate in NaCl Solution

Since chlorides are now heavily used in the areas of North America where D-cracking is prevalent it is recommended that either the NY State DOT or the Canadian CSA method be selected for inclusion in the research. The selection should be based on a review of the procedures and the level of precision reported by the using agencies.

3.3.8 -- **Thermal Coefficient of Expansion of Aggregates** – Measurement of the thermal coefficient of expansion (TCE) of unconfined aggregate is limited to two types of procedures given below. It must be recognized that the TCE may not be linear in range of temperature of interest – probably from about -20C to 60C. The range may be greater in some climate areas. Also, the TCE will be affected by changes in moisture as well. For most pavements a one-day soaked aggregate might be used. Differences in TCE from the bottom of the pavement (wetter) and the top (drier) may also be significant as to its effect on curling stresses.

(1) Length change along an axis of a rock core or a large piece of CA as the material is cycled through a range of temperatures. This would be possible on a crushed stone, but would be very difficult on a heterogeneous gravel and impossible on a natural sand. The Corps of Engineers has a procedure -- CRD C 125 Test of Linear Thermal Expansion of Coarse Aggregate (Strain Gage Method). Here aggregates with different moisture levels might be tested depending on the length measuring equipment.

(2) Use of a dilatometer where the FA or CA, or even a combined FA and CA is immersed in a liquid in a vessel which is cycled through the temperature range and the volumetric expansion characteristics of the aggregate can be determined by the change in volume of the liquid after subtracting out the effects from the fluid and the vessel. Texas A&M has successfully constructed a dilatometer and measured the Coefficient of Thermal Expansion of several aggregates. In other technologies their are also ASTM dilatometer methods. Since air must be evacuated from the system it appears that only vacuum saturated aggregate can be tested.

-- Texas A&M has developed a dilatometer test for TexDOT and FHWA (Wang, 1997)

-- ASTM E 228 Linear Thermal Expansion of Solid Materials with a Vitreous Silica Dilatometer

-- ASTM D 5515 Determination of the Swelling Properties of Bituminous Coal Using a Dilatometer

-- ASTM D 4535 Measurement of Thermal Expansion of Rock Using a Dilatometer

-- ASTM C 372 Linear Thermal Expansion of Porcelain Enamel and Glaze Frits and Fired Ceramic Whiteware Products by the Dilatometer Method

-- ASTM D 696 Coefficient of Linear Thermal Expansion of Plastics Between -30C and 30C

A third method is available -- estimating the TCE of aggregates from the principle minerals present in the aggregates, determined in routine petrographic analysis. One aspect of the study should involve comparing the measurement of aggregate TCE with that estimated from the petrographic analysis. Validation of the effect of aggregate TCE, for the selected method, on concrete would be done in the laboratory by measuring the thermal volume change properties of concrete.

3.3.9 – **Coarse Aggregate Drying Shrinkage** – One of the roles of CA in concrete is to restrain the shrinkage of cement paste and mortar as it dries with time. Some fine grained aggregate materials will also shrink and swell a significant amount with changes in moisture and relative humidity. This was actually measured on coarse aggregate particles from a known source with documentation of causing increased drying shrinkage of concrete.

(Meininger, 1966) In this particular case the drying shrinkage was about double that of normally expected for concrete. Increased volume change is an important factor that can increase **transverse cracking, faulting, punchouts, and spalling.** No specific method has been identified to measure directly the drying shrinkage properties of CA. Tests and research reported to date involve the testing of CA in concrete shrinkage specimens.

Techniques to measure directly particle volume change fall into the same two general methods described for thermal coefficient. The problem is that the time to moisture equilibrium in aggregate particles may be significantly longer than thermal equilibrium.

> (1) Length change along an axis of a rock core or a large piece of CA as the material is cycled through a range of moisture or relative humidity. This would be possible on a crushed stone, but would be difficult on a heterogeneous gravel and impossible on a natural sand. This method is selected for the research.
>
> (2) Use of a dilatometer where the CA is brought to moisture equilibrium and then immersed in a non-water liquid in a vessel or other aggregate volume measuring device. The aggregate is then brought to equilibrium at another moisture condition and the volume measured again. The challenge will be to come up with a volumetric measuring system that will have the required accuracy and not affect the moisture/RH condition of the aggregate particles. This method is not selected.

Again the third method available is estimating the shrinkage potential of a CA from petrographic properties. Validation of the effect of the aggregate on concrete would be done in the laboratory by measuring the drying shrinkage volume change properties of concrete. This method should be possible from the results of the petrographic analysis. Therefore it is selected.

-- <u>Mechanical Properties of Aggregates</u>

3.3.10 – **Fine Aggregate Breakdown and Slaking in Wet Attrition.**

The Micro Deval test of FA used in Canada (CSA A23.2-23A; Rogers and Senior, several papers) the California Durability Index (AASHTO T 210), and the ASTM C 1137 fine aggregate attrition test (Meininger, 1978) have been used to identify aggregates that tend to breakdown or slake fine minerals during mixing or handling in a wet environment. Fine aggregate has much more surface area than coarse aggregate and a significant amount of fines can be generated during concrete mixing influencing workability and drying shrinkage. Increased volume change or decreased workability is an important factor that can increase **transverse cracking, faulting, punchouts, and spalling.** Some type of wet attritioning test is needed for aggregates for PCCP.

Mico-Deval for FA – This appears to be a useful and practical test for measuring this property. It is used in Canada and France, and it is a recommended test from the NCHRP 4-

19 project. (Kandhal and Frazier, 1997) Rogers reports good within laboratory precision, and has coordinated inter-laboratory precision testing as well. This test for FA is selected for inclusion in the recommended research.

ASTM C 1137 for FA – This vane-type wet attritioning test is not recommended for inclusion in the research. Few labs have the equipment; the test is labor intensive; and, as shown by Rogers, et al in Ontario, the C 1137 test has a problem with a change in the attritioning action and test results as the vane wears. The Micro-Deval test appears to be more reliable and consistent as a wet attritioning test, and it can be run on both fine and coarse aggregates.

Durability Index Test -- Durability Index (AASHTO T 210) is another class of wet attritioning tests developed in California based on the sand equivalent test to detect the presence of active clay minerals from a wet attritioning process for both fine and coarse aggregate. Other tests of a similar nature were developed in Washington and Oregon, and ASTM and AASHTO standards have been published for Durability Index. These tests have been used more for base course and asphalt aggregates. However, this property of active clay fines associated with aggregates for PCCP should be considered to detect the effect of degradation and fines production from either fine or coarse aggregate on fresh concrete workability performance. This test is also selected for inclusion in the research.

3.3.11 -- **Coarse Aggregate Breakdown and Slaking in Wet Attrition** -- The Micro Deval test, discussed above, is also available in a CA option (OMOT, 1996; Rogers and Senior, several papers) The California Durability Index (AASHTO T 210) also includes test procedures for CA. While these CA tests have not been used widely for concrete aggregates they are recommended for inclusion in the research to see if a wet CA test will be related to performance, and to confirm that the wet CA tests show a different relationship to concrete that the dry LA abrasion test below. Fines can be generated during aggregate handling, and in concrete mixing, influencing workability and drying shrinkage. Increased volume change or decreased workability is a factor that can increase **transverse cracking, faulting, punchouts, and spalling**

3.3.12 -- Coarse Aggregate Breakdown in Dry Impact, Attrition, and Abrasion

LA Abrasion -- Its relation to performance of aggregate in PCCP in a general way has not been established. Some of the harder more brittle aggregates can give high losses in the test, while softer more resilient aggregates can give lower losses. The LA abrasion test is probably more related to degradation and breakdown of a coarse aggregate during transportation, handling, and batching where the particles are subjected to impact and surface attrition. Some investigations have shown an improvement in strength with lower LA abrasion losses from the same aggregate source where increased beneficiation in processing was employed. Research at the PCA regarding load transfer due to aggregate interlock was shown to be related to aggregate LA abrasion. So for cracks or undoweled joints an aggregate, less loss in the test may give better performance in **faulting**. (Nowlen, PCA, 1968) The test is used almost universally by highway agencies and is selected for inclusion in the research as a characterization test of CA and to see if it is related to aggregate strength and the **faulting** and **punchout** performance of PCCP where aggregate interlock is important. Bond may also be a factor in D-cracking performance where expelled water or solutions from CA pores during freezing can cause damage in the interface zone.

3.3.13 – **Coarse Aggregate-Mortar Bond** – A good way needs to be found to assess the quality and competency of the CA bond and the character of the interface zone between CA and mortar or paste. Bond is important in maintaining aggregate interlock at joints and cracks, and therefore are related to **faulting** and **punchouts**. Good bond in also important in resisting transverse **cracking** and **spalling**. No practical aggregate or concrete test has been identified. A separate research project might be initiated to develop a test to evaluate this property of CA and other procedures to investigate the bond of CA and the characteristics of the interface zone in concrete. Techniques of assessing bond might be mechanical tests of concrete, of aggregate surfaces with attached paste or mortar, permeability tests, or microscopic evaluations by observing the aggregate-paste interface or observing the effect of a dye or stain used in a thin section of the bonding zone. Hsu and Slate showed both the significance of the aggregate surface to bond strength, and they showed the difficulty of getting consistent results from mechanical bond tests. Limestone had a higher tensile bond than granite or sandstone. Polished aggregate surfaces gave the lowest bond. Good quality limestones develop better bond than other aggregates. (Hsu and Slate, 1963)

Surface energy is another approach that deserves consideration. Little at Texas A&M has reported in an award-winning AAPT paper that sophisticated surface energy measurements on aggregates are related to bond performance of aggregates in asphaltic concrete. The aggregate tests, at this point, are expensive and time consuming, but the researchers feel that the results are very significant and will be related to bond in concrete as well. Research in this area is needed.

Other techniques, with little background in the literature, that could be considered are:

-- The development of visual and electron microscope procedures for characterizing the CA surface with respect to minerals, roughness, and porosity.

-- The development of a surface texture measure for CA particles

If research is done on surface energy the characterizing of the aggregate surface should be included, as well, to see if the energy might be related to a convenient petrographic property.

3.3.14 – **Stress - Strain Response of CA, Modulus of Elasticity (E)** – Two types of CA response to load or stress are important to performance in PCCP:

-- Sustained load. Modulus of elasticity (E) and creep of CA in both compression and tension and how it influences concrete properties, are important to deflection, curling, and cracking in PCCP. These properties are important in **transverse cracking** and **spalling** frequency. Both destructive and non-destructive rock mechanics test methods for these properties could be used on rock cores from stone or large gravel particles. Time has not been available to investigate potential methods yet, but this type of data is regularly included in the literature, and it appears feasible to use or adapt these procedures. Selected for research are rock core tests of E and sustained creep properties in compression. As a minimum these properties should be included in the research on carbonate aggregate rock materials since the range of these properties is bound to be very broad considering the range of limestones and dolomites used in PCCP.

-- Impact response of rock to rapidly applied traffic loads will be significant to CA interlock at cracks and joints, affecting **faulting** and **punchouts**. Non-destructive, dynamic methods used to measure dynamic modulus values of rock materials may well be adapted to smaller aggregate material samples. This test is also selected for comparison to the conventional E from load tests and potential representation of the response of aggregate particles to rapid shifts in load near joints and cracks.

3.3.15 -- **Strength of Coarse Aggregate** – Normally the strength of the rock material in the aggregate is not measured. Instead the effect of the aggregate on concrete strength is tested through comparative tests of aggregates in concrete by flexure and/or compressive strength. Strength of coarse aggregates will be significant to CA interlock at cracks and joints, affecting **faulting and punchouts.** Actual strength or modulus of elasticity of aggregate materials might be measured by non destructive means, by extracting small cores from an aggregate for testing, or by crushing a collection of particles in a confining ring such as in the British Crushing Value test.

Methods of rock mechanics can be applied to determine compressive strength of rock cores. (ASTM D 2938) And that test should be selected for use in conjunction with any research of the strength or E of parent stone material in crushed stone aggregates.

The other approach is the measurement of the strength of a collection of CA particles restrained in a steel ring. The test that has been used in the UK is the British Crushing Value. A test on a collection of particles such as the British Crushing Value may be a valid test of the toughness of aggregates in joints and cracks when subjected to shear and impact under loading, and thus be related to aggregate performance with respect to faulting and punchouts. There is also a British aggregate impact value test, but data on the use of the test has not been found in the literature. More date is available on the crushing value test, and it has been shown to be related in a general way to rock core compressive strength. The crushing value test should be selected to give a basic strength value for the CA.

– <u>Petrographic/Chemical Properties of Aggregates</u>

3.3.16 – **Mineral Structure of Coarse and Fine Aggregate** -- The use of basic and advanced petrographic methods by a trained geologist or mineralogist is essential to the proper description of aggregate materials and an understanding of the performance of these materials in concrete. (Rogers; Erlin; Dolar-Mantuani). Petrographic characteristics can be related in one way or another to all six of the selected critical performance parameters. ASTM C 295 should be selected for both the CA and FA. In addition, various specialized evaluations should be made by the petrographer to relate to other research tests. Examples include the counting of percent mica particles in some fine aggregate size fractions, identification of reactive materials in aggregates, and the evaluation of the texture and minerals present at CA surfaces to relate to bonding. Petrography should be done under the supervision of a professional. However, once procedures have been established with analytical equipment, a technician can conduct routine analyses to gather data on the types of minerals and rocks present and their properties for consideration of the engineer or geologist.

3.3.17 -- **Acid Insoluble Residue** -- This is one of the characteristics of carbonate aggregates which indicates the quantity and size of non carbonate, usually siliceous material, inter mixed with the carbonate minerals in the rock. If the harder acid insoluble material is in sand sizes it will improve the **friction** properties of the material in PCC pavement surfaces. If the insoluble material passes the No 200 sieve, it is an indicator of clay minerals (shale, siltstone) interbedded with the carbonates and, if present in large quantities, may indicate poor durability of the material and/or contribute to higher drying shrinkage. Increased volume change is a factor that can increase **transverse cracking, faulting, punchouts, and spalling.** In Minnesota (Koubaa and Snyder) correlations were attempted between acid insoluble and pavement D-cracking durability performance. It did not work for all materials, and the test was not as good an indicator as other tests. Acid insoluble should be a selected test for research involving carbonate crushed stone fine and coarse aggregates and the carbonate fraction of gravel aggregates having more than about 40 percent carbonate.

3.3.18 -- **Aggregate Mineral X-Ray Diffraction Analysis (XRD)** — Is a widely used laboratory procedure of identifying the relative quantities of various common minerals in aggregate particles, and which can also be used to identify different clay minerals present in significant quantities in the minus 75μm (No. 200) material. XRD should be used as a supplement to petrographic analysis, and it should be included in research on carbonate aggregates to help identify the relative compositional split between limestone and dolomite, and to identify other material present in carbonate aggregates. Certain fine-grained dolomitic aggregates that do not give good performance have a characteristic higher d-spacing shown by the test. Recent use of the XRD procedure in research in Iowa and Minnesota shows that it can be an important tool in evaluating the mineral structure and constituents of aggregates. This would not be a routine QC test, but it is a test that can be used in source and ledge approval. Because of its sophistication XRD, along with XRF and TGA (discussed below), may best be applied in a cooperative effort between a highway agency and university researchers.

3.3.19 – **Elements Present in Aggregates** -- Coarse Aggregate X-Ray Fluorescence Analysis (XRF) are available to determine the quantity of different elements in aggregate samples; and from these quantities, the theoretical percentages of the different principle oxides can be calculated. Recent use of the XRF procedure in research in Iowa and Minnesota shows that it can be an important tool in evaluating the trace element constituents of aggregates. XRF should be a selected test for research into the properties and performance of carbonate aggregates

3.3.20 – **Compounds Present in Aggregates.** Coarse Aggregate Thermogravimetric Analysis (TGA) gives characteristic mass loss curves for different compounds and structures in carbonate aggregates and can be used to study the nature and performance of carbonate aggregates. (Schlorholtz and Bergeson, 1993) (Dubberke, ICAR, 1997) TGA should be a selected test for research into the properties and performance of carbonate aggregates

3.3.21 – **Fine Aggregate Mica Content.** It is recommended that during the petrographic analysis of fine aggregates used in the study that a count be made of mica particles in several size fractions. The methodology along with some references are included in ACI 221R-96 and in Gaynor's ACI Concrete International paper on fine aggregates for concrete. The count should only be made on fine aggregates with more than a trace of mica.

3.3.22 – **Organic Impurities** are not considered an important factor in aggregate effects on the performance of PCCP. Usually if a fine aggregate shows up with a dark color in the ASTM C 40 test in a sodium hydroxide solution changes will be made in mining, processing, or aggregate selection to avoid the use of an organic sand which may cause problems with concrete strength, setting, or control of air entrainment. A modified C 40 test might be used if an organic coating of contaminant is suspected in a CA. Also there are limits in FA and CA specifications on lightweight organic materials such as coal, lignite, and pieces of wood. These materials can be separated out by visual petrographic methods or can be measured using ASTM C 123 with a heavy liquid having a specific gravity of 2.0; these particles typically are not numerous in aggregate and do not cause damage other than surface imperfections. It is recommended that none of the tests for organic material be selected for the research.

3.3.23 – **Chlorides in Aggregates** -- From an aggregate perspective there are some carbonate aggregates that test high in chlorides when the test material is ground to a fine powder and the chlorides are extracted with an acid. Another test (the Soxhlet Extraction with hot water, using sugar-cube-size pieces of aggregate) is probably related more to the actual availability of chlorides from aggregate in concrete, and the Soxhlet Extraction can be used for aggregates as a referee test if those aggregates otherwise test high in chlorides. ACI Committee 222 (ACI 222R-96) on corrosion of steel in concrete has published recommended limits, and the test method is in ACI 222.1-96. It is recommended that chloride content of carbonate aggregates be determined by acid extraction as a screening test to identify those, which may be a factor in premature corrosion of steel in PCCP. Additional tests can then be made as needed.

3.3.24 – **Reactivity with Alkalis in Concrete.**

A new report on Alkali-Aggregate Reaction (AAR) in concrete is being published by ACI Committee 221. It reviews the status of Alkali Silica Reaction (ASR) tests and Alkali Carbonate Reaction (ACR) tests as of about a year ago. ASTM Committee C-9 is working on a revision to the ASTM specification C 33 Appendix on recommended AAR testing. It will be balloted soon. The FHWA has an ASR package through the Office of Technology Applications. The International Center for Aggregates Research (ICAR) is embarking on a

$300,000 study of ASR to study both identification tests and mitigation techniques. One method that needs to be developed is a modification of ASTM C 1260 with adjusted alkali solution normality as proposed by Stark in his SHRP work. An accelerated method is needed that will show a valid correlation with performance in the longer-term concrete prism test as used in Canada and just standardized by ASTM.

3.3.24.1-- **ASR Reactivity** --. Petrographic and laboratory techniques are available to identify potentially alkali silica reactive minerals in aggregates.

ASTM C 295 Practice for Petrographic Examination of Aggregates for Concrete

ASTM C 227 Alkali Reactivity Potential of Cement-Aggregate (Select as the Long-Term Test)

ASTM C 289 Potential Reactivity of Aggregates (Chemical Method) (Do Not Select)

ASTM C 1260 (AASHTO TP 14) Accelerated Potential Alkali Reactivity of Aggregates (Mortar Bar Method) (Select since many agencies are using as a screening test, but it gives false positives.)

Modified C 1260 according to Stark to Modify the Normality of the Alkali Solution in the Test to That Expected in the Concrete. This would eliminate the number of the false positives in C 1260.

ASTM C 1293 Alkali-Silica Reaction in Concrete Prisms (For Validation)

3.3.24.2 -- **ACR Reactivity** -- Petrographic and laboratory methods are available to identify carbonate rocks with the potential problem.

ASTM C 295 Practice for Petrographic Examination of Aggregates for Concrete

ASTM C 586 Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregate (Rock Cylinder Method) (Select for use with those carbonate aggregates showing the characteristic structure associated with ACR)

ASTM C 1105 Alkali-Carbonate Rock Reaction in Concrete Prisms (For Validation)

3.4 – Recommended Research Test Procedures Selected for Measuring Properties of Aggregates for PCCP.

3.4.1 -- Included are the aggregate tests marked as "Selected" in the far right column of Table 3 at the end of this chapter. The selected tests have been considered on the basis of the review of the literature and experience and also with the consideration of the tests and properties identified in the survey of highway agencies of providing a good relationship with performance. (The survey respondents in many cases did not give enough detail to identify the exact test.)

3.4.1.1 -- Tests of Fine Aggregate for All Aggregate Types:

Sieve Analysis
Amount of Minus 75μm (No. 200) Material

Equipment Analysis of Size Distribution of Minus 75μm (No. 200) Material
Sand Equivalent
Methylene Blue Value of Minus 75μm (No. 200) Material
XRD of Minus 75μm (No. 200) Material
Uncompacted Void Content of Fine Aggregate (AASHTO T 304)
Dilatometer for FA Thermal Coefficient of Expansion (TCE)
Durability Index (AASHTO T 210; ASTM C 3744)
Degradation by the Micro-Deval Apparatus (CSA A23.2-23A for FA)
ASTM C 227 Alkali Reactivity Potential of Aggregate
ASTM C 1260 (AASHTO TP 14) Accelerated Potential Alkali Reactivity
Modified ASTM C 1260 with Adjusted Alkali Solution Normality (Stark)
Petrographic Examination of Aggregates for Concrete (ASTM C 295)
  with additional emphasis on:
    Mica
    ASR & ACR Reactive Materials
    Minerals for Estimation of Thermal Coefficient

3.4.1.2 -- Tests of Coarse Aggregate for All Aggregate Types:

Uncompacted Void Content of Coarse Aggregate (AASHTO Provisional)
CA Particle Index
Computer Image Shape Evaluation
Flat and Elongated Particles
Absorption of Water – 15 and 24 Hour Soak, and Vacuum Saturation
Iowa Pore Index – Primary and Secondary
Gas Adsorption Analysis of CA Pore System
MgSO4 Sulfate Soundness
Hydraulic Fracture
Unconfined Freeze-Thaw of Aggregate in NaCl Solution (NY or CSA A23.2-24A)
Dilatometer for CA Thermal Coefficient of Expansion (TCE)
Degradation by the Micro-Deval Apparatus (Ontario Method for CA)
Durability Index (AASHTO T 210; ASTM C 3744)
LA Abrasion
Surface Energy of CA (Texas A & M)
British Crushing Value
Drying Shrinkage of CA Particles
ASTM C 227 Alkali Reactivity Potential of Aggregate
ASTM C 1260 (AASHTO TP 14) Accelerated Potential Alkali Reactivity
Modified ASTM C 1260 with Adjusted Alkali Solution Normality (Stark)
Petrographic Examination of Aggregates for Concrete (ASTM C 295)
  with additional emphasis on:
    CA Surface Properties and Minerals
    ASR & ACR Reactive Materials
    Minerals for Estimation of Thermal Coefficient
    Mineral/Rock Types for Estimation of Drying Shrinkage Potential

3.4.1.3 -- Tests on Carbonate Coarse Aggregates:

Rock Cores: Non Destructive -- Dynamic E, Wave Velocity
Destructive -- Core Strength, Core Modulus of Elasticity (E)
Acid Insoluble
Thermogravimetric Analysis (TGA)
X-Ray Fluorescence Analysis (XRF)
X-Ray Diffraction Analysis (XRD)
ASTM C 586 Alkali Reactivity of Carbonate Rocks (Rock Cylinder Method)

3.4.1.4 -- Tests on FA and CA for Paving Concrete Workability Research:

Combined Sieve Analysis, Combined Minus 75μm (No. 200), Max Size Aggregate
Equipment Analysis of Size Distribution of Combined Minus 75μm Material
Sand Equivalent of FA Portion
Methylene Blue Value of Combined Minus 75μm (No. 200) Material
XRD of Combined Minus 75μm (No. 200) Material
Uncompacted Void Content of Fine Aggregate (AASHTO T 304)
Degradation by the Micro-Deval Apparatus of FA and CA
Durability Index of FA and CA (AASHTO T 210; ASTM C 3744)
Uncompacted Void Content of Coarse Aggregate (AASHTO Provisional)
CA Particle Index
Computer Image Shape Evaluation
Flat and Elongated Particles in CA

3.4.2 -- Based on the consideration reviewed in this chapter the number of tests being selected for inclusion in the suite of tests of aggregate related to performance of PCCP:

Tests of Fine Aggregate for All Aggregate Types	14
Tests of Coarse Aggregate for All Aggregate Types	21
Tests for Carbonate Coarse Aggregate Research	6
Tests on FA and CA for Concrete Workability	12 (Some Same as Above)

Overall this represents about 45 independent tests which are believed to be related to performance of PCCP and which have been selected as tests which should be considered in research. Research should compare alternate procedures for confirmation of their relationship to performance in PCCP and potential for inclusion in a protocol for acceptance of aggregates for use in concrete mixtures for PCCP.

Table–3 Selected Aggregate Tests for Research Relating Aggregate Properties to PCCP Performance
12/31/97

Recommended Tests for Evaluatiing Aggregates Used in PCC Mixtures for Concrete Pavements

				Selection Criteria (Estimated Factors)				
Aggregate Property	Aggregate Test	Technique or Modif.	Rank	Prediction	Precision	Practical	Cost	Selected Yes / No
Physical —								
Gradation, CA&FA	Sieve Analy.& -75µm	T 27 & T 11	_1	H	H	H	M	Y
	Comb.Grading&MSA	By Calculation	_1	H	H	H	L	Y
Fines Charac. -75µm	(none)	Mech. Size Dist.	_2	M	H	H	H	Y
"	Sand Equiv.	T 176	_3	M	M	H	M	Y
"	Methylene Blue	TP___ (From 4-19)	_1	M	?	H	L	Y
	Minerals, Clay	XRD of Fines	_4	H	H	M	H	Y
FA Particle Shape	Uncompacted Voids	T 304	_1	H	M	H	L	Y
	Particle Index	ASTM D 3398	_3	H	M	L	H	N
	Proposed CAR Test	Proposed	_2	?	?	?	M	N
	Petrographic, Visual	C 295	_4	M	M	L	H	N
CA Particle Shape	Uncompacted Voids	TP___ (From 4-19)	_1	H	M	H	L	Y
	Particle Index	ASTM D 3398	_2	H	M	M	M	Y
	Computer Image	Developmental	_3	?	?	?	H	Y
	Crushed Faces	D 5821	_4	L	L	M	L	N
	Petrographic, Visual	C 295	_5	M	M	M	L	Y
	Flat & Elongated	D 4791	_4	M	M	L	L	Y
CA Absorption (Index Tests)	Absorption, Sp. Gr.,	T 85 – 15 Hr. Soak	_2	?	M	H	L	Y
	Absorption, Sp. Gr.,	C 127 – 24 Hr. Soak	_1	M	M	H	L	Y
	Absorption, Sp. Gr.,	Vac. Saturated	_3	M	M	M	M	Y
	Absorption, Sp. Gr.,	Water Aspirator	_4	?	L	M	L	N
CA Pore Properties (Index Tests)	Mercury Intrusion		_2	M	M	L	H	N
	Iowa Pore Index		_1	M	H	H	L	Y
	Pore Surface Area	N, H2O Vapor Adsorp.	_3	?	H	L	H	Y
CA Durability & Soundness (Index Tests)	Sulfate Soundness	T 104 Mg SO4	_2	M	M	M	M	Y
		T 104 Na SO4	_5	L	L	M	M	N
	Hydraulic Fracture	TP 12	_3	M	?	L	H	Y
	Unconf. Freeze Thaw	T103 A-50 Cyc Soakd	_7	M	M	M	M	N
		T103 B-16 Cyc Alcohl	_4	M	M	M	M	N
		T103 C-25 Cyc V. Sat	_6	L	?	L	M	N
		CSA, NY Cyc. in Na Cl	_1	M	M	M	M	Y
Thermal Coef.CA&FA	Dilatometer	Aggr. in Liquid-TAMU	_2	?	?	M	M	One or The Other
	Dilatometer	ASTM Dilatometer	_1	?	?	M	M	
	Petrographic	Assume Fr. Minerals	_3	?	M	M	M	Y
CA Drying Shrinkage	(none)	Particle Measurment	_1	?	?	L	M	Y
	(none)	Dilatometer Wet-Dry	_3	?	?	?	?	N
	Petrographic	Mineral&Rock Prop.	_2	?	?	?	M	Y

Table–3 (Continued) Selected Aggregate Tests for Research Relating Aggregate Properties to PCCP Performance

Recommended Tests for Evaluatiing Aggregates Used in PCC Mixtures for Concrete Pavements

Aggregate Property	Aggregate Test	Technique or Modif.	Rank	Selection Criteria (Estimated Factors)				
				Prediction	Precision	Practical	Cost	Selected
Mechanical —								
FA Breakdown in Wet Attrition, Slaking:								
	Micro Deval of FA	CSA A23.2-23A	_1	M	M	M	M	Y
	Vane Attrition	ASTM C 1137	_3	M	L	M	M	N
	Duribility Index	T 210	_2	M	M	M	M	Y
CA Breakdown in Wet Attrition, Slaking:								
	Duribility Index	T 210	_2	M	M	L	M	Y
	Micro Deval of CA	Ontario LS-618	_1	M	M	M	M	Y
CA Breakdown in Dry Attrition, Abrasion, Impact:								
	LA Abrasion Test	T 96	_1	?	M	H	L	Y
CA-Mortar Bond	Surface Energy	Texas A&M Method	_1	?	?	L	H	Y
	(none)	Petrographic, Surface	_2	?	?	M	M	Y
	(none)	Meas. Surf. Texture	_3	?	?	?	?	N
	Cleanness Value-CV	Caltrans Test 227	_4	L	M	M	M	N
CA Stress-Strain	Sustained (none)	Rock Core	_2 Cr. St.	H	M	M	M	Y
	Impact (none)	Rock Core, Dyn E	_1	M	M	H	L	Y
CA Strength	British Crush Value	BS ____	_1	M	?	M	M	Y
	Rock Core	ASTM D 2938	_2	M	?	M	M	Y
	British Impact Value	BS ____	_3	?	?	L	M	N
Petrographic/Chemical —								
Agg Mineral Structure	Petrographic Eval.	C 294/C 295	_1	M	M	M	M	Y
	Insoluble Residue	D 3042	_Carb	M	M	M	L	Y
	XRD		_2	M	M	M	H	Y
Elements	XRF		_Carb	M	M	M	H	Y
Compound Structure	TGA		_Carb.	M	M	M	H	Y
FA Mica Content	Petrographic Eval.	C 295, Point Count	_1	M	M	M	M	Y
	XRD	To ID Type of Mica	_2	M	?	L	M	N
Organic Impurities	Colorimetric FA, CA	C 40 or C 40 Modif.		L	M	M	M	N
	Petrographic Eval.	C 294, Wood, Coal ...		L	M	M	M	N
	Heavy Liquid, C 123	Wood, Coal, Lignite ...		L	M	M	M	N
Cl in Aggregate	Chem Analysis for Cl	Acid Sol. C 1152	_1	M	H	H	L	Y
		Water Sol. C 1218	_2	M	H	H	M	N
		Soxhlet Extr. ACI 222.	_3	H	?	M	H	N
Reactivity Test	ASR Mortar	C 227	_2 ASR	H	M	L	M	Y
	ASR Mortar	TP 14, C 1260	_4 ASR	M	M	M	M	Y
	ASR Acc. Mort. Modif	Stark/Nelson	_3 ASR	?	?	M	M	Y
	ASR Quick Chem	C 289	_5 ASR	L	M	M	M	N
	ACR Rock Cylinder	C 586	_2 ACR	M	M	M	M	Y
CA&FA Mineral Struct	Petrographic Eval.	C 294/C 295 for:						
		ASR React. Minerals	_1 ASR	M	M	M	M	Y
		ACR React. Minerals	_1 ACR	H	H	M	M	Y

Chapter 4

Research Plan for Laboratory Investigation to Evaluate and Validate Test Methods and Techniques for Measuring Aggregate Properties that Relate to PCCP Performance

4.0 -- Introduction

The six selected critical performance parameters are briefly summarized in Table 1, related to aggregate properties and tests in Table 2; and the selected potential aggregate tests are summarized in Table 3 and are listed at the end of Chapter 3. There is little chance that all of these aggregate tests and pavement responses can be researched in one study. However, there is merit in consideration of a coordinated group of research projects with the objective of identifying a set of aggregate tests, beginning the validation in the laboratory, and then recommending new tests and procedures for validation in study of pavement concrete in the field. Three potential laboratory research series are outlined below to study factors concerning:

(1) All types of aggregates as they affect PCCP through their influence on concrete volume change, durability, and strength properties;

(2) Carbonate coarse aggregates through a range of properties representing the extensive use of limestone and dolomite in PCC pavements in many regions; and

(3) Workability of concrete and how aggregate properties affect segregation and incomplete consolidation in PCCP construction.

This report is provided to initiate discussion and research on aggregates to better define and select aggregate tests shown to be related to the critical PCCP performance parameters. The research not only should compare the relationships between the candidate aggregate tests, but should also provide further validation of the relation of aggregate tests (and the properties they represent) to the performance of PCCP.

In recommending a suite of tests for routine use in approving aggregates for PCCP, a larger number of tests must be researched. Newly proposed or regionally used tests need to be compared to performance in concrete and also to the results of other nationally accepted tests to help narrow the choice to the more effective tests. The foundation of petrographic examination of aggregates is also very important in the suite of tests to identify the principal rocks and minerals present and to point out the potential problem areas with an aggregate that may need further examination by special tests.

4.1 -- All Aggregate Types

Many types of aggregates are used successfully in PCCP, but a number of important performance parameters indicate that deficiencies due to transverse cracks, spalling, faulting, punchouts, and map cracking are not totally understood or accounted for in the tests used for aggregates. Volume change due to thermal and drying shrinkage effects contributes to movement at joints and cracks. Certainly an aggregate that has a higher thermal coefficient or that causes higher drying shrinkage in PCCP will cause more tendency for cracks and joints to open, and promote more warping (curling) tendencies in concrete. Map cracking which is related to aggregate performance is often caused by ASR. Other factors such as grading and properties of fines will influence concrete strength, drying shrinkage, workability and air-entrainment.

4.2 -- Carbonate Aggregates

Ample evidence exists that carbonate aggregates (limestone, dolomite) are quite different from harder rocks and minerals in their performance in concrete. Carbonates cover the range from porous to dense, weak to strong, non-durable to durable. Yet there is not an obvious line of demarcation. In many areas very serviceable concrete is made from what would be judged to be too porous and weak in other areas. Also, manufactured carbonate fine aggregates, more often than not, give strengths in concrete higher than what would be expected from the higher mixing water (and w/c) needed to produce workable slumps. Sometimes greater quantities of minus No 200 fines with carbonates does not hurt strength or durability the way other minerals would. There seems to be a different bonding in carbonate aggregate concrete.

In the major middle part of the country encompassing many states where freezing and thawing and deicing salts are also a problem, the major aggregate durability problem is D-cracking where carbonate particles in both crushed stone and gravel coarse aggregates have sorptive properties (and perhaps other chemical phenomenon) that can cause the slow progressive deterioration. In concrete, salt exposure appears to increase the sorption of fine-grained carbonate coarse aggregates, allowing them to achieve higher levels of saturation quickly, resulting in more rapid freeze-thaw deterioration. (Koubaa, et al, 1997: Dubberke and Marks, 1985, 1989, 1997) This type of deterioration does not appear to occur with the harder rocks.

Carbonate aggregates can also lead to polishing and lower pavement friction depending on the mix of minerals and grain sizes present at the pavement surface. With respect to ACR a decision would have to be made whether to study carbonate reactivity in this research because the extent of the problem is limited to several specific regions. Work on ACR should be confined to those areas unless the petrography of the aggregates selected for study show that it is potentially a more widespread problem.

4.3 -- Workability and Consolidation of Pavement Concrete

The potential problems that can develop in PCCP due to poor workability and consolidation where discussed in Chapter 1. Factors such as segregation (with alternate areas with too much mortar and others with a rocky consistency) and voids near joints, edges, and cracks can provide the discontinuity for crack and spalls to begin. Also these areas do not provide the good aggregate positioning and interlock at joints and cracks. Workable, placeable concrete is needed to provide a consistent concrete placement that optimizes the potential of the concrete mixture. Research is proposed on the effect of aggregate grading, particle shape and angularity, degradation, and the effect of the properties of the minus 75μm (No. 200) fines on workability

4.4 -- A Three-Part Research Plan

It is proposed that research on aggregates for PCCP be done in three major divisions -- (a) Research on all types of aggregates; (b) Research on Carbonate Aggregates, and (c) Research on the effect of grading, particle shape and angularity properties, and properties of minus 75μm (No. 200) fines on workability and consolidation of PCCP mixtures.

In choosing aggregates for these studies, researchers should identify PCC pavements from around the country containing a range of aggregate types and performance; and ,with the assistance of highway agencies, gather performance data, and samples of aggregates. To the extent feasible aggregates should be used that are or have been in other SHRP, FHWA, or agency research projects. However, it is important that the proper range of aggregate types and properties be obtained for both carbonate and non-carbonate aggregates. It is anticipated that approximately 10 carbonate CA sources, 10 Non-carbonate CA sources, at least 10 FA sources will be involved in the study. Aggregates selected should include some that have been used in PCC pavements with incidence of frequent transverse cracking, spalling, faulting, and punchouts, as well as aggregates with a range of performance in ASR. For the carbonate aggregate study aggregates with a range in performance in D-cracking should be included.

For any concrete that is mixed and tested in this research a high strength condition should be included for each aggregate and pavement combination to begin to collect data on the effect of aggregates on concrete properties and performance.

In the following sections are the recommended research series relating concrete performance in the laboratory and any service record available for the aggregates to the selected aggregate tests to be considered for research these three studies.

4.4.1 – Research Plan for All Types of Aggregates

Aggregate Selection --

Coarse Aggregates --	8 Non-Carbonate CA, including 4 Crushed Stones & 4 Gravels 4 Carbonate CA, from the Carbonate Aggregate Study
Fine Aggregates --	3 Non-Carbonate Natural Sands 3 Non-Carbonate Manufactured FA 1 Carbonate Manufactured FA

Aggregate Tests --

Coarse Aggregates --

- Uncompacted Void Content of Coarse Aggregate (AASHTO Provisional)
- CA Particle Index
- Computer Image Shape Evaluation
- Flat and Elongated Particles
- Absorption of Water – 15 and 24 Hour Soak, and Vacuum Saturation
- Iowa Pore Index – Primary and Secondary
- Gas Adsorption Analysis of CA Pore System
- MgSO4 Sulfate Soundness
- Hydraulic Fracture
- Unconfined Freeze-Thaw of Aggregate in NaCl Solution (NY or CSA A23.2-24A)
- Dilatometer for CA Thermal Coefficient of Expansion (TCE)
- Degradation by the Micro-Deval Apparatus (Ontario Method for CA)
- Durability Index (AASHTO T 210; ASTM C 3744)
- LA Abrasion
- Surface Energy of CA (Texas A & M)
- British Crushing Value
- Drying Shrinkage of CA Particles
- ASTM C 227 Alkali Reactivity Potential of Aggregate
- ASTM C 1260 (AASHTO TP 14) Accelerated Potential Alkali Reactivity
- Modified ASTM C 1260 with Adjusted Alkali Solution Normality (Stark)
- Petrographic Examination of Aggregates for Concrete (ASTM C 295)
    - with additional emphasis on:
        - CA Surface Properties and Minerals
        - ASR & ACR Reactive Materials
        - Minerals for Estimation of Thermal Coefficient
        - Mineral/Rock Types for Estimation of Drying Shrinkage Potential

Fine Aggregates –

- Sieve Analysis
- Amount of Minus 75μm (No. 200) Material
- Equipment Analysis of Size Distribution of Minus 75μm (No. 200) Material
- Sand Equivalent
- Methylene Blue Value of Minus 75μm (No. 200) Material
- XRD of Minus 75μm (No. 200) Material
- Uncompacted Void Content of Fine Aggregate (AASHTO T 304)
- Dilatometer for FA Thermal Coefficient of Expansion (TCE)
- Durability Index (AASHTO T 210; ASTM C 3744)
- Degradation by the Micro-Deval Apparatus (CSA A23.2-23A for FA)
- ASTM C 227 Alkali Reactivity Potential of Aggregate
- ASTM C 1260 (AASHTO TP 14) Accelerated Potential Alkali Reactivity
- Modified ASTM C 1260 with Adjusted Alkali Solution Normality (Stark)

Petrographic Examination of Aggregates for Concrete (ASTM C 295)
with additional emphasis on:
Mica
ASR & ACR Reactive Materials
Minerals for Estimation of Thermal Coefficient

Concrete Mixtures (Include some HPC Conditions) – Two cement contents should be employed in air-entrained concrete proportioned for slip form paving. All coarse aggregates will be used with fine aggregate. All fine aggregates will be used with one coarse aggregate. Additional combinations of aggregates and/or cement contents may be selected to address particular performance in the field or to include several HPC conditions in the study.

Concrete Validation Tests – Workability, Volume Change, Strength, Fz-Tw, and ASR

Slump, Workability (Corps of Engineers), A/E, Mixing Water Demand
Compacting Factor and Vebe are potential workability tests
Drying Shrinkage
Thermal Coefficient
Strength – Compression, Splitting Tensile
Modulus of Elasticity (E) of Concrete Containing the Aggregate
CA-Mortar Bond – Petrography of Concrete (looking at CA interface)
Method C Concrete Freeze-Thaw Modified using cloth wrap and salt soaked aggr.
ASR Concrete Prism Test

Replication of Tests and Mixtures --

Aggregate Tests – Two tests per lot by same operator, each run on different days

Concrete Mixtures – Each mixture condition replicated three times, each on a different day. Batch conditions otherwise to be mixed in random order

Concrete Specimens from Mixtures – Test a minimum of two for both fresh and hardened concrete tests. Hold a third specimen in reserve for hardened concrete tests.

Analysis of Data – Run correlations between tests representing the same or similar properties. Also examine correlations between tests and performance of concrete (containing the aggregate) in the laboratory and also with any field performance data or service history. Examine the variability of within laboratory data from aggregate tests, concrete tests from the same batch, and examine the between-mixture variability for replicate mixture conditions.

4.4.2 -- Research Plan for Carbonate Aggregates

Research is needed to better understand the full range of carbonate aggregates that might be used in PCCP. Approximately half of the aggregates and corresponding PCCP included in this study (12 CA and 2 FA) should be limestone and dolomite with a wide range of properties. In this work with carbonate aggregates the concentration should be on D-cracking in freeze-thaw areas and on the strength performance and interface properties for both aggregates and concrete ranging from weak to very strong, as would be used in HPC. What are the advantages and disadvantages of providing compatibility between the properties of the mortar and the properties of the coarse aggregate.

Aggregate Selection --

Coarse Aggregates -- 10 Carbonate CA, including 6 Crushed Stones & 4 Gravels with a minimum of 35% Carbonate Particles

Fine Aggregates -- 5 Carbonate Manufactured FA
1 Natural Sand
Natural Sand – With Carbonate Minus 75μm (No. 200) Material

Aggregate Tests --

Coarse Aggregates --
Rock Cores: Non Destructive -- Dynamic E, Wave Velocity
Destructive -- Core Strength, Core Modulus of Elasticity (E)
Acid Insoluble
Thermogravimetric Analysis (TGA)
X-Ray Fluorescence Analysis (XRF)
X-Ray Diffraction Analysis (XRD)
ASTM C 586 Alkali Reactivity of Carbonate Rocks (Rock Cylinder Method)

Fine Aggregates --

No Additional Tests, Carbonate Fine Aggregates Tested the Same as the First Study Above

Concrete Mixtures (Include some HPC Conditions) -- Two cement contents should be employed in air-entrained concrete proportioned for slip form paving. All coarse aggregates will be used with fine aggregate. All fine aggregates will be used with one coarse aggregate. Additional combinations of aggregates and/or cement contents may be selected to address particular performance in the field or to include several HPC conditions in the study.

The four conditions should be studied:

1. CA Weak w/ Mortar Weak
2. CA Weak w/ Mortar Strong
3. CA Strong w/ Mortar Weak
4. CA Strong w/ Mortar Strong

Concrete Validation Tests --

Slump, Workability (Corps of Engineers), A/E, Mixing Water Demand
Compacting Factor and Vebe are potential workability tests
Drying Shrinkage
Thermal Coefficient
Strength – Compression, Splitting Tensile
Modulus of Elasticity (E) of Concrete Containing the Aggregate
CA-Mortar Bond – Petrography of Concrete (looking at CA interface)
Method C Concrete Freeze-Thaw Modified using cloth wrap and salt soaked aggr.
ASR Concrete Prism Test

Replication of Tests and Mixtures --

Aggregate Tests – Two tests per lot by same operator, each run on different days

Concrete Mixtures – Each mixture condition replicated three times, each on a different day. Batch conditions otherwise to be mixed in random order

Concrete Specimens from Mixtures – Test a minimum of two for both fresh and hardened concrete tests. Hold a third specimen in reserve for hardened concrete tests.

Analysis of Data – Run correlations between tests representing the same or similar properties. Also examine correlations between tests and performance results from concrete simulation tests in the laboratory and also with any field performance data or service history. Examine the variability of within laboratory data from aggregate tests, concrete tests from the same batch, and examine the between-mixture variability for replicate mixture conditions.

4.4.3 -- Research Plan for Workability of Paving Concrete

Aggregate Selection --

Coarse Aggregates -- Cubical Shaped Crushed Stone
Very Flat, Elongated, Angular Crushed Stone
Spherical, Rounded Gravel
Fine Aggregates -- Manufactured FA (FAA Value 45+)
Natural Sand (FAA Value 42-43)
Natural Sand (FAA Value 39-)
50-50 Blend of Natural Sand and Manufactured FA

Aggregate Tests --

Run on Combined *Coarse Aggregate* and *Fine Aggregate* Materials, Since They Are Mixed in the Concrete –

Combined Sieve Analysis, Combined Minus 75μm (No. 200), Max Size Aggregate
Equipment Analysis of Size Distribution of Combined Minus 75μm Material

Sand Equivalent of FA Portion
Methylene Blue Value of Combined Minus 75μm (No. 200) Material
XRD of Combined Minus 75μm (No. 200) Material
Uncompacted Void Content of Fine Aggregate (AASHTO T 304)
Degradation by the Micro-Deval Apparatus of FA and CA
Durability Index of FA and CA (AASHTO T 210; ASTM C 3744)
Uncompacted Void Content of Coarse Aggregate (AASHTO Provisional)
CA Particle Index
Computer Image Shape Evaluation
Flat and Elongated Particles in CA

Concrete Mixtures (Include some HPC Conditions) -- Two cement contents should be employed in air-entrained concrete proportioned for slip form paving. All coarse aggregates will be used with fine aggregate. All fine aggregates will be used with one coarse aggregate. Additional combinations of aggregates and/or cement contents may be selected to address particular performance in the field or to include several HPC conditions in the study.

Gradings Should Include – Gap Graded, Graded Down the .45 Power Curve, and Added Minus 75μm (No. 200) Material of clay material in one case and non-clay fines in the other.

Concrete Validation Tests --

For a study of the effect of grading on the workability of the concrete a procedure is needed to assess the workability and placeability of low slump concrete consolidated by vibration. It is proposed that the recommended workability test or tests from the Corps of Engineers FHWA Study be used for the evaluation.

Another series of tests to demonstrate the consolidation workability of the paving mixtures could be adapted from a study in the NAA-NRMCA Laboratory, where concrete was over-vibrated in a cylinder to study segregation and the thickness of the mortar layer created at the surface. A condition of under-vibration can also be used to observe voids due to incomplete consolidation. After hardening the cylinders can be split in tensile splitting to observe the concrete cross section.

Replication of Tests and Mixtures --

Aggregate Tests – Two tests per lot by same operator, each run on different days

Concrete Mixtures – Each mixture condition replicated three times, each on a different day. Batch conditions otherwise to be mixed in random order

Concrete Specimens from Mixtures – Test a minimum of two for both fresh and hardened concrete tests. Hold a third specimen in reserve for hardened concrete tests.

Analysis of Data – Run correlations between tests representing the same or similar properties. Also examine correlations between tests and performance results from concrete simulation tests in the laboratory and also with any field performance data or service history. Examine the variability of within laboratory data from aggregate tests, concrete tests from the same batch, and examine the between-mixture variability for replicate mixture conditions.

4.5 – Validation Options

Ultimately service records for aggregates in PCCP (gathered in some consistent way) will be important for field validation of a proposed suite of tests. Near-term research can focus on relating tests (properties) of aggregates with laboratory performance of concrete. References to high performance concrete, in general, refers to high-strength concrete. In some cases concrete mixtures might be formulated to yield other "high-performance" properties such as a modulus of elasticity within a certain range or to proportion a mixture with enhanced workability. Any research that is done relating aggregate properties to concrete properties should be done over a range of concrete strength levels, rather that the limited strength level normally used for PCCP – 4000 to 6000 psi. As a minimum two strength levels 4000 and 8000 psi should be included. A number of aggregates may be adequate at 4000 psi, but because of bond properties, high mixing water demand, or weak mineral structure may not perform at 8000 psi.

As an alternative to a specific field installation for validation in this study, a listing could be developed of research PCC pavements that are available around the country and for which aggregates could be obtained from the same or similar sources. This might well provide a dozen projects where aggregate properties and sources are known and where records and condition surveys are available. It might require a visit to each potential DOT to look at the pavement and retrieve the pertinent records and reports. If some of these projects can be used samples of the concrete containing the aggregate would have to be obtained to aid in investigating the service record of that aggregate in the pavement and , perhaps, other nearby PCC pavements.

One option instead of detailed characterization of the minus No 200 fines is to run comparative drying shrinkage studies of the aggregate in concrete with various proportions of the fines materials to judge its effect on drying shrinkage. These tests might take six months, but may be worth doing on a source approval basis. Thermal Coefficient validation tests could be run on specimens made from the same concrete.

Petrographic Examination of Aggregate in Concrete -- This is essential to the recognition of mechanisms of deterioration and to the development of service record data for an aggregate source. Comparisons must be made to verify that the material in the concrete is of the same or very similar lithologic composition as the current aggregate material being mined and processed. If there are differences, then a determination must be made as to whether the differences will impact on the mechanisms of deterioration under consideration. Types of distress/performance that can be particularly identified through petrographic evaluation methods are: ASR and ACR-related **Map Cracking**; **D-Cracking**, problems with Fresh Concrete Workability and consolidation, and Popouts.

Aggregate Interlock Texture of Cracked Concrete -- The University of Minnesota is looking at the use of a surface area measurement of a crack or joint surface of concrete as a measurement of potential aggregate interlock. Various aggregates could be compared in concrete mixtures in slab-like specimens that are fractured. Weaker coarse aggregates will tend to break through the particles and stronger aggregates will break around the particles producing more relief and the potential for aggregate interlock load transfer with larger joint movements and crack openings. Aggregate interlock will help reduce **Faulting** but may increase **Spalling** depending on the loads and the strength of the concrete. A test of aggregate interlock potential is a procedure for measuring surface texture in joints and cracks has been used. It is the 'volumetric surface texture ratio' (VSTR). (Cuttell, M. B. Snyder, et. al.) Load transfer by aggregate interlock depends not only on the surface texture, but on the tightness of the crack or joint. Wide joint openings due to volume change movements will negate aggregate interlock, even though the texture is high.

Lab Freeze-Thaw of Aggregate in Concrete – Methods involving testing coarse aggregate in concrete in the laboratory are used by a number of states as the referee test for the acceptance of aggregate with respect to freezing and thawing. In many research projects the testing of freeze-thaw resistance in concrete represents the performance criteria against which other properties are compared since actual field performance data of aggregate in service in concrete pavement are often not available. A number of options are available for moisture treatment of the aggregate before mixing in concrete, curing of the concrete, and access to water during the freezing and thawing cycle. Agencies normally use the rapid freezing and thawing of CA in Concrete using ASTM C 666 (AASHTO T 161 & TP 17). Options include:

*Method A -- Freezing and Thawing in **Water**, Specimen in Boot or Other Container*
*Method B -- Freezing in **Air** and Thawing in Water, Specimen not in Container*
*Method B (Modified) -- **Chloride** Treatment of Aggregate Before Freeze-Thaw*
*Method C -- Freezing in Air (**Moist Cloth Wrapped**) and Thawing in Water*

Routine freezing and thawing testing often involves overnight (1 day) soaking of the coarse aggregate before mixing in concrete, moist curing of the concrete, and then freezing in air, thawing in water. Other options are also available.

Validation Options for Rapid Freezing and Thawing of Aggregates in Concrete

Treatment of C. Aggr	Curing of Conc	Freeze-Thaw Options	Evaluation Options
As Received Moist Cond.	Moist	B- Freeze in Air Thaw in Water	Sonic Modulus Relative E & DF
Soaking Overnight	Moist with Drying Cycle	A- Freeze in Water Thaw in Water	Expansion of Concrete
Vacuum Saturation	Extended Moist Cure	C- Freeze in Terry Cloth Wrap Thaw in Water	Impact Freq. Evaluation
Soaking in NaCl Soln.			

A modified Method B test using salt-treated aggregate gave good correlation with performance of PCCP in Minnesota (Koubaa and Snyder). They have also proposed that salt-treatment might be tried with the Method C test of aggregates. The VPI single cycle test also was related to performance, as well.

Pretreatment of aggregates by vacuum saturation that fills all the pore space with water will cause any aggregate with medium or high absorption to fail in freezing and thawing no matter which cycle is used. Most states subject the aggregate to only one day of soaking prior to mixing the concrete. Michigan has used a vacuum saturated aggregate approach for many years. (Vogler and Grove, 1989) The vacuum saturated aggregate approach has been criticized as overly severe. In work done at the NAA-NRMCA laboratory a one-day-soaking pretreatment (without vacuum saturation) followed by freezing and thawing in water appeared to rank coarse aggregate in the general order of reported performance in **D-Cracking** using Ohio Aggregates.

The new freeze-thaw test procedure developed under SHRP using a terry cloth wrapped concrete specimen (Method C) and impact frequency condition evaluation should be investigated for use in approving coarse aggregates. It provides a more reliable procedure to the freeze in water option rather than the use of rigid containers which can cause premature damage to specimens in Method A. Also the Method C is more realistic of field exposure by keeping the concrete continuously wet as opposed to the method B Freeze in Air where the specimen can dry during the freezing cycle if early damage does not occur. Of course the salt treatment option used in the Minnesota research appears to be a valid approach.

4.6 -- Practice for Establishing a Service Record for an Aggregate Source. This might be a follow-on project after tests are identified that are related to PCCP mixture performance in the laboratory

-- Develop a Recommended Standard Practice for Investigation of the Service Record of an Aggregate Many specifications for aggregates for PCCP will allow the use of materials that do not meet some of the specified tests if they can be shown to exhibit good performance in service. However there is not standard practice for the establishment of the service record of an aggregate in concrete. In the selection of aggregates for use in validating tests related to performance emphasis is needed on petrography to make use of existing resources.

By studying how aggregates perform in service will provide a better basis for specifications, and will provide more input to the best use of aggregates in HPC. Two references – (1) Rogers, 1990, and (2) Koubaa and Snyder, 1996 – provide excellent examples of using petrography to relate pavement performance to aggregate characteristics to improve specifications and use of aggregates. They provide techniques to obtain field performance feed back from pavements that have been in service for many years. Procedures for establishing the service record for aggregates used in PCC pavements would involve using petrographic methods for examining the performance of the aggregate in concrete and then comparing it to the aggregate currently produced at the source. Procedures should be outlined for determining if the aggregates are comparable and reporting on the performance of the aggregate in concrete with respect to alkali reactivity, freeze-thaw performance (if exposed), and the contribution of the aggregate to the quality of the interface zone (porosity, voids, bond, etc.)

4.7 -- Products -- Output Expected from the Research

From the results of the research those tests that show the best correlation with performance of concrete in the laboratory or, preferably, performance in PCC pavements in the field should be selected for use in a proposed suite of tests looking at the general performance areas:

Fresh Concrete Properties (workability, control of slump, and air content)

Grading
Minus No 200 Properties
Degradation in a wet environment – micro deval or durability index
Particle shape, angularity, texture

Strength, Bond, Aggregate Interlock

Dry Degradation and Impact Resistance – LA Abrasion, for example
Strength -- British Crushing Value, for example
Surface Energy, may be a useful new property related to bond

ASR – New AASHTO and ASTM techniques, or modifications thereof

Durability in freeze-thaw, in the presence of salts

Volume Change

Thermal
Drying Shrinkage

New tests and petrographic procedures for the evaluation of aggregate for PCCP will include aggregate tests related to volume change in paving concrete, tests of aggregate degradation during mixing of concrete, and tests of CA strength and surface properties. From the carbonate aggregate study a better understanding of the range of strength and durability properties of the aggregate and how they affect PCCP. Additional tools will be validated for the investigation of the durability and structure of carbonate aggregates. From the workability study an understanding will be gained of the effects of grading and properties of fines in the mixture on the consistency and placeability of paving concrete. As for the use of the products in practice, from the results of these studies, and depending on the type of aggregate, and the severity of the weathering exposure it will be feasible to develop a decision tree approach where the first step is the petrographic classification of aggregates into carbonate and non-carbonate or hard and soft rock for evaluation protocols. Another division would be freeze-thaw exposure for the concrete vs. non- freeze-thaw exposure. Validated aggregate test procedures that are simple and quick can be used for acceptance and quality control, while those that are more time consuming, sophisticated, and/or expensive can be used for source approval and the investigation of the performance of aggregates in PCC pavements.

It is anticipated that some type of "decision tree" would be a product of the research effort. It would be used in selecting the tests to be run on a particular fine or coarse aggregate (or a mixed aggregate in some cases.) Initially the first round of tests would be based on the PCCP type, design, and climate and on the observed types of rocks and minerals present from the petrographic analysis. At this point any suspected potential problems can be identified for any supplementary tests like ACR or mica's effect on workability, etc. After the first round of tests, additional tests would be called for depending on performance in the first round. For example, there may be no point in running freeze-thaw tests on a coarse aggregate if the vacuum saturated absorption is less than 0.5 or 1.0 percent. Development of a "decision tree" or "informed testing protocol" should be examined to see under which conditions it is not necessary to run certain tests – such as the more time consuming durability or reactivity types of tests, or the testing of thermal coefficient for a limestone.

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Appendix – Standard Tests and Specifications for Aggregates Used in PCCP (Principally AASHTO and ASTM Standards)

ASTM, the American Society for Testing and Materials, is recognized worldwide as a primary nonprofit standardization organization which includes representatives of users, producers, and general interest groups. The organization's purpose is the development of voluntary consensus standards for materials, products, systems, and services. ASTM develops both standard specifications and standard methods of test needed to ensure compliance with them. ASTM also develops many other standard practices and nomenclature

ASSHTO, the American Association of State Highway and Transportation Officials, is a similar group representing highway or transportation departments from each of the 50 States, the District of Columbia, Puerto Rico, several Canadian provinces, various U. S. territories; the U. S. Department of Transportation; and various commissions and authorities. AASHTO also develops both specifications and test methods, many of which are similar to ASTM standards. Recently AASHTO has published a number of provisional standards based on products from the Strategic Highway Research Program (SHRP). Specifications and test procedures published by AASHTO generally allow agencies to select specification limits and test options that are based on their needs in a particular state or area.

Other test methods are listed as well. Many of these are used in a limited geographical area and/or have been reported by researchers to be a good way to measure an aggregate property or may be related to performance.

Specifications

1. Coarse Aggregate Size:

◆ AASHTO M 43 (ASTM C 448) Standard Sizes of Coarse Aggregate.

2. Aggregates for Portland Cement Concrete:

◆ AASHTO M 6 Fine Aggregate for PC Concrete

◆ AASHTO M 80 Coarse Aggregate for PC Concrete

◆ ASTM C 33 Concrete Aggregates (fine and coarse)

◆ AASHTO M 195 (ASTM C 330) Lightweight Aggregates for Structural Concrete

◆ "Proposed Draft for Aggregates for Concrete Including for Use in Roads and Pavements," Document CEN/TC154/SC2/N135, British Standards Institute, Secretariat of CEN/TC154/SC2, Comite European de Normalisation, November, 1994, 26 pages.

3. Practices - General

◆AASHTO R 1 (ASTM E 380) Metric Practice Guide

◆ AASHTO R 10 Definitions of Terms for Specifications Procedures

◆ AASHTO R 11 (ASTM E 29) Practice for Indicating Which Places of Figures Are to Be Considered Significant in Specified Limiting Values

◆ AASHTO M 145 The Classification of Soils and Soil-Aggregate, Fill Materials, and Base Materials

◆ AASHTO M 146 Terms Relating to Subgrade, Soil-Aggregate, and Fill Materials

◆ ASTM D 8 Definitions of Terms Relating to Materials for Roads and Pavements

◆ ASTM C 125 Terminology Relating to Concrete and Concrete Aggregates

Testing

4. General Testing

◆ AASHTO M 92 (ASTM E 11) Wire Cloth Sieves for Testing Purposes

◆ AASHTO M 132 (ASTM E 12) Terms Relating to Density and Specific Gravity

◆ AASHTO M 231 Weights and Balances Used in Testing

◆ ASTM Manual of Aggregate and Concrete Testing (appears in ASTM Volume 04.02 in the back in the gray pages)

◆ ASTM C 1077 Practice for Laboratories Testing Concrete and Concrete Aggregates

5. Sampling and Sample Preparation

◆ AASHTO T 2 (ASTM D 75) Sampling Aggregates

◆ AASHTO T 248 (ASTM C 702) Reducing Field Samples of Aggregate to Testing Size

◆ AASHTO T 87 (ASTM D 421) Dry Preparation of Disturbed Soil and Soil-Aggregate Samples for Test

◆ AASHTO T 146 (ASTM D 2217) Wet Preparation of Disturbed Soil Samples for Test

6. Particle Size Analysis of Aggregates

- AASHTO T 27 (ASTM C 136) Sieve Analysis of Fine and Coarse Aggregates
- AASHTO T 11 (ASTM C 117) Amount of Material Finer than the No. 200 (75µm) Sieve
- AASHTO T 88 (ASTM D 422) Particle Size Analysis of Soils
- Method to Calculate Combined Particle Size Analysis of Aggregate
- Method to Calculate Maximum Size of Aggregate (MSA)
- Test on the Effect of Combined Particle Size Analysis of Aggregate on Joint Spalling (Air Force)

7. Properties of Fines in Aggregates

- AASHTO T 176 (ASTM D 2419) Sand Equivalent Test for Plastic Fines in Graded Aggregates and Soils
- AASHTO T 89 (ASTM C 4318) Determining the Liquid Limit of Soils
- AASHTO T 90 (ASTM C 4318) Determining the Plastic Limit and Plasticity Index of Soils
- AASHTO ________ Proposed by 4-19 Methylene Blue Value of Minus 75µm Fine Material in an Aggregate
- Proposed by 4-19 Particle Size Distribution of Minus 75µm Fine Material in an Aggregate by Laser Device
- California Test 227 Evaluating Cleanness of Coarse Aggregate (Cleanness Value -- CV)
- Methods of Identification of the Actual Clay Minerals Present and an Estimate of Quantity in the Minus No. 200 Material

8. Soundness of Aggregates (Unconfined Aggregate Samples)

- AASHTO T 104 (ASTM C 88) Soundness of Aggregate by Use of
  - -- Sodium Sulfate or
  - -- Magnesium Sulfate

- AASHTO T 103 Soundness of Aggregates by Freezing and Thawing
  - Method A -- **Total Immersion in Water**, 50 Cycles, after 24 hr soak
  - Method B -- **Partial Immersion in Alcohol Solution**, 16 Cycles after Vacuum Saturation with the alcohol solution
  - Method C -- **Partial Immersion in Water**, 25 Cycles after Vacuum Saturation with Water
  - Method NY -- **Using a Na Cl Brine Solution,** 25 Cycles
  - CSA A23.2-24A -- **Freeze-Thaw of Aggregate in NaCl Solution**

- AASHTO TP 12 Hydraulic Fracture of Coarse Aggregate

9. Durability of Aggregates by Freezing and Thawing in Concrete

- AASHTO T 161 TP17 (ASTM C 666) Resistance of Concrete to Rapid Freezing and Thawing
  - Method A -- Freezing and Thawing in **Water**, Specimen in Boot or Other Container
  - Method B -- Freezing in **Air** and Thawing in Water, Specimen not in Container
  - Method B (Modified) -- **Chloride** Treatment of Aggregate or Concrete before Freeze-Thaw
  - Method C -- Freezing in Air (**Moist Cloth Wrapped**) and Thawing in Water

- AASHTO TP 18 Quality Factor and Fundamental Transverse Frequency of Concrete Prisms by impact resonance

- ASTM C 671 Critical Dilation of Concrete Specimens Subjected to Freezing

- ASTM C 682 Evaluation of Frost Resistance of Coarse Aggregates in Air-Entrained Concrete by Critical Dilation Procedures (ASTM C 671)

- VPI Single Cycle, Slow Cooling Freezing Test of Aggregate in Concrete

10. Abrasion and Degradation Resistance of Aggregates

- AASHTO T 96 (ASTM C 131) Resistance to Abrasion (degradation by abrasion and impact) of Small-Size Coarse Aggregate by Use of the Los Angeles Machine (Dry Test)

- ASTM C 535 Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine (Dry Test)

- AASHTO T 210 (ASTM C 3744) Aggregate Durability Index (DI) (Wet Test)
  - Note: WA and OR also have wet degradation tests related to performance.

- ASTM C 1137 Degradation of Fine Aggregate Due to Attrition (Wet Test)

◆ Ontario MOT Test LS-618 Resistance of **Coarse Aggregate** to Degradation by Abrasion in the Micro-Deval Apparatus (Wet Test)

◆ CSA A23.2-23A Resistance of **Fine Aggregate** to Degradation by Abrasion in the Micro-Deval Apparatus (Wet Test)

11. Deleterious Materials in Aggregates

◆ AASHTO T 21 (ASTM C 40) Organic Impurities in Sand for Concrete

◆ AASHTO T 71 (ASTM C 87) Effect of Organic Impurities in Fine Aggregate on Strength of Mortar

◆ AASHTO T 112 (ASTM C 142) Clay Lumps and Friable Particles in Aggregate

◆ AASHTO T 113 (ASTM C 123) Lightweight Pieces in Aggregate

◆ Test for Mica in Fine Aggregate (Or Use Petrographic Techniques to Type and Estimate Amount)

12. Petrographic Evaluation of Aggregates

◆ ASTM C 294 Nomenclature of Constituents of Natural Mineral Aggregates

◆ ASTM C 295 Practice for Petrographic Examination of Aggregates for Concrete

◆ ASTM C 856 Practice for Petrographic Examination of Hardened Concrete

13. Particle Shape of Aggregates

◆ ASTM D 4791 Flat or Elongated Particles in Coarse Aggregate

◆ ASTM C 1252 (AASHTO TP 33 and AASHTO T 304) Uncompacted Void Content of Fine Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading)

◆ ASTM D 5821 Percent of Fractured Particles in Coarse Aggregate

◆ AASHTO ________ Proposed by 4-19 Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading) or void content in the unit weight test of aggregate AASHTO T 19, ASTM C 29

- Proposed Tests for Aggregate Particle Shape by Image Analysis (Coarse & Fine ?)

- ASTM D 3398 Particle Index – to be used for Coarse Aggregate only; it is too involved to use for fine aggregate

- Tests for Aggregate Particle Shape by Visual Examination (Coarse & Fine, using a microscope) The Corps of Engineers has methods for this.

- CAR Test for Fine Aggregate Particle Shape

14. Alkali Aggregate Reactivity of Aggregates

- ASTM C 227 Alkali Reactivity Potential of Aggregate

- ASTM C 289 Potential Reactivity of Aggregates (Chemical Method)

- ASTM C 586 Potential Alkali Reactivity of Carbonate Rocks for Concrete Aggregate (Rock Cylinder Method)

- ASTM C 342 Volume Change Potential of Cement-Aggregate Combinations

- ASTM C 441 Mineral Admixture Effectiveness in Preventing Excessive Expansion Due to Alkali-Aggregate Reaction

- ASTM C 1260 (AASHTO TP 14) Accelerated Potential Alkali Reactivity of Aggregates (Mortar Bar Method)

- ASTM C 1105 Alkali-Carbonate Rock Reaction in Concrete Prisms

- ASTM C 1293 Alkali-Silica Reaction in Concrete Prisms

15. Moisture Content of Aggregate

- AASHTO T 255 (ASTM C 566) Total Moisture Content of Aggregate by Drying

- AASHTO T 217 Moisture in Soils (and Fine Aggregate) by Means of a Calcium Carbide Gas Pressure Moisture Tester (Speedy Moisture Meter)

- AASHTO T 142 (ASTM C 70) Surface Moisture in Fine Aggregate (Using a Pycnometer or Flask)

◆ AASHTO T 239 (ASTM D 3017) Moisture Content in Place by Nuclear Methods (shallow depth)

16. Specific Gravity, Absorption, Porosity, and Unit Weight of Aggregates

◆ AASHTO T 84 (ASTM C 128) Specific Gravity and Absorption of Fine Aggregate

◆ AASHTO T 85 (ASTM C 127) Specific Gravity and Absorption of Coarse Aggregate

◆ Vacuum Saturated Absorption of Coarse Aggregate, compared to that with water aspirator, 15 hr, and 24 hr soak.

◆ AASHTO T 19 (ASTM C 29) Unit Weight and Voids in Aggregate

◆ Iowa Pore Index Test of Coarse Aggregate

◆ Mercury Intrusion Pore Size Distribution Test of Coarse Aggregate

◆ ASTM C 830 Apparent Porosity, Liquid Absorption, Apparent Specific Gravity, and Bulk Density of Refractive Shapes by Vacuum Pressure

◆ Gas Adsorption Surface Area and Pore Size Distribution Test of Coarse Aggregate

17. Frictional Properties of Aggregates and Pavements

◆ AASHTO T 279 (ASSTM D 3319) Accelerated Polishing of Aggregates Using the British Wheel

◆ AASHTO T 242 (ASTM E 274) Frictional Properties of Paved Surfaces Using a Full-Scale Tire (Skid Trailers)

◆ AASHTO T 278 (ASTM E 303) Measuring Surface Frictional Properties Using the British Pendulum Tester (BPT)

◆ ASTM D 3042 Insoluble Residue in Carbonate Aggregates (acid insoluble)

◆ ASTM E 707 Skid Resistance of Paved Surfaces Using the NC State University Variable-Speed Friction Tester

◆ ASTM E 660 Accelerated Polishing of Aggregates or Pavement Surfaces Using a Small-Wheel Circular Polishing Machine

18. Effect of Aggregate Strength, Bond, and Creep on Concrete Properties

- Test Effect of Coarse Aggregate on Concrete Strength

- Test Effect of Coarse Aggregate Bond on Concrete Strength and Other Properties (mechanical, visual, petrographic, permeability, thin section dye method)

- Test Effect of Coarse Aggregate on Concrete Modulus of Elasticity, Creep, and Strain Capacity

- CRD C 71 Ultimate Strain Capacity of Concrete

- British Crushing Value Test of Coarse Aggregate Particles in a Confined Steel Container

- ASTM D 2936 Direct Tensile Strength of Intact Rock Core Specimen

- ASTM D 2938 Unconfined Compressive Strength of Intact Rock Core Specimen

19. Chemistry and Physics Tests

- XRD Test of Coarse Aggregate by X-Ray Diffraction to Identify Minerals and Measure the Dolomite D-Spacing

- XRF Test of Trace Elements in Coarse Aggregate by X-Ray Fluorescence

- TGA Test for Thermogravimetric Analysis of Coarse Aggregate

- Chloride in Aggregate as it Affects Corrosion of Steel in Concrete (ACI Provisional Test Method ACI 222.1 Using the Soxhlet Extraction), Compared to Extraction from a Powdered Aggregate Sample – Acid Extraction (ASTM C 1152) and/or Water Extraction (ASTM C 1218)

20. Volumetric Tests of Aggregates

- CRD C 125 Test of Linear Thermal Expansion of Coarse Aggregate (Strain Gage Method)

- CRD C 39 Test of Coefficient of Thermal Expansion of Concrete

- AASHTO T 160 Length Change of Hydrated Cement Mortar

- AASHTO T 157 Affect of Aggregates on Drying Shrinkage of Concrete

- Thermal Dilatometer for FA and/or CA Thermal Coefficient of Expansion (CTE). Some possibilities are:

  -- Texas A&M has developed a dilatometer test for TexDOT and FHWA (Wang, 1997)

  -- ASTM E 228 Linear Thermal Expansion of Solid Materials with a Vitreous Silica Dilatometer

  -- ASTM D 5515 Determination of the Swelling Properties of Bituminous Coal Using a Dilatometer

  -- ASTM D 4535 Measurement of Thermal Expansion of Rock Using a Dilatometer

  -- ASTM C 372 Linear Thermal Expansion of Porcelain Enamel and Glaze Frits and Fired Ceramic Whiteware Products by the Dilatometer Method

  -- ASTM D 696 Coefficient of Linear Thermal Expansion of Plastics Between -30C and 30C
- Measurement of CA Particle Drying Shrinkage

- CA Particle Drying Shrinkage Dilatometer

- CA Drying Shrinkage of Mortar and Concrete Using a Ring Test