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Aggregate Tests for Portland Cement Concrete Pavements: Review and Recommendations

This digest summarizes the findings from NCHRP Project 4-20C, "Aggregate Tests Related to Performance of Portland Cement Concrete Pavements: State of the Knowledge." It was prepared by Dr. Amir N. Hanna, NCHRP Senior Program Officer, from the contractor's final report authored by Dr. Kevin J. Folliard and Mr. Kurt D. Smith. Dr. Folliard served as principal investigator.

INTRODUCTION

This digest summarizes the findings of the research conducted under NCHRP Project 4-20C to identify aggregate tests related to the performance of portland cement concrete (PCC) pavements and to provide guidance on their use for evaluating and selecting aggregates for use in specific pavement applications. The information and guidance presented in this digest pertain to normal-density aggregates and may not apply to lightweight, heavyweight, or recycled aggregates.

Aggregates typically make up 70 to 80 percent of the total volume of PCC and have a major impact on the properties of the mixture. They significantly affect many fresh and hardened concrete properties and the long-term performance of the pavement structure. Despite their obvious importance, little consideration is often given to the testing of aggregates. Many aggregate and aggregate-related tests currently in use are empirical, without any direct relation to pavement performance. Furthermore, some of the most commonly used test methods are not easy to perform and do not yield reproducible results. User-friendly, reproducible, precise tests that relate key aggregate properties to pavement performance are needed for use in conjunction with performance-related specifications. NCHRP Project 4-20 and subsequently Projects 4-20A, 4-20B, and 4-20C were initiated to address this need.

NCHRP Project 4-20C was conducted to identify, using readily available information, a set of aggregate tests that relate to PCC pavement performance and to provide guidance on their use for specific paving applications. This objective was accomplished by conducting a comprehensive review of literature and current practices and building on the preliminary findings of three earlier related NCHRP projects (Fowler et al., 1996; Meininger, 1998; and Folliard and Sabol, 1999). Particular consideration was also given to the findings of another NCHRP project that dealt with aggregate tests for hot-mix asphalt (HMA) pavements (Kandhal and Parker, 1998).

PAVEMENT PERFORMANCE PARAMETERS

Jointed plain concrete pavements (JPCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP) are the three common types of PCC pavements. JPCP are unreinforced, jointed pavements with doweled or undoweled transverse joints generally spaced at no more than 5 m apart. JRCP are jointed, reinforced pavements with doweled joints at a longer spacing (typically about 9 to 12 m) and contain steel reinforcement of about 0.15 to 0.25

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percent of the cross-sectional area distributed throughout the slab. CRCP have no regularly spaced transverse joints but contain a significant amount of longitudinal steel reinforcement (typically 0.6 to 0.8 percent of the cross-sectional area). Each of these pavement types responds differently to traffic and environmental loading and, therefore, exhibits different performance characteristics and trends.

Pavement performance is generally expressed in terms of the extent of distresses that adversely affect the functional effectiveness or structural integrity of the pavement (e.g., cracking and faulting) or in terms of functional measures (e.g., roughness and surface friction). Table 1 lists the various distresses for each pavement type, as recognized by the Long-Term Pavement Performance (LTPP) distress identification manual (SHRP, 1993). This comprehensive list, however, does not include several distresses that relate to the properties of the materials used in pavement construction (e.g., alkali-aggregate reactivity and sulfate attack). Detailed information on the detection, analysis, and treatment of these materials-related distresses (MRD) are described in several reports (Van Dam et al., 2002a; Van Dam et al., 2002b; Sutter et al., 2002). Some of the identified distresses have a more detrimental effect on pavement performance and serviceability than others. Also, not all of these distresses are strongly influenced by the properties of the aggregates used in the concrete; some are not influenced by aggregate properties at all.

Based on a review of the distress mechanisms and an examination of related literature, 11 key performance parameters have been identified as having a critical effect on pavement performance and also as being related to aggregate properties. Eight of these distresses (alkali-aggregate reactivity, blowups, D-cracking, longitudinal cracking, roughness, spalling, surface friction, and transverse cracking) occur in all pavement types; two distresses (corner breaks and transverse joint faulting) occur only in jointed concrete pavements; and one distress (punchouts) occurs only in CRCP.

Alkali-Aggregate Reactivity

Alkali-aggregate reactivity (AAR) refers to the deleterious chemical reactions that occur between the alkalis (Na_2O and K_2O) in the cement paste and susceptible aggregates in the PCC mixture. Alkali-silica reactivity (ASR) and

TABLE 1 Distress types for portland cement concrete pavements (SHRP, 1993)

Jointed Concrete Pavements (JPCP and JRCP)	Continuously Reinforced Concrete Pavements (CRCP)
Corner Breaks	D-Cracking
D-Cracking	Longitudinal Cracking
Longitudinal Cracking	Transverse Cracking
Transverse Cracking	Map Cracking and Scaling
Joint Seal Damage	Polished Aggregate
Spalling of Longitudinal Joints	Popouts
Spalling of Transverse Joints	Blowups
Map Cracking and Scaling	Transverse Construction Joint Deterioration
Polished Aggregate	Lane-to-Shoulder Dropoff
Popouts	Lane-to-Shoulder Separation
Blowups	Patch/Patch Deterioration
Faulting of Transverse Joints and Cracks	Punchouts
Lane-to-Shoulder Dropoff	Spalling of Longitudinal Joints
Lane-to-Shoulder Separation	Water Bleeding and Pumping
Patch/Patch Deterioration	Longitudinal Joint Seal Damage
Water Bleeding and Pumping	

alkali-carbonate reactivity (ACR) are the two known forms of AAR (Van Dam et al., 2002a). ASR is far more prevalent than ACR; it represents a significant problem in both pavements and structures.

ASR results from the reaction of the alkalis in the cement with the siliceous components of certain aggregates. This reaction produces a gel that significantly expands in the presence of moisture, causing cracking of the surrounding cement matrix and the development of an irregular, map-like cracking, generally less than 50 mm deep, most often over the entire slab area. However, ASR can also lead to internal horizontal cracks at greater depths within the slab. With continued advancement, large pieces of concrete may dislodge from the center portions of the slab, and joint spalling, blowups, and other pressure-related distresses may also occur. A handbook depicting ASR distress in pavements and highway structures is available to aid in identifying ASR distress (Stark, 1991).

ACR is caused by a chemical reaction between the alkalis in the cement and certain carbonate aggregates. Although the mechanisms for ACR are not as well understood as those for ASR, ACR's occurrence involves expansion caused by the breaking down of dolomite into calcium carbonate and magnesium hydroxide. This "dedolomitization" leads to map-like cracking on the pavement surface and other expansion-related distresses (e.g., joint spalling or blowups). Aggregate mineralogy is the most important factor influencing the development of AAR, although aggregate size and porosity also play a role (Farny and Kosmatka, 1997).

Blowups

Blowups are localized upward movements that occur at joints and cracks and are often accompanied by shattered or fragmented concrete in that area. Blowups result from excessive expansive pressures that occur in the pavement because of intrusion of incompressibles into joints and cracks, presence of reactive aggregates, or extremely high pavement temperatures and moisture conditions (Hoerner et al., 2001).

Blowups generally take several years to develop and occur when the pavement can no longer accommodate continued slab expansions. They are more commonly associated with JRCP designs constructed with long joint spacing and, therefore, experience large slab movements. Deteriorated joints or the presence of D-cracking may also contribute to the development of blowups.

The influence of coarse aggregate on the development of blowups in concrete pavements has long been recognized (Woods et al., 1945). The development of blowups is largely influenced by the coefficient of thermal expansion of the concrete that is strongly related to the coefficient of thermal expansion of the coarse aggregate. Other aggregate properties affecting blowups include aggregate mineralogy (AAR susceptibility) and elastic modulus.

D-Cracking

D-cracking, or durability cracking, appears as a series of closely spaced, crescent-shaped cracks along joints or cracks. The cracking and accompanying staining (from calcium hydroxide or calcium carbonate residue) often appear in an hourglass shape on the pavement surface.

D-cracking occurs when water in certain aggregates freezes, leading to expansion and cracking of the aggregate and/or surrounding mortar. The rapid expulsion of water from the aggregates may also contribute to dissolution of soluble paste components (Van Dam et al., 2002a). D-cracking deterioration often begins at the bottom of the slab where free moisture is available. Generally, it takes 10 to 20 years (sometimes more) for D-cracking to develop depending on the aggregate type and pore structure, climatic factors, availability of moisture, and concrete properties.

The coarse aggregate type plays a role in the development of D-cracking. Most D-cracking-susceptible aggregates are of sedimentary origin commonly composed of limestone, dolomite, or chert (Stark, 1976). Key aggregate properties related to D-cracking susceptibility are mineralogy, pore structure, absorption, and size (Schwartz, 1987). To mitigate the development of D-cracking, many midwestern states have specified a smaller maximum aggregate size, although this reduction often results in concrete mixtures with greater shrinkage and reduced aggregate interlock capabilities. The presence of deicing salts exacerbates the potential for D-cracking for certain carbonate aggregates (Dubberke and Marks, 1985).

Longitudinal Cracking

Longitudinal cracking is cracking that runs predominantly parallel to the centerline of the pavement near the longitudinal joint, at mid-slab locations, or in the wheel paths.

Longitudinal cracking is primarily caused by late or inadequate sawing of the longitudinal contraction joints or by settlements or movements of the foundation. Stresses that promote slab cracking at the weakened location (i.e., beneath the sawcut and formed longitudinal joints) occur in the concrete pavement shortly after placement because of concrete shrinkage, decreases in temperature, and the presence of thermal and moisture gradients in the slab. However, if the joints are sawed late or are not sawed deep enough, longitudinal cracking will occur at weak locations elsewhere in the slab (Okamoto et al., 1994). ASR, the presence of expansive pressures in the slab, foundation instabilities, and longitudinal cracking in an underlying pavement layer may also contribute to the development of longitudinal cracking.

Primary concrete properties affecting the development of longitudinal cracking include the thermal and shrinkage characteristics, elastic modulus, and bond strength between coarse aggregates and mortar. This bond strength is influenced by the quality of the mortar (e.g., water-to-cement [w/c] ratio or water-to-cementitious-material [w/cm] ratio, presence of pozzolans, and degree of bleeding) and aggregate properties (e.g., surface texture, size, and mineralogy). Other aggregate properties affecting the development of longitudinal cracking include aggregate coefficient of thermal expansion, gradation, elastic modulus shape, angularity, hardness, strength, and abrasion resistance.

Roughness

Although "roughness" and "smoothness" are often used interchangeably when describing the surface characteristics of a pavement (Grogg and Smith, 2001), this digest uses the term "roughness." Roughness is what is actually measured on a pavement surface; it refers to the deviations from a planar surface occurring along a longitudinal profile of the pavement that have amplitudes and wavelengths of such magnitudes as to adversely affect the rideability of the pavement.

Roughness can be viewed as an overall performance indicator because it accounts for the effects of the different distresses that develop on a pavement, such as faulting, spalling, cracking, or punchouts. Roughness may also result from foundation instabilities (such as frost heave or swelling soils) or may be "built in" during construction paving operations. Concrete or aggregate properties that affect each individual distress will also impact roughness. Initial roughness is influenced by the workability and harshness of the concrete mixture that are affected by the aggregate gradation, shape, angularity, and texture.

Spalling

Spalling is the cracking, breaking, chipping, or fraying of the concrete edges within a few feet of a joint or crack (SHRP, 1993). Transverse and longitudinal joint spalling are common distresses of jointed concrete pavements (JCP). Spalling also occurs at transverse cracks of both JCP and CRCP—an indication of crack movement and deterioration. Factors contributing to spalling include

- Presence of incompressibles in the joints or cracks that restrain slab expansion,
- Slab curling and warping due to temperature and moisture gradients,
- Presence of AAR or D-cracking,
- Insufficient air voids in the concrete mixture,
- Localized weak areas in the concrete due to poor consolidation,
- Improper placement, and
- Corrosion of embedded steel.

Concrete properties that contribute to spalling include workability, durability-related characteristics, coarse aggregate-mortar bond, and strength. These properties relate to aggregate gradation, size, mineralogy, texture, strength, and elastic modulus.

Surface Friction

Surface friction refers to the force developed at the tire-pavement interface to resist sliding when braking forces are applied (Henry, 2000). It is particularly important in wet weather conditions because water on the pavement acts as a lubricant to reduce the direct contact between the tire and the pavement surface.

Surface friction of the concrete pavement is largely influenced by the overall texture of the pavement that is controlled by the surface finish and to a lesser extent by the texture of the aggregate particles, especially the fine aggregates. Tining, grooving, turf dragging, and other constructed surface textures provide a macrotexture that is generally greater and more durable than that produced with a concrete mixture containing fine aggregate with high-polish resistance. However, when the macrotexture abrades or becomes worn with time, the wear resistance of the aggregates becomes more important. Some soft aggregates, such as limestone, are particularly susceptible to polishing that results in poor surface friction. Key aggregate properties that influence the pavement surface friction include aggregate hardness, mineralogy, shape, angularity, texture, and abrasion resistance.

Transverse Cracking

Transverse cracks develop on all concrete pavement types, predominantly perpendicular to the pavement centerline. The mechanisms involved in developing transverse cracks differ by pavement type. Transverse cracking of JCP is caused by drying shrinkage of the concrete, decrease in temperature, curling/warping, repeated traffic loading, existence of transverse cracking in an underlying paving layer, and late or inadequate transverse joint sawing. JPCP are designed with short joint spacings that normally eliminate the development of transverse cracks; JRCP are designed such that some transverse cracks would develop and be held tightly together with the reinforcing steel to reduce deterioration. CRCP are designed such that transverse cracks would occur at 0.9- to 2.4-m intervals and be held tightly with the heavy longitudinal reinforcement to prevent deterioration. Characteristics of the transverse cracking in CRCP depend on concrete properties (drying shrinkage, thermal properties, tensile strength, creep, and elastic modulus), reinforcing steel properties (bar diameter and coefficient of thermal expansion), and environmental conditions (AASHTO, 1993).

Drying shrinkage, thermal expansion/contraction, strength, and elastic modulus of the concrete and coarse aggregate-mortar bond influence transverse cracking of all concrete pavement types. Related aggregate properties include coefficient of thermal expansion, texture, mineralogy, elastic modulus, gradation, size, and hardness.

Propagation and widening of transverse cracks may occur due to traffic and environmental loading, leading sometimes to spalling and faulting. This deterioration is caused by the loss of aggregate interlock and its contribution to shear load transfer across the crack. Aggregate interlock is influenced by several aggregate properties, including size, shape, angularity, texture, strength, and abrasion resistance.

Corner Breaks

A corner break is a broken area of the corner of a slab as defined by a diagonal crack that intersects the longitudinal joint (or free edge) and the transverse joint at approximately a 45° angle (SHRP, 1993). Corner breaks are most commonly found on nondoweled JPCP, but they also occur on JRCP; they range in length from 0.3 m to half the total slab length or width.

Corner breaks result primarily from the loss of support beneath slab corners due to pumping and erosion. When significant erosion occurs, the slab corners become virtually unsupported; repeated traffic loads will then cause cracking, particularly if the transverse joints are not doweled. Upward curling of the slab corners can also contribute to development of such breaks.

Concrete properties that contribute to the development of corner breaks include strength, elastic modulus, coarse aggregate-mortar bond, and coefficient of thermal expansion. These properties are related to the strength, elastic modulus, coefficient of thermal expansion, size, shape, angularity, texture, mineralogy, and abrasion resistance of the aggregates.

Transverse Joint Faulting

Transverse joint faulting is the difference in the vertical elevation of abutting slabs at the transverse joints. Generally, the elevation of the approach slab is higher than the elevation of the leave slab, although occasionally the opposite may occur. Faulting can also occur across transverse cracks in all pavement types.

Joint faulting develops in conjunction with pumping because of poor load transfer efficiency across the transverse joint. Pumping occurs at transverse joints when the approach slab first deflects under a wheel load, forcing free water and suspended fines beneath the leave slab (McGhee, 1995). When the wheel then crosses the transverse joint, a sudden rebound of the approach slab occurs, followed by a rapid deflection of the leave slab. This action forces the water and suspended fines onto the pavement surface and back under the approach slab, eventually raising the approach slab and causing the difference in elevation across the joint. Occasionally, settlements or other foundation movements could lead to differences in elevation across transverse joints. Load transfer across transverse joints is provided by aggregate interlock and/or dowel bars; the latter provides a higher level of load transfer efficiency.

Because the elastic modulus of the concrete strongly influences the deflection response of the slab, it also affects transverse joint faulting. Elastic modulus, coefficient of thermal expansion, gradation, size, shape, angularity, texture, and abrasion resistance of the aggregates influence the transverse joint faulting.

Punchouts

Punchouts are localized areas of distress that occur on CRCP. They are characterized by a failed rectangular section of concrete that is enclosed by (1) two closely spaced transverse cracks, (2) a short intersecting longitudinal crack, and (3) the outside pavement edge. Most punchouts occur on the outside pavement edge, although some punchouts occur adjacent to the longitudinal joint. Punchouts occur at locations where two closely spaced (typically less than 0.6 m apart) transverse cracks exist, where support beneath the cracks (particularly at the outside edges) has been reduced due to pumping and erosion, and where aggregate interlock across the cracks has diminished.

Concrete properties that influence the development of punchouts include elastic modulus, strength, drying shrinkage, and coefficient of thermal expansion. Related aggregate properties include the elastic modulus, strength, and coefficient of thermal expansion. Other aggregate factors that influence crack spacing and aggregate interlock include the aggregate gradation, size, shape, angularity, texture, and abrasion resistance.

Other Performance Parameters

Other concrete pavement performance parameters (e.g., map cracking, scaling, and popouts) relate to properties of the aggregate but do not have a significant effect on the functional or structural performance of the pavement.

Map cracking (other than AAR related) appears as a series of surficial cracks that often occur because of plastic shrinkage or certain construction practices (e.g., overfinishing of the surface and poor curing). Plastic shrinkage is affected by the bleeding characteristics of concrete, which are influenced by aggregate gradation (especially the amount and nature of material passing the #200 sieve). Scaling is the deterioration of the upper 3 to 13 mm of the concrete surface caused by low air content, high water-cement ratio, overfinishing of the surface, poor curing, or application of deicing chemicals. Aggregate properties affecting scaling include porosity, mineralogy, and absorption. Popouts are small pieces of concrete that have become dislodged from the pavement surface because of expansion of unsound aggregates due to moisture and temperature changes.

These distresses do not significantly affect the functional or structural performance, but they affect the aesthetics of the pavement. Because of their limited impact on pavement performance, these parameters will be considered no further.

The identified key performance parameters are listed in Table 2 together with concrete and aggregate properties that affect their development.

AGGREGATE PROPERTIES RELATED TO PAVEMENT PERFORMANCE

Aggregate properties that have a significant impact on concrete pavement performance (as summarized in Table 3) can be grouped into the following categories:

- Physical properties,
- Mechanical properties,
- Chemical and petrographic properties,
- Durability properties, and
- Other aggregate-related properties.

Physical Properties

Physical properties include absorption; gradation; properties of microfines; shape, angularity, and texture; and thermal expansion.

Absorption

Information on the absorption capacity of an aggregate is used for adjusting the batching water quantities and achieving the target w/c or w/cm ratio. The absorption of aggregates may also affect the workability of concrete, as some aggregates with higher absorptions will absorb large amounts of water if the concrete is batched and mixed in a relatively dry condition. Also, some aggregates with higher absorption capacities have also been observed to break down during the mixing and placing of concrete pavements, mainly because of the lower strengths associated with their inherent higher porosities (Meininger, 1998). The breakdown of aggregates during the construction phase creates additional microfines (material passing the #200 sieve) that reduce workability and often lead to the addition of water to obtain the desired workability. This excess of microfines and increase in mix water tend to increase the drying shrinkage of concrete that contributes to increased transverse (and longitudinal) cracking of the pavement.

Aggregate absorption may also have a significant impact on the resistance to freezing and thawing, which often manifests itself in pavements as D-cracking. Aggregates that absorb large amounts of water may suffer damage upon freezing as the freezing water is dispelled from the aggregate. The pore structure of the aggregate (e.g., pore size distribution) is of particular significance when considering the potential for freezing and thawing distress. Although certain aggregates exhibiting higher absorption may be prone to D-cracking, many aggregates with relatively high absorptions are quite durable. Therefore, local experience and familiarity with a specific aggregate type or source should be considered in assessing the relationship of absorption to aggregate durability. Some researchers (Pigeon and Pleau, 1995) have suggested a maximum absorption capacity value as necessary for preventing aggregate-related damage from freezing and thawing cycles, and several state DOTs have imposed limits on absorption for concrete aggregates.

Gradation

The particle size distribution or gradation of fine and coarse aggregates has a significant effect on the fresh concrete properties (e.g., water demand, air content, segregation, and bleeding) and the hardened concrete properties (e.g., strength, permeability, drying shrinkage, and coarse aggregate-mortar bond). Most states specify an AASHTO No. 57 coarse aggregate and an AASHTO M 6 fine aggregate for concrete pavements (ACPA, 1999). However, some states (e.g., Minnesota) now use well-graded blends of aggregates to provide dense packing and minimize cement content.

Properties of Microfines

Although the amount of microfines (material passing the #200 sieve) is generally low (i.e., less than 4 percent), it may greatly affect concrete properties. Microfines in high amounts or containing clay could lead to decreased slump, increased water demand, difficulties in entraining air, and increased shrinkage.

Shape, Angularity, and Texture

The shape, angularity, and texture of aggregates affect several concrete properties, such as workability, water demand, and coarse aggregate-mortar bond strength. An aggregate with a smooth surface texture and more spherical shape will tend to require less mixing water and exhibit better workability than an aggregate with a rough surface texture and more angular shape. Aggregate surface texture affects coarse aggregate-mortar bond strength; rougher aggregates tend to bond better than smoother aggregates.

Thermal Expansion

The thermal properties of aggregates affect several key pavement performance parameters, including transverse and longitudinal cracking, faulting of joints and cracks, and punchouts. Because aggregates constitute a large portion of the concrete volume, the coefficient of thermal expansion (CTE) of concrete is closely related to that of the aggregates. The CTE of concrete plays an especially important role in CRCP (McCullough et al., 1995), where some performance problems, such as spalling and punchouts, have been attributed to the use of concrete containing siliceous river gravel with high CTE values.

TABLE 2 Primary concrete pavement performance parameters affected by aggregate properties

Pavement Type	Performance Parameter	Manifestation	Mechanism(s)	PCC Properties	Aggregate Properties
All PCC Pavements	Alkali-Aggregate Reactivity	Shallow map cracking and joint/crack spalling, accompanied by staining and exudate	Chemical reaction between alkalis in cement paste and either susceptible siliceous or carbonate aggregates		Mineralogy Size Porosity
	Blowups	Upward lifting of PCC slabs at joints or cracks, often accompanied by shattered PCC	Excessive expansive pressures caused by incompressibles in joints, alkali-aggregate reactivity (AAR), or extremely high temperature or moisture conditions	Coefficient of thermal expansion	Coefficient of thermal expansion Mineralogy
	D-Cracking	Crescent-shaped hairline cracking generally occurring at joints and cracks in an hourglass shape	Water in aggregate pores freezes and expands, cracking the aggregate and/or surrounding mortar.	Air-void quality	Mineralogy Pore size distribution Size
	Longitudinal Cracking	Cracking occurring parallel to the centerline of the pavement	Late or inadequate joint sawing, presence of alkali-silica reactivity (ASR), expansive pressures, reflection cracking from underlying layer, traffic loading, loss of support	Coefficient of thermal expansion Coarse aggregate-mortar bond Shrinkage	Coefficient of thermal expansion Gradation Size Mineralogy Shape, angularity, and texture Hardness Abrasion resistance Strength
	Roughness	Any surface deviations that detract from the rideability of the pavement	Development of pavement distresses, foundation instabilities, or "built in" during construction	Any that affects distresses Elastic modulus Workability	Any that affect distresses Gradation Elastic modulus
	Spalling	Cracking, chipping, breaking, or fraying of PCC within a few feet of joints or cracks	Incompressibles in joints, D-cracking or AAR, curling/ warping, localized weak areas in PCC, embedded steel, poor freeze-thaw durability	Coefficient of thermal expansion Coarse aggregate-mortar bond Workability Durability Strength Air-void quality Shrinkage	Gradation Mineralogy Texture Strength Elastic modulus Size
	Surface Friction	Force developed at tire-pavement interface that resists sliding when braking forces applied	Final pavement finish and texture of aggregate particles (mainly fine aggregates)		Hardness Shape, angularity, and texture Mineralogy Abrasion resistance
	Transverse Cracking	Cracking occurring perpendicular to the centerline of the pavement	PCC shrinkage, thermal shrinkage, traffic loading, curling/warping, late or inadequate sawing, reflection cracking from underlying layer, loss of support	Shrinkage Coarse aggregate-mortar bond Coefficient of thermal expansion Strength	Coefficient of thermal expansion Gradation Size Shape, angularity, and texture Mineralogy Hardness Abrasion resistance Strength

TABLE 2 Primary concrete pavement performance parameters affected by aggregate properties (continued)

Pavement Type	Performance Parameter	Manifestation	Mechanism(s)	PCC Properties	Aggregate Properties
Jointed PCC Pavements	Corner Breaks	Diagonal cracks occurring near the juncture of the transverse joint and the longitudinal joint or free edge	Loss of support beneath the slab corner, upward slab curling	Strength Coarse aggregate-mortar bond Coefficient of thermal expansion Elastic modulus	Coefficient of thermal expansion Gradation Size Mineralogy Shape, angularity, and texture Hardness Abrasion resistance Strength
	Transverse Joint Faulting	Difference in elevation across transverse joints	Pumping of fines beneath approach side of joint, settlements or other foundation instabilities	Elastic modulus	Size Gradation Shape, angularity, and texture Abrasion resistance Elastic modulus Coefficient of thermal expansion
Continuously Reinforced PCC Pavements	Punchouts	Localized areas of distress characterized by two closely spaced transverse cracks intersected by a longitudinal crack	Loss of support beneath slab edges and high deflections	Elastic modulus Strength Shrinkage Coefficient of thermal expansion	Elastic modulus Strength Coefficient of thermal expansion Size Shape, angularity, and texture Abrasion resistance

TABLE 3 Primary aggregate properties affecting key performance parameters

Aggregate Property	KEY PERFORMANCE PARAMETERS									
	AAR	Blowups	D-Cracking	Longitudinal Cracking	Roughness*	Spalling	Surface Friction**	Transverse Cracking	Corner Breaks	Joint Faulting	Punchouts
Absorption			X								
Abrasion Resistance				X			X	X	X	X	X
Angularity				X			X	X	X	X	X
Coefficient of Thermal Expansion		X		X		X		X	X	X	X
Elastic Modulus		X		X	X	X		X	X	X	X
Gradation				X	X	X		X	X	X	X
Hardness				X			X	X	X		
Mineralogy	X	X	X	X		X	X	X	X		
Porosity and Pore Structure	X		X								
Shape				X		X		X		X	X
Size	X		X	X		X		X		X	X
Strength				X		X		X	X		X
Texture				X		X	X	X	X	X	X

* Because roughness is affected by the presence of distresses, any aggregate properties that influence the development of those distresses will also influence the development of roughness.

** Surface friction is mainly affected by the polish resistance of fine aggregates because of the presence of the mortar-rich layer at the top surface of PCC pavements.

Mechanical Properties

Mechanical properties include abrasion resistance, elastic modulus, polish resistance, and strength.

Abrasion Resistance

Abrasion-resistance properties of aggregates affect both fresh and hardened concrete properties. The effect of aggregate abrasion resistance on pavement performance is influenced by (1) the breakdown of aggregates during handling, stockpiling, mixing, and constructing PCC pavements; (2) the abrasion of aggregates at or near the surface of the pavements (mainly caused by studded tires); and (3) the abrasion of aggregates across abutting joint or crack faces.

The breakdown of aggregates, especially the breakdown of fine aggregates, during handling and later when mixed in the concrete may lead to the production of excess microfines. This aggregate breakdown tends to adversely affect concrete workability, ability to entrain air, and constructability (i.e., placing, compacting, and finishing). Increasing water content to offset the reduction in workability would increase the w/c ratio and lead to a reduced strength and an increased drying shrinkage.

Elastic Modulus

The elastic modulus of aggregates has a major effect on the elastic modulus of concrete. Although there is not always a linear relationship between the elastic moduli of concrete and aggregates, a higher-modulus aggregate generally produces a higher-modulus concrete (Meininger, 1994). Coarse aggregate also affects the shape of the concrete stress-strain curve, especially the hysteresis behavior of the curve. For example, Baalbaki et al. (1991) showed that the nonlinear behavior exhibited by a certain sandstone coarse aggregate manifested itself in a similar nonlinear behavior in concrete containing the same aggregate. This behavior can be attributed to the inherent nonlinear behavior caused by existing cracks and pores in the sandstone aggregate (Morgenstern and Phukan, 1966).

The elastic modulus of aggregates is rarely measured directly. The modulus of rock cores can be measured, but the variability has been found to be high; because of this high variability, measuring the modulus of most gravel samples is not feasible. Thus, measuring the elastic modulus of concrete is the most practical means for gaining information on the aggregate's impact on the stress-strain behavior.

Polish Resistance

Frictional properties of the concrete pavement surface is strongly affected by the macrotexture of the surface (which is commonly tined or grooved) and affected to a lesser extent by the microtexture of the surface. Because the surface of concrete pavements is composed primarily of mortar and is initially devoid of coarse aggregates, the polishing resistance of fine aggregates is the most critical parameter in determining frictional properties. The coarse aggregate becomes an influencing factor only in cases where the top surface of the pavement has been severely abraded (e.g., because of studded tires or chain use).

Strength

The strength of coarse aggregates could have a measurable effect on concrete strength if good bonding between the coarse aggregates and mortar is maintained to force the failure through the aggregates rather than around them.

Chemical and Petrographic Properties

Chemical and petrographic properties include mineralogy.

Mineralogy

The assessment of the mineralogical composition and structure of aggregates helps in tracking changes in an aggregate source (e.g., from ledge to ledge) and in identifying potentially harmful materials, such as reactive silica minerals. In addition, certain coarse aggregates, such as crushed limestone, exhibit enhanced bonding with mortar, partly because of increased physical adhesion from aggregate texture, but also possibly because of chemical bonding. Therefore, assessing aggregate mineralogy may be useful in predicting coarse aggregate-mortar bond strength.

Durability Properties

Durability properties include AAR and freezing and thawing resistance.

Alkali-Aggregate Reaction

Much progress has been made in understanding the mechanisms of AAR and in developing appropriate test methods since AAR was first identified in 1940 (Stanton, 1940). A comprehensive approach for testing aggregate reactivity and selecting means of controlling ASR was developed and adopted by the Canadian Standards Association (Fournier et al., 1999). This approach outlines a recommended testing methodology and identifies mitigation measures based on the degree of aggregate reactivity, the size of the concrete element and environmental conditions in which it will be placed, and the expected service life of the structure. Other guidelines for assessing ASR in concrete were developed by the Portland Cement Association (PCA, 1998) and under the AASHTO Lead States program efforts (AASHTO, 2000).

In the United States, ASR is a much more predominant problem than ACR. The mechanisms of ASR have been studied extensively over the past 60 years and are fairly well understood. Aggregates containing certain reactive silica minerals break down under long-term exposure to the intrinsically highly alkaline pore solution in concrete. The alkali hydroxides in the pore solution (mainly NaOH and KOH) then react with the "broken down" silica and form a gel (known as ASR gel) that absorbs water, leading to expansion and subsequent cracking of the concrete. The potential for this reaction and damage depends on the chemical composition of the cement (e.g., alkali content) and other pozzolanic or cementitious materials, reactivity of the aggregates, mixture proportions, and environmental conditions (especially moisture conditions). Aggregates susceptible to ASR are either those composed of poorly crystalline or metastable silica materials, which usually react relatively quickly and result in cracking within 5 to 10 years, or those involving certain varieties of quartz, which are slower to react in field applications (ACI, 1998).

Freezing and Thawing Resistance

Freezing and thawing damage in concrete pavements can be caused by different mechanisms. The most common cause of damage is the lack of an air-void system capable of tolerating hydraulic and osmotic pressures that develop during freezing and thawing cycles. Concrete mixtures with an adequate air-void system can still, however, suffer from freezing and thawing damage when the aggregates exhibit poor frost resistance. A common manifestation of aggregate-related freezing and thawing damage in concrete pavements is D-cracking. Aggregate popouts that typically have no significant effect on pavement performance can also occur because of freezing and thawing cycles.

D-cracking is caused by aggregates with a certain range of pore sizes, and the damage may be accentuated in the presence of deicing salts for some carbonate aggregates. Coarse aggregates are the primary concern, and for each specific aggregate type, there generally exists a critical aggregate size below which D-cracking is not a problem. Crushing certain aggregates below this critical threshold to avoid D-cracking has been reported, although it is not always economically or practically feasible. Smaller aggregates translate into shorter escape paths for freezing water, thereby reducing hydraulic pressure and subsequent damage. However, not all aggregates when crushed to relatively small sizes are immune to D-cracking; some carbonate aggregates still show poor durability when their particle size is reduced. Another method reported to improve the frost resistance of concrete containing certain aggregates prone to D-cracking is to increase the entrained air content of the mixture to help alleviate hydraulic pressure developed near aggregate particles (Schlorholtz, 2000). Although decreasing aggregate particle size and increasing the entrained air content of concrete have been identified as potential methods of mitigating D-cracking, the most common practical approach is to identify nondurable aggregates and preclude their use.

Coarse aggregate particles exhibiting relatively high absorption and having medium-sized pores (i.e., 0.1 to 5 μm) generally experience the most freezing and thawing problems because of higher potential for saturation. Larger pores typically do not get completely filled with water and do not result in frost damage; water in finer pores may not freeze as readily because of freezing point depression (ACI, 1996a). Aggregates of sedimentary origin such as limestones, dolomites, and cherts are most commonly associated with D-cracking (Stark, 1976).

Other Aggregate-Related Properties

The aggregate properties and tests previously discussed are those most related to concrete pavement performance. However, some other aggregate properties influence concrete properties but have limited impact on pavement performance or are only relevant for special circumstances or applications.

Creep and Drying Shrinkage

Creep and drying shrinkage characteristics of concrete have a significant impact on restrained shrinkage cracking of concrete, which is a major cause of transverse and longitudinal cracking in concrete pavements. Creep and shrinkage of concrete is mainly manifested within the hydrated cement paste (Mehta and Monteiro, 1993). However, aggregates, particularly coarse aggregates, provide restraint against both creep and shrinkage. Generally, stronger (and stiffer) aggregates provide higher restraint and result in less drying shrinkage cracking and creep in concrete than weaker aggregates. Aggregates exhibiting better bond with mortar also provide increased restraint.

Laboratory and field experience has indicated that shrinkage of concrete can be linked to the mineralogy of coarse aggregates. Limestone, dolomite, granite, and feldspar are typically considered low-shrinkage aggregates, whereas aggregates containing sandstone, shale, slate, hornblende, and greywacke typically exhibit higher shrinkage (ACI, 1989). Thus, a detailed petrographic analysis of aggregates could provide insight into shrinkage potential.

In some instances, aggregates can have a large direct impact on concrete shrinkage. For example, highly porous aggregates can lead to increased shrinkage if the aggregates are not soaked prior to use in making the concrete. Also, some fine-grained aggregates may undergo volume change upon drying (Meininger, 1998). In general, concrete shrinkage is governed by restraint effects; aggregates have a minor effect.

Impurities and Chlorides in Aggregates

The presence of impurities or chlorides in concrete aggregates generally does not play a significant role in concrete pavements.

TEST METHODS FOR MEASURING AGGREGATE PROPERTIES

This section provides information on relevant aggregate properties and related test methods and presents recommendations regarding the test methods best suited for measuring each of these properties. Most of the recommended tests are American Association of State Highway and Transportation Officials (AASHTO) or American Society for Testing and Materials (ASTM) test methods that are commonly used by state DOTs, testing laboratories, and other agencies. In a few cases, the recommended tests are not currently standard test methods but seem to relate to the pavement's field performance. The recommended test methods were selected with consideration to the methods' ability to predict performance, repeatability, precision, and user-friendliness and also to the availability and cost of test equipment. Wherever possible, test methods that involve the testing of aggregates were identified. However, when testing of an aggregate sample may not yield information or data necessary to predict the performance, tests on mortar or concrete specimens containing these aggregates that provide the desired information were considered.

A survey distributed to state DOTs in 1995 (Fowler et al., 1996) generated information on aggregate tests used at that time. Table 4 lists these tests and the extent of their use according to the responses received from 43 state highway agencies. Information from this survey; published literature; and unpublished practices of state, local, and industry organizations were used to synthesize and assess the current state of practice, to identify tests that are still in need of improvement or tests that have yet to be developed, and to recommend a set of aggregate tests that relate to pavement performance.

TABLE 4 Use of standard aggregate or aggregate-related tests by state DOTs (Fowler et al., 1996)

Property		Most Popular Test Method	State DOTs Citing Usage of Test		
			Yes	N o	N/A
Basic Aggregate Properties	Grading	AASHTO T 27 AASHTO T 11	39 39	2 2	1 1
	Specific gravity	AASHTO T 84 AASHTO T 85	39 37	2 4	2 2
	Absorption	AASHTO T 84 AASHTO T 85	39 37	2 4	2 2
	Unit weight and voids	AASHTO T 19	34	7	2
	Petrographic analysis	ASTM C 295	10	31	2
Durability	Soundness	AASHTO T 104	30	11	2
	Freezing and thawing resistance	AASHTO T 161	11	30	2
	Internal pore structure	AASHTO T 85	13	28	2
	Degradation resistance	AASHTO T 96 ASTM C 535	32 10	9 31	2 2
Chemical Reactivity	Alkali-silica reaction	ASTM C 227 ASTM C 295 ASTM C 289	11 7 6	30 34 35	2 2 2
	Alkali-carbonate reaction	ASTM C 295	6	35	2
Dimensional Change	Drying shrinkage	ASTM C 157	5	36	2
Deleterious Substances		AASHTO T 21	33	8	2
Frictional Resistance		AASHTO T 242	12	29	2
Particle Shape and Texture		ASTM D 4791	14	27	2

Physical Properties

Absorption

The most commonly used methods to assess aggregate absorption are AASHTO T 84 (*Specific Gravity and Absorption of Fine Aggregate*) and AASHTO T 85 (*Specific Gravity and Absorption of Coarse Aggregate*). These tests also generate data on the specific gravity of aggregates, which is an input parameter for proportioning concrete mixtures. There is a general relationship between aggregate absorption and specific gravity, with lower absorption capacities yielding higher specific gravity values (Koubaa et al., 1997). Other test methods used to assess aggregate absorption such as nitrogen absorption and mercury intrusion porosimetry (Gregg and Sing, 1982) may provide useful information on internal porosity, pore structure, and absorption capacity. However, these tests are rarely used by state DOTs and testing laboratories, the tests are relatively expensive to perform, and there are limited data to relate test results to field performance.

Gradation

Aggregate gradations are routinely measured at quarries, pits, ready-mixed plants, and state DOT laboratories using AASHTO T 27 (*Sieve Analysis of Fine and Coarse Aggregates*). This test determines the maximum-size aggregate (MSA) for coarse aggregates and the fineness modulus (FM) for fine aggregates—parameters needed for mixture proportioning.

Properties of Microfines

AASHTO T 176 (*Plastic Fines in Graded Aggregates and Soils by the Use of the Sand Equivalent Test*) is a simple and quick test for determining the relative amounts of clay-like materials in aggregates. The test involves placing a sample of fine aggregate in a clear cylinder, adding water and a dispersing agent, agitating the sample, and waiting for 20 min for the sand to settle to the bottom (and the clay to form a layer above the sand). The sand equivalent is defined as 100 times the ratio of the height of the sand divided by the height of the sand + clay. The higher the sand equivalent value, the lower the clay (or clay-like material) content. This test is a quick screening test to determine the potential presence of clay in the aggregate microfines; it does not discern whether clay actually is present or in what proportion.

AASHTO TP 57 (*Standard Test Method for Methylene Blue Value of Clays, Mineral Fillers, and Fines*) was identified as a means for quantifying the amount of clays, organic material, and iron hydroxides in fine aggregates used in HMA (Kandhal and Parker, 1998). In this test, the amount of methylene blue dye needed to adsorb onto the material passing #200 sieve is measured and a methylene blue value (MBV) is calculated (Hosking, 1992). Different clay minerals may have different detrimental effects on the concrete (Lan and Millon-Devigne, 1984). The methylene blue test does not have the ability to differentiate between the three clay minerals typically found in mineral aggregates (kaolinite, illite, and smectite); Yool et al. (1998) have proposed modifications to the test to help differentiate the type and amount of clay present in a given aggregate sample. The specific type of clay present in an aggregate can be identified using X-ray diffraction analysis.

Shape, Angularity, and Texture

The uncompacted void test is the most common aggregate test used to assess shape, angularity, and surface texture (AASHTO T 304, *Uncompacted Void Content of Fine Aggregates,* and AASHTO TP 56, *Uncompacted Void Content of Coarse Aggregates [As Influenced by Particle Shape, Surface Texture, and Grading])*. Both versions of the test measure the loose uncompacted void content of an aggregate sample as it is passed through a funnel into a container of known volume (the size of the apparatus and its components are, of course, larger for the coarse aggregate version of the test). When testing different aggregates with identical gradations, an indication of angularity, sphericity, and surface texture can be obtained (Kandhal and Parker, 1998). Generally, the higher the uncompacted void content of an aggregate, the higher will be the water demand to obtain the same workability. For fine aggregates, a difference in void content of 1 percent may correspond to a difference in concrete mixing water requirement of 1.8 to 4.8 kg/m^3 (Gaynor and Meininger, 1983).

When assessing the particle shape, angularity, and texture of coarse aggregates, the uncompacted void test appears to have benefits over other methods because it does not require performing detailed petrographic evaluations of shape and texture; counting crushed aggregate faces; or manually measuring individual particle length, width, and thickness (Meininger, 1998). However, it is not currently feasible to directly use uncompacted void contents of aggregates for proportioning concrete mixtures or identifying potential workability problems in paving mixtures because of the lack of correlations with field performance.

The measurement of flat and elongated particles using ASTM D 4791 (*Test Method for Flat or Elongated Particles in Coarse Aggregates*) provides useful information on the potential impact of aggregate shape on fresh and hardened concrete properties. The method relies on the manual measurement of aggregate dimensions. It has been incorporated into the Superpave approach for HMA pavements and thus has been performed by a number of state DOTs and testing laboratories. Very few state DOTs measure flat or elongated particles separately; most states measure the ratio of the maximum dimension to the minimum dimension (e.g., 3:1, 4:1, 5:1) to determine the percentage of flat and elongated particles (Kandhal and Parker, 1998). Specifications often stipulate the maximum percentage of aggregate particles meeting a specific ratio. However, researchers (Rogers, 2002) have recommended limiting the amount of particles for different ratios. Limiting the amount of flat and elongated particles in coarse aggregates helps to minimize water demand, reduce mixture harshness, and improve finishability. Although ASTM D 4791 may not provide a comprehensive measure of aggregate shape, it can be used as a screening test in identifying aggregates that could adversely affect concrete workability. The use of image analysis techniques to assess aggregate shape has increased in recent years and appears to be a promising approach; however, no standard tests or appropriate protocols are currently available.

Thermal Expansion

Despite the importance of aggregate thermal properties, no accepted test methods exist to accurately measure the CTE of aggregates. However, the CTE of concrete is a good indicator of the thermal characteristics of aggregates.

In recent years, the Federal Highway Administration has developed a test method for measuring the CTE of concrete—now available as AASHTO Provisional Standard TP 60 (*Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete*). In this test, a concrete test cylinder is submersed under water in a temperature-controlled bath, water temperature is cycled between 10°C and 50°C, and length change measurements are made using of a submersible linear variable differential transformer (LVDT). These data are then used to calculate the CTE from the slope of the length change versus temperature curve. Thermal properties of aggregates can directly be measured using a dilatometer or similar equipment; however, no standard tests exist for this purpose.

Mechanical Properties

Abrasion Resistance

The Micro-Deval test appears to be the best indicator for assessing the potential for aggregate breakdown. This method was developed in the 1960s in France, has been used extensively in Canada, and is now included in the Canadian Standards Association (CSA) specifications. It is a wet attrition test that is available in two versions, one for fine aggregates (CSA A23.2-23A—*Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*) and one for coarse aggregates (Ontario MOT Test LS-618, *Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*). The coarse aggregate version of this test is now available as AASHTO TP 58 (*Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*). The test subjects an aggregate sample to wet attrition by placing it in a steel jar with steel balls (9.5 mm in diameter) and water, then rotating the jar at 100 rpm for 2 h for coarse aggregates or 15 min for fine aggregates. Aggregate damage is assessed by mass loss at the completion of the test using a 1.25-mm sieve and a 75-µm sieve for coarse and fine aggregates, respectively.

The Micro-Deval test for fine aggregates has been found to correlate well with magnesium sulfate soundness testing but has better within- and multi-laboratory precision and is less sensitive to aggregate grading (Rogers et al., 1991). Specifications stipulate a maximum mass loss for fine and coarse aggregates.

A dry abrasion method that has been used extensively to study aggregate abrasion is AASHTO T 96 (*Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*). A 1995 survey (Fowler et al., 1996) indicated that this method was used by most state DOTs (32 out of 43). The test appears to have some merit in predicting aggregate breakdown or degradation during handling, but it has a limited ability to predict pavement performance.

Aggregate abrasion properties may also affect the surface wear or abrasion at or near the top surface of pavements. This is generally a concern only when studded tires are used. This abrasive action will affect pavement smoothness and may also lead to exposing and polishing the coarse aggregates. The Los Angeles Abrasion and Impact test is the most commonly used test for assessing potential damage (Fowler et al., 1996), although its ability to predict pavement performance is not well documented.

Aggregate surface texture and abrasion properties may also affect abrasion across abutting joints or crack faces. Wet and dry attrition tests should provide useful information on this mechanism in wet and dry environments.

Elastic Modulus

The elastic modulus of concrete is measured by ASTM C 469 (*Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*), which measures the elastic behavior of the concrete up to 40 percent of the ultimate compressive strength. The Poisson's ratio is often measured on the same test specimen.

Polish Resistance

Because of inherent difficulties in directly measuring the polish resistance of fine aggregates, other indicator tests or past field performance has been used in selecting and specifying fine aggregates for pavements. ASTM D 3042 (*Test for Acid Insoluble Residue in Carbonate Aggregates*) appears to be the most widely used and accepted test for assessing the potential polishing of fine carbonate aggregates. The Transport and Road Research Laboratory of the United Kingdom has reported that data obtained from the acid insoluble residue test best relate to skid resistance of concrete pavements. The test assesses the noncarbonate (usually siliceous) material intermixed with the carbonate minerals of the aggregate. The presence of acid insoluble material in the sand fraction generally improves skid resistance, but the material's presence in the microfines may indicate clay minerals that adversely affect concrete workability and shrinkage (Meininger, 1998).

For the rare instances where coarse aggregates are expected to be exposed, AASHTO T 279 (*Accelerated Polishing of Aggregates Using the British Wheel*) can be used. Field testing of pavements using a skid trailer according to AASHTO T 242 (*Frictional Properties of Paved Surfaces Using a Full-Scale Tire*) is used by many state DOTs, thereby allowing for the validation of related laboratory tests (Henry, 2000).

Strength

No AASHTO or ASTM methods are available for measuring aggregate strength directly. However, the British aggregate crushing value test has been used for many years and appears to present a reasonable approach for assessing the relative strength of a graded concrete aggregate. In this test, load is applied to a graded coarse aggregate sample in a steel cylinder for a 10-min period, after which the change in gradation is measured. Another approach to measuring aggregate strength is the testing of rock cores in uniaxial compression, although this method produces highly variable results and cannot be used for testing most gravel samples.

Because the effects of aggregate strength on concrete strength are not always obvious and vary depending on materials and mixture proportions, strength characteristics (compressive, flexural, and tensile strength) of concrete containing the subject aggregate can be related to aggregate crushing value. Aggregate strength has a direct impact on the strength of concrete containing pozzolans or slag and low w/c ratios. In such cases, failure could occur in the coarse aggregate itself. Thus, assessing aggregate strength is only relevant where high-strength concrete (e.g., more than 40–50 MPa) is used.

Chemical and Petrographic Properties

Mineralogy

Evaluating the mineralogical characteristics of aggregates through a petrographic analysis provides insights into the effects of aggregate properties on concrete pavement performance. Some of the useful information that can be obtained from examining the aggregate using ASTM C 295 (*Guide for Petrographic Examination of Aggregates for Concrete*) includes the following:

- Identification of minerals with potential for ASR or ACR;
- Estimation of mica content (from point count) in given size fraction of fine aggregate for use in analyzing material retained on the #200 sieve and its effect on workability (Rogers, 2002);
- Assessment of minerals and structure of carbonate aggregates that could be linked to the durability of carbonate aggregates (Oyen et al., 1998);
- Assessment of thermal and shrinkage potential based on the identified types and amounts of minerals present in an aggregate sample (Meininger, 1998);
- Assessment of aggregate surface texture and mineralogy that can be related to bonding with mortar; and
- Development of petrographic database for aggregate sources to serve as a basis for field service records linking aggregate sources to pavement performance (Meininger, 1998).

Other useful techniques for studying aggregate mineralogy are X-ray diffraction analysis (XRD), thermogravimetric analysis (TGA), and X-ray fluorescence analysis (XRF). These techniques allow for the identification and quantification of minerals and compounds present in aggregates and are particularly useful for the assessment of clays (in fine aggregates) and the carbonate aggregates. XRD analysis has been reported to be a good method of identifying nondurable dolomite aggregates and harmful clays (e.g., smectites) present in the microfines (Dubberke and Marks, 1989). TGA and XRF have also been reported to be good indicators of the durability of carbonate aggregates (Dubberke and Marks, 1989; Dubberke and Marks, 1992).

Durability Properties

Alkali-Aggregate Reaction

Over the past 60 years, different test methods have been developed and used to assess the potential reactivity of aggregates with varying degrees of success. Although accelerated tests have been developed and widely used that are effective in assessing aggregate reactivity when aggregates are tested either in mortar or concrete, tests have not yet been developed for evaluating an aggregate sample's susceptibility to ASR reactivity. However, these accelerated tests, together with a sound petrographic analysis of the aggregate source, could provide a good means for assessing aggregate reactivity.

When considering the use of a specific aggregate in concrete pavements, the first step in assessing the potential for ASR expansion and cracking is the performance of a petrographic analysis by a trained petrographer. ASTM C 295 (*Guide for Petrographic Examination of Aggregates for Concrete*) is the most commonly used approach and is recommended for the identification of minerals that may potentially lead to AAR-induced damage in concrete. Because petrographic analysis may not identify certain reactive materials (some may not be readily identified by optical microscopy), the results of the analysis should not be used summarily to reject or accept an aggregate for use on concrete (Rogers and Fournier, 1991). Information can also be obtained through petrography on other physical, chemical, and mineralogical properties of aggregates that may affect other concrete properties.

From the range of accelerated tests proposed for assessing aggregate reactivity, AASHTO T 303 (*Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction*) and ASTM C 1293 (*Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction*) seem most appropriate.

AASHTO T 303, often referred to as the accelerated mortar bar test, is based on the method developed by Oberholster and Davies (1986). Mortar bars made with the subject aggregate (after being processed to a standard gradation) are removed from the molds after 24 h and placed in water at 80°C for the next 24 h. After removal from the water bath, the bars are measured for initial length and then stored in a 1 normal NaOH solution for 14 days. Length change measurements are made periodically during this storage period, although only the total expansion at the end of the 14-day soaking period is typically used in specifications. ASTM C 1260 states that aggregates with expansion values less than 0.10 percent can be considered innocuous, aggregates with expansions between 0.10 and 0.20 percent are considered potentially reactive, and aggregates with expansions greater than 0.20 percent are considered reactive. CSA, however, specifies an expansion limit of 0.15 percent for all aggregates except limestone aggregates, which have a limit of 0.10 percent (Fournier et al., 1999). Because of the extreme nature of this test (e.g., highly alkaline soak solution and high temperature), the test is quite severe and may identify some aggregates that have performed well in other tests and in field applications as being reactive (Bérubé and Fournier, 1992). Thus, aggregates should not be rejected solely based on AASHTO T 303 results unless petrographic examination (ASTM C 295) confirms that the material is similar to known deleteriously reactive aggregates (ACI, 1998).

ASTM C 1293, which is commonly referred to as the concrete prism test, is currently recognized as the most reliable test method for predicting field performance. The test involves casting concrete with a cement content of 420 kg/m^3, using cement having an equivalent alkali content (defined as $Na_2O + 0.658\ K_2O$) between 0.8 percent and 1.0 percent. Additional alkalis (NaOH) are then added to the mixing water to obtain a total alkali content of 1.25 percent (by mass of cement), which yields a total alkali content in the concrete mixture of 5.25 kg/m^3. Magni et al. (1987) found that this boosted alkali content was necessary to identify slowly reactive aggregates, including argillites and greywackes. The concrete prisms are stored over water (to minimize leaching) at 38°C, and an expansion limit after one year of 0.04 percent is typically imposed (CSA, 2000).

Although ASTM C 1293 has been found to accurately predict field performance, it requires a relatively long period of time—as long as 2 years when assessing concrete containing pozzolans or slag (Fournier et al., 1999). This excessive length of time may affect the ability for an aggregate source to be approved for a specific job, and furthermore, the properties of aggregate produced at a given source may vary substantially over much shorter periods because of variability through the rock strata. Attempts to accelerate this test by increasing the temperature to 60°C (Touma et al., 2001; De Grosbois, 2000) produced comparable results within 3 months (compared with a year). However, additional testing is still required to verify the appropriateness of this accelerated test procedure.

Other test methods that have been used to assess aggregates with regard to ASR include ASTM C 227 (*Method for Potential Alkali Reactivity of Cement-Aggregate Combinations*) and ASTM C 289 (*Test Method for Potential Alkali-Silica Reactivity of Aggregates [Chemical Method]*). Because the results of these tests do not relate to field performance, their usage has continued to decline in favor of AASHTO T 303 and ASTM C 1293.

ACR is a less common durability problem in the United States than ASR is. CSA offers guidance for identifying ACR-susceptible aggregates by testing the quarried carbonate aggregates in accordance with CSA A23.2-26A (*Determination of Potential Alkali-Carbonate Reactivity of Quarried Carbonate Rocks by Chemical Composition*). The test involves the analysis for CaO, MgO, and Al_2O_3 to differentiate relatively pure limestones or dolomites (which are generally not affected by ACR) from potentially reactive aggregates, such as dolomitic limestones. This test has helped to remove some of the difficulty in identifying reactive dolomitic limestones by petrographic examination (ACI, 1998). If the aggregate is not found to be "potentially expansive" when tested according to CSA A23.2-26A, the aggregate can be considered durable with regard to ACR but still must be assessed for ASR. However, if the results of this chemical analysis indicate that the aggregate is "potentially expansive," the aggregate must be tested according to ASTM C 1293 (*Concrete Prism Test*); 0.04-percent expansion limit at 1 year is required for acceptance.

Freezing and Thawing Resistance

The laboratory assessment of aggregates for D-cracking has historically taken the form of either accelerated freezing and thawing testing of concrete containing the subject aggregate or direct testing of aggregates.

The most commonly used test to assess the frost resistance of concrete is AASHTO T 161 (*Resistance of Concrete to Rapid Freezing and Thawing*), in which concrete beams are subjected to repeated freezing and thawing cycles. Although this method has received criticism over the years for a variety of reasons, including its unrealistic severity (especially for Procedure A), it is still the most commonly used test by state DOTs for freezing and thawing evaluation. Various modifications have been proposed for this test to provide better correlation with field performance.

In accordance with AASHTO T 161, concrete beams are moist cured for 14 days at 23 ± 1.7°C prior to being subjected to cycles of freezing and thawing. This extended period of moist curing, coupled with the fact that the beams are not subjected to drying conditions prior to the freezing and thawing cycles, have drawn significant criticism because the high level of saturation of the concrete (and aggregates) prior to exposure to freezing conditions were not considered typical of field conditions (Phileo, 1986). Upon completion of the moist curing, the beams are subjected to cyclic freezing and thawing cycles, where the temperature of the specimens is lowered from 4.4°C to –17.8°C and then raised back from –17.8°C to 4.4°C in a total cycle time of 2 to 4 h. This rate of temperature change is also quite severe and not typical of that experienced in field structures.

AASHTO T 161 allows for two options for the exposure conditions for the beams during the freezing and thawing cycles: either freezing and thawing in water (Procedure A) or freezing in air and thawing in water (Procedure B). While Procedure A has been often criticized for its severity (compared with actual field conditions) and the use of rigid containers that may cause premature specimen damage, Procedure B has been criticized for not being severe enough (perhaps because of the drying of the specimens during the freezing cycle). Because of these concerns, a modified version of AASHTO T 161, generally referred to as Procedure C, was developed by Janssen and Snyder (1994), with the objective of better simulating field conditions. The method involves wrapping the beams in terry cloth, rather than placing them in rigid containers, to avoid premature specimen failure and to prevent drying of the beams during the freezing cycle.

To assess the D-cracking potential for a given aggregate in concrete, researchers have used modified versions of AASHTO T 161 procedures. These included variations of the freezing and thawing cycle time and exposure conditions of the beams (in water or air, in rigid containers or cloth wrap). To assess the salt susceptibility of carbonate aggregates, researchers have modified Procedure B by soaking the coarse aggregates in chlorides before casting and testing the concrete (Koubaa and Snyder, 1996).

When assessing freezing and thawing damage using AASHTO T 161 procedures, nondestructive measurements—such as resonant frequency, pulse velocity, and length change measurements—are often used. Data obtained from resonant frequency tests (or pulse velocity) are used to calculate a durability factor (DF). A DF value of 100 signifies that no measurable damage has occurred in the sample, and this value decreases with increasing internal damage. Different minimum DF values have been suggested by researchers (Neville, 1981; Fowler, et al., 1996) and by state DOTs (Embacher and Snyder, 2001).

Stark (1976) found that a DF value determined from the change in dynamic modulus may not be an appropriate index for evaluating D-cracking potential and recommended the use of length change measurements as an indicator of damage. Stark also recommended modifying the AASHTO T 161 method to reduce the number of freezing and thawing cycles to two per day. Stark found that this modified test produced better correlation with field-observed D-cracking, especially when the threshold for damage was defined by 0.035-percent length increase after 350 freeze-thaw cycles.

Many agencies, including most state DOTs and CSA, have developed guidelines for performing AASHTO T 161 and interpreting test results and expressed satisfaction with the ability to relate test results to D-cracking potential in concrete pavements. Based on the review of available information and data, the following conclusions are provided:

- AASHTO T 161 (Procedure C) appears to be the most viable concrete test to assess D-cracking. The use of a cloth wrap avoids potential premature damage caused sometimes by the rigid containers and prevents specimen drying during freezing cycles.
- Length change or dilation measurements are good measures for assessing D-cracking potential, especially with slow freezing and thawing (e.g., two cycles per day).
- A DF based on dynamic modulus measurements from AASHTO T 161 may not indicate field performance as length change measurements.
- Soaking carbonate aggregates in chloride solution before casting and testing concrete in accordance with AASHTO T 161 is a viable method of assessing salt susceptibility of aggregates in a freezing and thawing environment.
- Relating laboratory freezing and thawing test data to field performance records of D-cracking can be used to select the version of AASHTO T 161 and method of data interpretation that relate best to field performance.

Although accelerated freezing and thawing tests on concrete can provide valuable information on the susceptibility of aggregates to D-cracking, these tests are quite time consuming and laborious. For example, AASHTO T 161 requires anywhere from 40 days to over 6 months depending on cycling rate for 300 cycles. There is a need for developing faster methods that preferably test aggregates directly.

Different aggregate tests have been used by highway agencies, testing laboratories, and researchers in an attempt to predict the potential for D-cracking. One of the simplest and most common approaches is to test the resistance of unconfined aggregate particles to freezing and thawing cycles in water, alcohol, or salt solutions. In these unconfined tests, mass loss (using a specified sieve) is calculated, reported, and often cited in specifications. Several unconfined freezing and thawing tests have been used involving a variety of methods of conditioning (1) aggregates prior to testing, (2) exposure conditions during testing, and (3) duration of test (Meininger, 1998).

AASHTO T 103 (*Soundness of Aggregates by Freezing and Thawing*) includes three procedures. In Procedure A, aggregates are soaked in water for 24 h prior to start of test and then fully immersed in water for 50 freezing and thawing cycles. In procedure B, aggregates are vacuum saturated in alcohol-water solution (0.5 percent by mass ethyl alcohol) for 15 min and then partially immersed in alcohol-water solution for 16 freezing and thawing cycles. Procedure C is similar to Procedure B except that water is used instead of water-alcohol solution, and the number of freezing and thawing cycles is increased from 16 to 25. In CSA A23.2-24A (*Test Method for the Resistance of Unconfined Coarse Aggregate to Freezing and Thawing*), aggregates are soaked in 3-percent sodium chloride solution for 24 h and then fully immersed in sodium chloride solution for five freezing and thawing cycles. This procedure has been reported to give good precision and correlation with freezing and thawing damage in concrete pavements (Senior and Rogers, 1991).

AASHTO T 104 (*Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate*) is one of the most common tests performed by state DOTs, being used by 31 of the 43 respondents in a 1995 survey (Fowler et al., 1996). The test is routinely performed on aggregate sources and often used as a quality control test rather than as an indicator of field performance. The test, which subjects aggregate samples to cyclic soaking in sulfate solution followed by oven drying, was designed to simulate freezing and thawing action in concrete. The test triggers crystallization and/or hydration pressures in the pores of aggregates, which can lead to significant damage and mass loss. Most state DOTs and testing laboratories tend to use sodium sulfate, but magnesium sulfate generally produces less variation in mass loss values for a specific aggregate sample. Soundness test by use of magnesium sulfate provides some useful information on field performance that makes it a potential indicator of freezing and thawing resistance of aggregates. Different limits on mass loss have been proposed depending on exposure condition (CSA, 2000; Fowler et al., 1996).

In response to the need for tests that directly assess D-cracking potential of aggregates, two specific methods have been developed and used by some researchers and state DOTs: the Iowa Pore Index Test (IPIT) and the Washington Hydraulic Fracture Test (WHFT).

The IPIT was developed to quantify the volume of micropores in aggregates that has been found to correlate with the potential for D-cracking (Marks and Dubberke, 1982). The test involves placing a 9-kg dried aggregate sample in a pressure meter, filling the vessel with water, and subjecting the sample to a pressure of 241 kPa. The volume of water forced into the sample in the first minute, referred to as the “primary load,” is reported to represent the volume of macropores in aggregates. The volume of water injected into the sample in the subsequent 14 min, expressed in units of milliliters, is then recorded, labeled the “secondary load,” and reported to represent the amount of micropores in aggregates. Schwartz (1987) reported that this test was a good indicator of D-cracking in Illinois for crushed carbonate aggregates, but not for carbonate gravels. This difference is most likely because of the rapid early absorption exhibited by gravels under the test conditions (Winslow, 1987). Rogers (2002) reported a good correlation between the IPIT and the field performance of aggregates in Ontario. Aggregates with greater than 2-percent absorption after 24 h and with IPIT secondary loads greater than 27 mL generally exhibited poor field performance (Rogers and Senior, 1994). The IPIT provides a good indication of D-cracking potential because of its reported ability to predict field performance (especially for crushed carbonate aggregates).

The WHFT was developed to assess the resistance of coarse aggregates to freezing and thawing damage, particularly D-cracking (Janssen and Snyder, 1994). The method involves forcing water into aggregate particles under pressure and measuring the amount of fracturing that occurs within the aggregates as the pressure is released and the internal water is expelled. The original version of this test method was criticized because of the reported significant difference in results for test samples and especially between different operators and laboratories. The initial WHFT test results were reported not to correlate well with freezing and thawing damage in concrete (Meininger, 1998); improvements were made later (Hietpas, 1998; Embacher and Snyder, 2001). These improvements included modifying testing apparatus, incorporating models to correlate direct outputs of the WHFT (particle size distribution of tested sample) to length changes (or dilation) from AASHTO T 161, developing a calibration procedure to provide for a similar pressure release rate regardless of the equipment used (Hietpas, 1998), and implementing a larger test chamber to allow testing of 600 aggregate particles in one test. With these modifications, the WHFT appears appropriate for assessing the D-cracking potential of aggregates.

Other Aggregate-Related Properties and Tests

Creep and Drying Shrinkage

No standard tests to directly measure the creep and shrinkage of aggregates are currently available; tests on mortar or concrete containing the subject aggregates have served as reasonable indicators or validation tests. When creep and shrinkage properties are considered critical for the design of a concrete pavement, concrete containing the subject aggregate can be tested for creep using ASTM C 152 (*Test Method for Creep of Concrete in Compression*) and for shrinkage using AASHTO T 160 (*Length Change of Hardened Hydraulic Cement Mortar and Concrete*).

Impurities and Chlorides in Aggregates

Several tests are available for evaluating aggregate sources that may contain appreciable amounts of impurities. AASHTO T 21 (*Organic Impurities in Fine Aggregate for Concrete*) is a simple and quick test where the user observes the color when a fine aggregate is placed in a sodium hydroxide solution; a dark color represents the potential presence of organic impurities. If a specific aggregate produces a dark color in this test, potential effects of these impurities should be assessed using AASHTO T 71 (*Effects of Organic Impurities on Strength of Mortar*) in mortar containing the aggregate.

AASHTO T 112 (*Clay Lumps and Friable Particles in Aggregates*) can be used to determine the presence of clay lumps or friable particles in an aggregate sample. AASHTO T 113 (*Lightweight Pieces in Aggregate*) can be used for determining the amount of lightweight pieces in aggregates, such as coal or lignite (CSA, 2000), by immersing the sample in a heavy liquid (specific gravity of 2.0). This method can also identify harmful chert in coarse aggregates (Kosmatka and Panarese, 1988).

For most aggregate sources, the chloride content is quite low and not of concern for corrosion of reinforcing steel. However, for sea-dredged aggregates, aggregates contaminated by deicing salts (because of their proximity to stockpiles), recycled concrete aggregates, and certain carbonate aggregates, the measurement of chloride content may be more relevant. Where there are concerns regarding the presence of appreciable chlorides in an aggregate and the potential for corrosion, the aggregate should be tested for chloride content. The testing of aggregates for total chloride content may provide misleading results as the value obtained may overestimate the actual availability of chlorides, especially for quarried carbonate aggregates (Rogers and Woda, 1992). To provide a more accurate estimate of the amount of available chlorides from aggregates, the Soxhlet Extraction method (ACI, 1996b) is recommended (Meininger, 1998).

RELEVANT TEST METHODS

Based on the review, the following test methods are considered appropriate for measuring specific aggregate or aggregate-related property.

- Absorption
  - — AASHTO T 84, *Specific Gravity and Absorption of Fine Aggregate*
  - — AASHTO T 85, *Specific Gravity and Absorption of Coarse Aggregate*

- Aggregate gradation
  - — AASHTO T 27, *Sieve Analysis of Fine and Coarse Aggregates*

- Properties of microfines
  - — AASHTO T 11, *Materials Finer Than No. 200 Sieve in Mineral Aggregates by Washing*
  - — AASHTO T 176, *Plastic Fines in Graded Aggregates and Soils by the Use of the Sand Equivalent Test*
  - — AASHTO TP 57, *Standard Test Method for Methylene Blue Value of Clays, Mineral Fillers, and Fines*
  - — X-ray diffraction analysis (to identify types of clay)

- Aggregate shape, angularity, and texture
  - — AASHTO T 304, *Uncompacted Void Content of Fine Aggregates*
  - — AASHTO TP 56, *Uncompacted Void Content of Coarse Aggregates (As Influenced by Particle Shape, Surface Texture, and Grading)*
  - — ASTM D 4791, *Test Method for Flat or Elongated Particles in Coarse Aggregates*

- Aggregate thermal expansion
  - — AASHTO TP 60-00, *Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete*

- Aggregate abrasion
  - — CSA A23.2-23A, *Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*
  - — AASHTO TP 58, *Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro Deval Apparatus*
  - — AASHTO T 96, *Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*

- Elastic modulus
  - — ASTM C 469, *Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*

- Polishing
  - — ASTM D 3042, *Test for Acid Insoluble Residue in Carbonate Aggregates*

- Aggregate strength
  - — *British Standard 812 (Part 3)—Aggregate Crushing Value*

- Aggregate mineralogy
  - — ASTM C 295, *Guide for Petrographic Examination of Aggregates for Concrete*
  - — X-ray diffraction analysis (XRD)
  - — Thermogravimetric Analysis (TGA)
  - — X-ray fluorescence analysis (XRF)

- Alkali-aggregate reactivity
  - — ASTM C 295, *Guide for Petrographic Examination of Aggregates for Concrete*
  - — AASHTO T 303, *Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction*
  - — ASTM C 1293, *Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction*
  - — CSA A23.2-26A, *Determination of Potential Alkali-Carbonate Reactivity of Quarried Carbonate Rocks by Chemical Composition*

- Freezing and thawing resistance (D-cracking)
  - AASHTO T 161 (modified Procedure C), *Resistance of Concrete to Rapid Freezing and Thawing*
  - CSA A23.2-24A, *Unconfined Freezing and Thawing of Aggregates in NaCl Solution*
  - AASHTO T 104, *Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate* (only magnesium sulfate is recommended)
  - IPIT
  - Modified WHFT (based on modifications detailed by Embacher and Snyder [2001])

- Creep and shrinkage
  - AASHTO T 160, *Length Change of Hardened Hydraulic Cement Mortar and Concrete*
  - ASTM C 512, *Test Method for Creep of Concrete in Compression*

- Aggregate Impurities
  - AASHTO T 21, *Organic Impurities in Fine Aggregate for Concrete*
  - AASHTO T 71, *Effects of Organic Impurities on Strength of Mortar*
  - AASHTO T 112, *Clay Lumps and Friable Particles in Aggregates*
  - AASHTO T 113, *Lightweight Pieces in Aggregates*
  - Provisional Standard Test Method for Water-Soluble Chloride Available for Corrosion of Embedded Steel in Mortar and Concrete Using the Soxhlet Extractor (available in ACI 222.1R-96)

GUIDANCE FOR SELECTING AGGREGATE TESTS

This section provides guidance on selecting aggregate or aggregate-related tests for a specific concrete pavement application. It includes discussions on the relevant issues and a flowchart to aid in selecting appropriate test methods. However, aggregate or aggregate-related properties that are considered of lesser importance to concrete pavement performance (e.g., presence of chlorides and impurities) are not discussed.

Approach for Selecting Aggregate Tests

Most of the test methods recommended for assessing aggregate property performance involve the direct measurement of aggregate properties; others involve the indirect assessment of aggregate properties through testing of mortar or concrete specimens. For some properties, different test methods that may be used either separately or in combination have been identified. Because many aggregate properties affect pavement performance and different test methods can be used for evaluating them, a process to select the appropriate tests for a specific pavement application has been proposed. This process considers the following items:

- Pavement type and design,
- Climatic/environmental conditions,
- Traffic loading,
- Materials and mixture proportions,
- Test limits and acceptance criteria,
- Frequency of aggregate testing, and
- Field performance histories of aggregates.

Pavement Type and Design

A close examination of the aggregate properties affecting concrete pavement performance revealed that the majority of these properties affect the performance of the three pavement types (JPCP, JRCP, and CRCP). Only three pavement performance parameters were found to be specific to a single pavement type (corner breaks and faulting of JCP and punchouts of CRCP); these parameters relate to the same aggregate properties that influence the other performance parameters.

Some aggregate and concrete properties are particularly relevant to the performance of a specific pavement type and, therefore, warrant serious consideration. For example, because thermal properties of aggregates have a significant effect on the performance of CRCP, it is necessary to place additional emphasis on the properties that affect thermal cracking (e.g., coefficient of thermal expansion) while considering other relevant properties (e.g., aggregate strength, elastic modulus, texture, size, and shape).

Climatic/Environmental Conditions

Climatic and environmental conditions to which the pavement will be exposed also affect performance. Of obvious importance is the exposure to freezing and thawing cycles that could lead to aggregate-related problems, such as D-cracking. The use of deicing salts could also influence the frost resistance of certain carbonate aggregates. The aggregate test selection process should take these factors into account when considering pavements constructed in locations with potential for freezing and thawing or substantial use of deicing salts.

Exposure to ambient conditions with relatively large fluctuations in temperature may exacerbate thermal curling stresses, requiring special consideration to the thermal properties of aggregates. Also, fluctuations in thermal and moisture conditions and gradients (through the thickness of the slab) influence transverse cracking, and extremely high temperatures increase the likelihood of blowups. Because water is an essential ingredient for ASR expansion, pavements constructed with alkali-reactive aggregates in high-humidity regions are likely to exhibit a fast rate of deterioration.

Corrosion of embedded steel may be a concern for pavements constructed in wet regions and subjected to significant applications of deicing chemicals or in a marine environment. For example, dowel bars, tie bars, and reinforcing steel could become susceptible to corrosion because of infiltration of water and deicing chemicals through joints and cracks.

Traffic Loading

Traffic-loading factors (e.g., volume of traffic or truck weight and axle configuration) have a significant impact on the performance of concrete pavements. Higher-quality aggregates are particularly specified for pavements subjected to heavy traffic loadings; marginal aggregates are sometimes allowed for use in pavements subjected to lighter traffic loadings. For example, Pennsylvania DOT specifies aggregates based on average daily traffic (ADT), and Iowa DOT uses a "durability classification" system that requires use of more durable aggregates (with regard to D-cracking) for heavily traveled interstate roads but permits use of less durable aggregates for less-traveled secondary roads. The specification of aggregate quality or performance as a function of traffic loading varies widely among highway agencies. However, the data obtained from tests on a specific aggregate source and from a documented record of its field performance could be used to relate aggregate properties to pavement performance.

The use of studded tires or chains is quite limited in the United States. However, this type of traffic loading requires special consideration. Because a mortar-rich layer is generally available on the pavement surface, the frictional properties of the pavement are greatly influenced by the polish resistance of fine aggregates. However, studded tires or chains tend to abrade away the pavement's top layer and expose the coarse aggregates, thereby increasing the effect on frictional properties.

Materials and Mixture Proportions

The selection of aggregate tests should also consider other concrete constituent materials and mixture proportions. Because high-strength concretes with low w/cm ratios tend to exhibit strong bonding that causes failure to occur through the coarse aggregate particles, aggregates with higher inherent strengths and rough surface texture are preferred for such concrete mixtures. Testing the relative strength of a graded sample of aggregate and the strength of concrete containing that aggregate is, therefore, warranted.

If pozzolan or slag is to be used in the concrete in sufficient quantity to control ASR, testing is still needed to ensure that the aggregate-binder combination will adequately reduce expansion. Attention should also be given to aggregates that tend to break down during handling and mixing and adversely influence workability or air-void stability.

Test Limits and Acceptance Criteria

Wherever appropriate, information related to test limits and acceptance criteria proposed by researchers, state DOTs, and other specifications for key aggregate tests are cited. These criteria or limits are provided for guidance; other values that are known to relate better to performance should be used if available.

Frequency of Aggregate Testing

For a given aggregate source, certain basic aggregate properties (e.g., absorption, specific gravity, and gradation) are generally measured routinely as part of a standard quality control program or to provide values needed for proportioning of concrete mixtures. Other aggregate properties, such as ASR, will be measured only periodically, typically on an annual basis. In addition, aggregate sources are often included in preapproving concrete mixtures for paving applications, and these mixtures are periodically tested for conformance with various performance-based specifications. The agency's quality assurance (QA) programs generally stipulate the frequency of testing aggregate sources; this frequency varies among state DOTs. While no specific guidance on frequency of testing is provided, it is strongly suggested that an aggregate source be retested whenever substantially different aggregate deposits or ledges are encountered at a pit or quarry.

Field Performance Histories of Aggregates

Collecting and maintaining field performance histories of aggregates used in concrete pavements should help in determining which laboratory test methods best relate to pavement performance and in relating aggregate type and mineralogy to certain performance parameters (e.g., AAR and D-cracking).

If a substantial field performance history for a specific aggregate source is available, it could be used judicially to accept or reject the aggregate for use in paving concrete without the need for laboratory assessment. For example, the Iowa DOT has maintained records of field performance histories for most of the aggregates (except for new sources) used in highway applications and used this information for project acceptance; a few other DOTs have maintained reliable long-term performance histories for aggregates. When solely used to accept a specific aggregate source, the performance history must document sufficient information relevant to the planned application. For example, CSA (2000) and ACI (1998) stipulated the following conditions for the acceptance of a specific aggregate use on the basis of field performance histories relating to AAR:

- The cement content and the alkali content of the cement used in the field concrete should be the same as or higher than that proposed in the new structure.

- The concrete examined should be at least 10 years old.
- The exposure conditions of the field concrete should be at least as severe as those expected for the proposed structure.
- In the absence of conclusive documentation, a petrographic examination should be performed to demonstrate that the aggregate in the structure is sufficiently similar to that under investigation.
- The possibility of pozzolans or slag having been used and the effects of w/cm ratio on ASR should be considered.

Similar guidelines should be followed when considering field performance histories related to other performance parameters. For example, when using field performance data to assess D-cracking, the proposed aggregate should be from the same source and bed and exhibit a similar gradation and maximum size as that in the existing concrete. Also, related concrete properties, such as air content, strength, and permeability, should be considered.

Because of the inherent lack of acceptable performance field histories in most areas, some laboratory testing is generally required. As adequate performance records become available, more confidence can be placed on directly using these records to accept or reject aggregates for a specific use. Nevertheless, caution should be taken in the interpretation of field performance data and in their use in selecting aggregate sources.

Selection of Aggregate Tests

The recommended aggregate tests have been classified into categories, designated Level I and Level II. Level I tests are the tests that are considered essential for evaluating specific aggregate properties, and Level II tests are the tests that either are optional or are to be performed depending on the results of Level I testing. Some of Level II tests tend to be longer in duration and may be more difficult to conduct. Level I and II tests are listed in Table 5.

Not all of the proposed Level I and II tests need to be performed for every pavement type. Options are provided that allow, for example, the use of one Level I test and not another. Also, data for many of the proposed aggregate tests are readily available because these tests are typically performed as part of the regular state DOT's QA programs.

Figure 1 is a flowchart to help determine if a specific aggregate property is relevant to concrete pavement. Each test can be used solely either to assess a specific property or to serve as the first step or screening test for a more complex property. For some aggregate properties, more than one Level I test has been proposed for assessing a specific property. The figure also illustrates a proposed aggregate testing process for a specific pavement. It provides an approach for selecting tests from each of the four aggregate property categories and includes provisions for identifying tests required for climatic or related conditions (e.g., freezing and thawing tests in certain climates). The results of some tests may be interpreted as "pass" or "fail" or in terms of qualitative information that sometimes presents a potential concern in need of special attention. Depending on the results of such a test, additional testing may be required.

Some of the proposed tests may be used to assess more than one aggregate property category. For example, petrographic analysis of aggregates may be used to assess the overall mineralogical composition of an aggregate as part of the chemical and petrographic properties and also to identify potentially reactive minerals with regard to AAR as part of the durability properties. Another example is the suggested use of XRD to study clay minerals in fines as part of the physical properties and overall aggregate mineralogy as part of the chemical and petrographic properties. These tests are grouped under multiple categories for completeness, but they should not be performed more than once for a given aggregate sample. Also, comprehensive petrographic analysis would yield essential information on overall mineralogy of aggregates as well as the presence of potentially reactive materials.

CONCLUSIONS AND SUGGESTED RESEARCH

The study provided information on concrete pavement performance parameters and aggregate properties that affect these parameters and identified a set of tests that can be used to assess these properties. The following is a summary of the findings of the study:

- The most important concrete pavement performance parameters include (1) blowups, D-cracking, longitudinal cracking, roughness, spalling, surface friction, and transverse cracking of all pavement types; (2) corner breaks and faulting of JPCP; and (3) punchouts of CRCP.
- The aggregate properties that most affect the performance parameters of concrete pavements include physical properties (absorption; gradation; properties of microfines; shape, angularity, and texture; and thermal expansion); mechanical properties (abrasion resistance, elastic modulus, polish resistance, and strength); chemical and petrographical properties (mineralogy); and durability properties (alkali-aggregate reactivity and freezing and thawing resistance).
- Specific test methods can be used to assess aggregate properties that are expected to impact pavement performance, and a systematic approach can be used to select the appropriate tests for specific applications.
- Further research into aggregates proprties, test mehods, and a relationship to pavement performance is needed to enhance the findings of this study. The following are suggested research topics:

TABLE 5 Level I and II tests

Level	Property	Test Method
I	Absorption	AASHTO T 84, *Specific Gravity and Absorption of Fine Aggregate* AASHTO T 85, *Specific Gravity and Absorption of Coarse Aggregate*
	Aggregate gradation	AASHTO T 27, *Sieve Analysis of Fine and Coarse Aggregates*
	Properties of microfines	AASHTO T 11, *Materials Finer than No. 200 Sieve in Mineral Aggregates by Washing*
		AASHTO T 176, *Plastic Fines in Graded Aggregates and Soils by the Use of the Sand Equivalent Test*
	Aggregate shape, angularity, and texture	AASHTO T 304, *Uncompacted Void Content of Fine Aggregates* AASHTO TP 56, *Uncompacted Void Content of Coarse Aggregates (As Influenced by Particle Shape, Surface Texture, and Grading)* ASTM D 4791, *Test Method for Flat or Elongated Particles in Coarse Aggregates*
	Aggregate thermal expansion	AASHTO TP 60-00, *Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete*
	Aggregate abrasion	CSA A23.2-23A, *Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* AASHTO TP 58, *Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* AASHTO T 96, *Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*
	Elastic modulus	ASTM C 469, *Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*
	Polishing	ASTM D 3042, *Test for Acid Insoluble Residue in Carbonate Aggregates*
	Aggregate strength	*British Standard 812 (Part 3), Aggregate Crushing Value*
	Aggregate mineralogy	ASTM C 295, *Guide for Petrographic Examination of Aggregates for Concrete*
	Alkali-aggregate reactivity	ASTM C 295, *Guide for Petrographic Examination of Aggregates for Concrete* AASHTO T 303, *Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction* CSA A23.2-26A, *Determination of Potential Alkali-Carbonate Reactivity of Quarried Carbonate Rocks by Chemical Composition*
	Freezing and thawing resistance (D-cracking)	CSA A23.2-24A, *Unconfined Freezing and Thawing of Aggregates in NaCl Solution* AASHTO T 104, *Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate* (only magnesium sulfate is recommended) Iowa Pore Index Test Modified Washington Hydraulic Fracture Test (based on modifications detailed by Embacher and Snyder [2001])
II	Properties of microfines	AASHTO TP 57, *Standard Test Method for Methylene Blue Value of Clays, Mineral Fillers, and Fines*
	Aggregate mineralogy	X-ray diffraction analysis (XRD) Thermogravimetric analysis (TGA) X-ray fluorescence analysis (XRF)
	Alkali-aggregate reactivity	ASTM C 1293, *Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction*
	Freezing and thawing resistance (D-cracking)	AASHTO T 161 (modified Procedure C), *Resistance of Concrete to Rapid Freezing and Thawing*

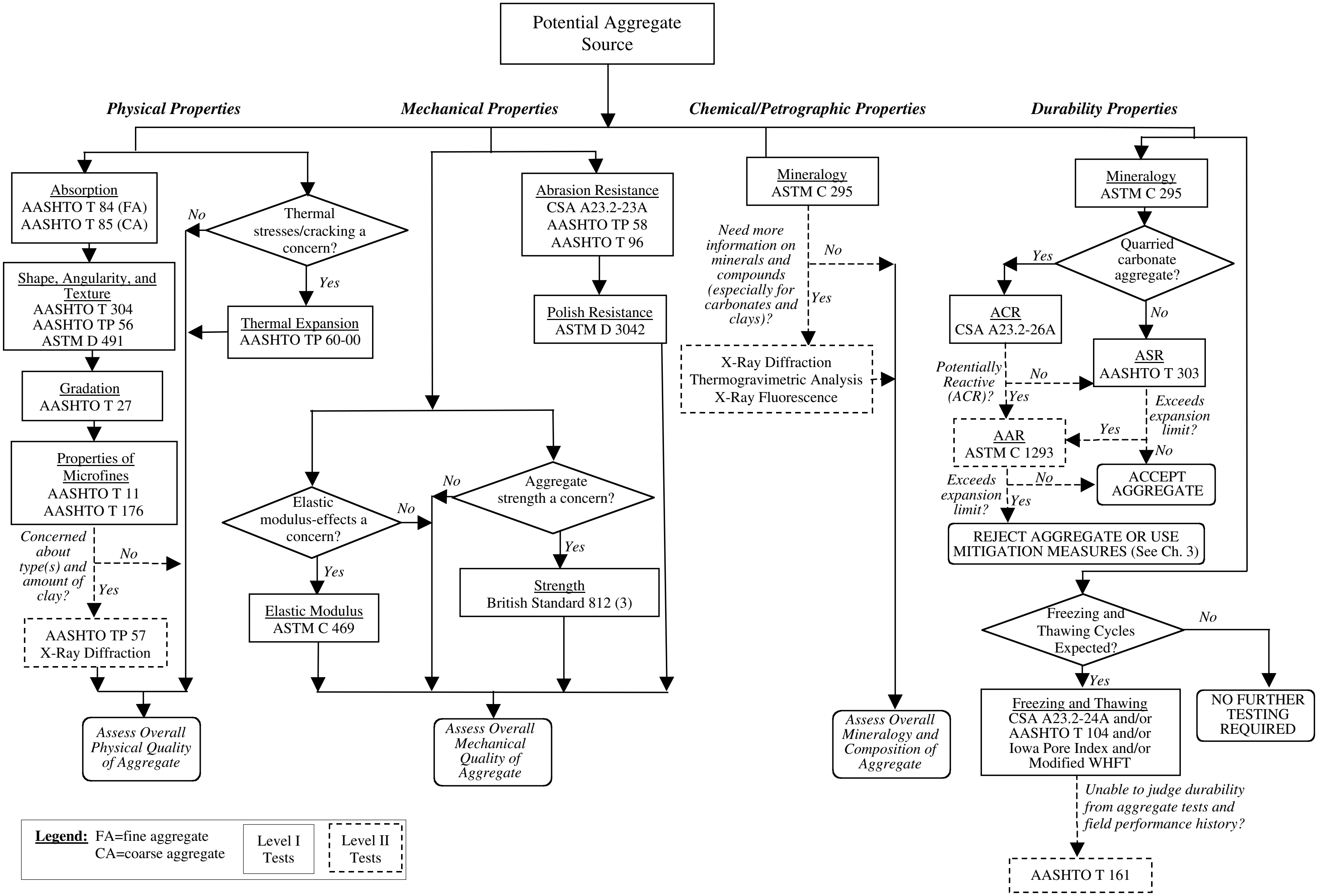

Figure 1. Aggregate test selection process.

- *Development of a database on aggregegate performance.* Aggregate properties and test methods that appear closely related to pavement performance were identified using the state of the knowledge. However, limited field perfmance data were available to confirm validity of these findings. Although some state DOTs have developed comprehensive and long-term field data on major aggregate sources, there is a general lack of sufficient documentation of such information for most aggregate sources and types used in highway applications. Developing long-term databases on how different aggregate types and sources perform in pavements will help establish the extent of relevance of the various test methods to performance and will further refine the findings of this study.
- *Aggregate characterization.* Thorough chacterization of aggregate is essential for accurately relating aggregate sources, types, and variability to performance. Enhanced approaches for petrographic examinations and mineralogical and chemical analyses are needed to better characterize aggregates.
- *D-cracking tests.* There is no clear consensus among practitioners as to which test method best predicts D-cracking potential. A research effort is needed to (1) investigate the ability of the various test methods to predict D-cracking potential and (2) identify or develop appropriate test methods.
- *Improved ASR tests.* A current test method that apprears to accurately assess an aggregate's potential for ASR requires 1 year to complete, or even longer when a reactive aggregate is used in a concrete mixture containing other cementitious materials and admixtures. Other rapid tests do not always yield results that are compatible with performance records. There is a need to develop an approach for accurately, but also rapidly, assessing the aggregate's potential for reactivity.
- *Impact of microfines on performance.* The properties of microfines (material finer than the #200 sieve) may have a significant impact on pavement performance, although correlations between these properties and field performance have not been documented. Some test methods are capable of identifying the presence and amount of clay-like materials, but not relating these results to pavement performance. Further research is neded to detrmine the efects of microfines on fresh and hardened concrete properties.

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), *AASHTO Guide Specification for Highway Construction*, Section 56X, "Portland Cement Concrete Resistant to Excessive Expansion Caused by Alkali-Silica Reaction," http://leadstates.tamu.edu/ASR/library/gspec.stm, 2000.

American Association of State Highway and Transportation Officials (AASHTO), *Guide for Design of Pavement Structures*, 1993.

American Concrete Institute (ACI), "Guide to Durable Concrete: Chapter 3—Alkali-Aggregate Reaction," ACI Committee 201 Draft Report, balloted and approved, 1998.

American Concrete Institute (ACI), "Guide for Use of Normal Weight Aggregate in Concrete," *ACI Report 221R*, 1996a.

American Concrete Institute (ACI), "Provisional Standard Test Method for Water-Soluble Chloride Available for Corrosion of Embedded Steel in Mortar and Concrete Using the Soxhlet Extractor," *ACI Report 222.1R*, 1996b.

American Concrete Institute (ACI), "Guide for Use of Normal Weight Aggregates in Concrete," *ACI Report 221R-89*, 1989.

American Concrete Pavement Association (ACPA), *Summary of Concrete Pavement Design and Construction Practices in the United States*, Skokie, IL, 1999.

Baalbaki, W., Benmokrane, B., Chaalal, O., and Aitcin, P-C., "Influence of Coarse Aggregate on Elastic Properties of High-Performance Concrete," *ACI Materials Journal*, Vol. 88, No. 5, pp. 499-503, September-October, 1991.

Bérubé, M-A., and Fournier, B., "Effectiveness of the Accelerated Mortar Bar Method, ASTM C9 Proposal P214 or NBRI, for Assessing Potential AAR in Quebec (Canada)," *Proceedings of the Ninth International Conference on Alkali-Aggregate Reaction in Concrete*, Concrete Society, Slough (U.K.), pp. 92-101, 1992.

Canadian Standards Association (CSA), *Concrete Materials and Methods of Concrete Construction/Methods of Test for Concrete,* A23.1-00/A23.2-00, 2000.

De Grosbois, M., "Evaluation of the Potential Alkali-Reactivity of Concrete Aggregates: Performance of Testing Methods and a Producer's Point of View," *Pro-*

ceedings of 11th International Conference of Alkali-Aggregate Reactivity in Concrete, Quebec City, QC, Canada, pp. 267-276, 2000.

Dubberke, W., and Marks, V. J., "Evaluation of Carbonate Aggregates Using X-Ray Analysis," *Transportation Research Record 1250*, Transportation Research Board, National Research Council, pp. 17-24, 1989.

Dubberke, W., and Marks, V. J., "Thermogravimetric Analysis of Carbonate Aggregates," *Transportation Research Record 1362*, Transportation Research Board, National Research Council, pp. 38-43, 1992.

Dubberke, W., and Marks, V. J., "The Effect of Salt on Aggregate Durability." *Transportation Research Record 1031*, Transportation Research Board, National Research Council, pp. 27-34, 1985.

Embacher, R. A., and Snyder, M. B., "Refinement and Validation of the Hydraulic Fracture Test," Draft Final Report, Minnesota Department of Transportation, 2001.

Farny, J. A., and Kosmatka, S. H., "Diagnosis and Control of Alkali-Aggregate Reactions in Concrete," *Publication IS413.01T*, Portland Cement Association, Skokie, IL, 1997.

Folliard, K. J., and Sabol, S. A., "Aggregate Tests Related to Performance of Portland Cement Concrete, Phase I," Unpublished Interim Report, NCHRP Project 4-20B, 1999.

Fournier, B., Bérubé, M-A., and Roger, C. A., "Proposed Guidelines for the Prevention of Alkali-Silica Reaction in New Concrete Structures," *Transportation Research Record 1668*, Transportation Research Board, National Research Council, pp. 48-59, 1999.

Fowler, D. W., Zollinger, D. G., Carrasquillo, R. L., and Constantino, C. A., "Aggregate Tests Related to Performance of Portland Cement Concrete, Phase I," Unpublished Interim Report, NCHRP Project 4-20, 1996.

Gaynor, R. D., and Meininger, R. C., "Evaluating Concrete Sands," *Concrete International*, Vol. 5, No. 12, pp. 53-60, 1983.

Gregg, S. J., and Sing, K. S. W., *Adsorption, Surface Area and Porosity,* Second Edition, Academic Press, London, United Kingdom, 1982.

Grogg, M. G., and Smith, K. D., "PCC Smoothness: Best Practices for Constructing Quality PCC Pavements," *FHWA Technical Summary*, Federal Highway Administration, Washington, DC, 2001.

Henry, J. J., "Evaluation of Pavement Friction Characteristics," *NCHRP Synthesis of Highway Practice 291*, Transportation Research Board, National Research Council, 2000.

Hietpas, J. J., "Refinement and Validation of the Washington Hydraulic Fracture Test," Master's Degree Thesis, University of Minnesota, Department of Civil Engineering, 1998.

Hoerner, T. E., Smith, K. D., Yu, H. T., Peshkin, D. G., and Wade, M. J., "PCC Pavement Evaluation and Rehabilitation," Reference Manual, NHI Training Course 131062, National Highway Administration, Arlington, VA, 2001.

Hosking, R., "Road Aggregates and Skidding," Transportation Research Laboratory, State-of-the-Art Review 4, HMSO, London, 1992.

Janssen, D. J., and Snyder, M. B., "Resistance of Concrete to Freezing and Thawing," *SHRP-C-391*, Strategic Highway Research Program, Transportation Research Board, National Research Council, 1994.

Kandhal, P. S., and Parker, Jr., F., "Aggregate Tests Related to Asphalt Concrete Performance in Pavements," *NCHRP Report 405*, Transportation Research Board, National Research Council, 1998.

Kosmatka, S. H., and Panarese, W. C., *Design and Control of Concrete Mixtures*, Thirteenth Edition, Portland Cement Association, 1988.

Koubaa, A., Newcomb, D. E., and Snyder, M. B., *Mitigating Concrete Aggregate Problems in Minnesota*, Final Report, Minnesota Department of Transportation, 282 pp., 1997.

Koubaa, A., and Snyder, M. B., "Evaluation of Frost Resistance Tests for Carbonate Aggregates," *Transportation Research Record 1547*, Transportation Research Board, National Research Council, pp. 35-45, 1996.

Lan, T. N., and Millon-Devigne, P., *Bulletin of the International Association of Engineering Geology*, Vol. 29, 1984.

Magni, E. R., Rogers, C. A., and Grattan-Bellew, P. E., "The Influence of the Alkali-Silicate Reaction on Structures in the Vicinity of Sudbury, Ontario," *Proceedings of the Seventh International Conference on Concrete Alkali-Aggregate Reactions* (Ed. P. E. Grattan-Bellew), Noyes, New Jersey, pp. 17-22, 1987.

Marks, V. J., and Dubberke, W., "Durability of Concrete and the Iowa Pore Index Method," *Transportation Research Record 853*, Transportation Research Board, National Research Council, pp. 25-30, 1982.

McCullough, B. F., Zollinger, D. G., and Dossey, T., "Effect of Aggregates on Pavement Performance," *Center for Transportation Research Report 1244-13F*, The University of Texas at Austin, 1995.

McGhee, K. H., "Design, Construction, and Maintenance of PCC Pavement Joints," *NCHRP Synthesis of Highway Practice 211*, Transportation Research Board, National Research Council, 1995.

Mehta, P. K., and Monteiro, P. J. M., *Concrete Structure Properties and Materials*, Prentice Hall, 1993.

Meininger, R. C., "Degradation Resistance, Strength, Toughness, and Related Properties," *ASTM STP 169C, Significance of Tests and Properties of Concrete and Concrete Making Materials*, pp. 388-400, 1994.

Meininger, R. C., "Aggregate Tests Related to Performance of Portland Cement Concrete Pavement," Unpublished Final Report, NCHRP Project 4-20A, 1998.

Morgenstern, N. R., and Phukan, A. L. T., "Non-Linear Deformation of Sandstone," Proceedings, *First Inter-*

national Congress on Rock Mechanics, Vol. 1, pp. 543-548, 1966.

Neville, A. M., *Properties of Concrete*, Pitman Publishing, Ltd., London, United Kingdom, 1981.

Oberholster, R. E. and Davies, G., “An Accelerated Method for Testing the Potential Reactivity of Siliceous Aggregates,” *Cement and Concrete Research*, Vol. 16, pp. 181-189, 1986.

Okamoto, P. A., Nussbaum, P. J., Smith, K. D., Darter, M. I., Wilson, T. P., Wu, C. L., and Tayabji, S. D., “Guidelines for Timing Contraction Joint Sawing and Earliest Loading for Concrete Pavements, Volume 1—Final Report,” *FHWA-RD-91-079*, Federal Highway Administration, McLean, VA, 1994.

Oyen, C. W., Fountain, K. B., McClellan, G. H., and Eades, J. L., “Thin-Section Petrography of Concrete Aggregates: Alternative Approach for Petrographic Number Evaluations of Carbonate Aggregate Soundness,” *Transportation Research Record 1619*, Transportation Research Board, National Research Council, pp. 18-25, 1998.

Phileo, R. E., “Freezing and Thawing Resistance of High Strength Concrete,” *NCHRP Synthesis of Highway Practice 129*, Transportation Research Board, National Research Council, 1986.

Pigeon, M., and Pleau, R., *Durability of Concrete in Cold Climates*, E & FN Spon, 244 pp., 1995.

Portland Cement Association (PCA), *Guide Specification for Concrete Subject to Alkali-Silica Reactions*, 1998.

Rogers, C. A., Personal Communications, 2002.

Rogers, C. A., Bailey, M., and Price, B., “Micro-Deval for Evaluating the Quality of Fine Aggregate for Concrete and Asphalt,” *Transportation Research Record 1301*, Transportation Research Board, National Research Council, 1991.

Rogers, C. A., and Fournier, B., “Petrography and Alkali-Aggregate Reactions,” *Petrography and Alkali-Aggregate Reactivity—Course Manual*, CANMET, Ottawa, pp. 71-124, 1991.

Rogers, C. A., and Senior, S. A., “Recent Developments in Physical Testing of Aggregates to Ensure Durable Concrete,” *Advances in Cement and Concrete*, Proceedings of Engineering Foundation Conference, American Society of Civil Engineers, 1994.

Rogers, C. A., and Woda, G., “The Chloride Ion Content of Coarse Aggregates from Southern Ontario,” *Engineering Report 17,* Second Edition, Ontario Ministry of Transportation, 1992.

Schlorholtz, S., *Determine Initial Cause for Current Premature Portland Cement Concrete Deterioration*, Iowa Department of Transportation Project TR-406, pp. 95-103, 2000.

Schwartz, D. R., “D-Cracking of Concrete Pavements,” *National Cooperative Highway Research Program Synthesis of Highway Practice 134*, Transportation Research Board, National Research Council, 1987.

Senior, S. A., and Rogers, C. A., “Laboratory Tests for Predicting Coarse Aggregate Performance in Ontario,” *Transportation Research Record 1301*, Transportation Research Board, National Research Council, pp. 97-106, 1991.

Stanton, T. E., “Expansion of Concrete Through Reaction Between Cement and Aggregate,” *Proceedings of the American Society of Civil Engineers*, Vol. 66, No. 10, pp. 1781-1811, 1940.

Stark, D., “Characteristics and Utilization of Coarse Aggregates Associated with D-Cracking,” *Bulletin RD047.01P*, Portland Cement Association, Skokie, IL, 1976.

Stark, D., “Handbook for the Identification of Alkali–Silica Reactivity in Highway Structures,” *SHRP-C/FR-91-101*, Strategic Highway Research Program, Washington, DC, 1991.

Strategic Highway Research Program (SHRP), “Distress Identification Manual for the Long-Term Pavement Performance Project,” *SHRP-P-338*, Strategic Highway Research Program, Washington, DC, 1993.

Sutter, L. L., Peterson, K. R., Van Dam, T. J., Smith, K. D., and Wade, M. J., “Guidelines for Detection, Analysis, and Treatment of Materials-Related Distress in Concrete Pavements, Volume 3: Case Studies Using the Guidelines,” *FHWA-RD-01-165*, Federal Highway Administration, Washington, DC, 2002.

Touma, W., Fowler, D., Carrasquillo, R., Folliard, K. J., and Nelson, N. R., “Characterizing the Alkali-Silica Reactivity of Aggregates Using ASTM C 1293, ASTM C 1260, and Their Modifications,” *Transportation Research Record 1757*, Transportation Research Board, National Research Council, pp. 157-165, 2001.

Van Dam, T. J., Sutter, L. L., Smith, K. D., Wade, M. J., and Peterson, K. R., “Guidelines for Detection, Analysis, and Treatment of Materials-Related Distress in Concrete Pavements, Volume 1: Final Report,” *FHWA-RD-01-163*, Federal Highway Administration, Washington, DC, 2002a.

Van Dam, T. J., Sutter, L. L., Smith, K. D., Wade, M. J., and Peterson, K. R., “Guidelines for Detection, Analysis, and Treatment of Materials-Related Distress in Concrete Pavements, Volume 2: Guidelines for Description and Use,” *FHWA-RD-01-164*, Federal Highway Administration, Washington, DC, 2002b.

Winslow, D. N., “The Rate of Absorption of Aggregates,” *Cement, Concrete, and Aggregates*, Vol. 19, No. 2, pp. 154-158, 1987.

Woods, K. B., Sweet, H. S., and Shelburne, T. E., “Pavement Blowups Correlated with Source of Coarse Aggregate,” *Proceedings, Highway Research Board*, Volume 25, Highway Research Board, Washington, DC, 1945.

Yool, A. I. G., Lees, T. P., and Fried, A., “Improvements to the Methylene Blue Dye Test for Harmful Clay in Aggregates for Concrete and Mortar,” *Cement and Concrete Research*, Vol. 28, No. 10, pp. 1417-1428, 1998.