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Guide for Design and Proportioning of Concrete Mixtures for Pavements

Reported by ACI Committee 325



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Guide for Design and Proportioning of Concrete Mixtures for Pavements

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Guide for Design and Proportioning of Concrete Mixtures for Pavements

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Concrete mixtures intended for pavements have purposes and desired characteristics that are different from other types of mixtures, such as structural or mass concrete. Thus, a guide for designing concrete mixtures specific to paving, such as highways, streets, airfields, and parking lots, is necessary. This guide describes a method for designing mixtures and selecting trial mixture proportions for hydraulic-cement concrete made with and without supplementary cementitious materials, chemical admixtures, and fibers. The guide provides a method that focuses on designing the concrete mixture in the context of pavement structural design, concrete production, construction operations, and the environment in which the pavement will reside. Trial mixture proportions are for concrete consisting of normalweight aggregates and concrete with workability suitable for various types of pavement construction, such as slipform, fixed-form, and laser-guided screeding. The method provides an initial approximation of proportions intended to be analyzed to assess their performance potential for mixing, transporting, placing, screeding and

consolidating, finishing, texturing, and time-of-setting. The method also considers the hardened concrete performance parameters of strength, durability, abrasion resistance, skid resistance, smoothness, and dimensional and shape stability. Methods of checking for incompatibilities of materials in given construction environments are included, as well as methods for aggregate grading optimization. Resulting proportions should be checked by preparing and analyzing trial mixtures in the laboratory, then in the field, and adjusting as necessary to produce the desired concrete characteristics. Special concrete pavement mixtures, such as pervious concrete or roller-compacted concrete, are not included in the document. This is a dual-unit document; however, paired values stated in inch-pound and SI units are usually not exact equivalents. Therefore, either system should be used independently of the other.

Keywords: aggregate optimization; aggregates; cementitious materials; fly ash; incompatibility; intermediate aggregate; mixture proportioning; mixtures; pavements; slag cement.

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CHAPTER 1—INTRODUCTION**1.1—General**

This document is intended to be used as a supplement to **ACI 211.1**, specifically for paving concrete mixtures. **ACI 211.1** provides an in-depth discussion of concrete mixture characteristics and technology. It is unnecessary to repeat

this information within this guide. Rather, this guide will point out the concepts specific to paving mixtures that are not fully developed in **ACI 211.1**. Additionally, concepts of materials' compatibility, durability, solutions for alkali-silica and sulfate reactions, and aggregate grading optimization are more fully developed in this document. Mixtures considered in this document would be suitable as paving mixtures for airports, highways, streets, or parking lots.

1.2—Mixture design goals

The design of a concrete mixture suitable for paving includes the desired outcomes of production, construction, service life, economy, and sustainability. Material selection and mixture proportioning are the means of obtaining the goals of the mixture design, and should consider materials suitability and availability in relation with the proposed production technology and construction constraints.

Ideally, the concrete mixture design method will assist the mixture designer to (**Transtec Group, Inc. 2010**):

- (a) Identify important performance criteria that are functions of the climate, weather during construction, service conditions, and importance of the project
- (b) Identify mixture performance criteria (such as strength and durability)
- (c) Identify recommended test methods
- (d) Assess the impact of changes in weather, construction procedures, materials, and proportions on constructability and service performance
- (e) Provide methods for aggregate blending
- (f) Produce mixture proportions based on all the above
- (g) Provide mixture performance criteria optimization opportunities

A successful mixture design will meet the performance criteria of the paving contractor for: the mixture's ability to be properly mixed, transported, placed, screeded and consolidated, finished, and textured without segregation within the constraints of the proposed construction operation; schedule (including weather); production technology; and material availability. A successful mixture design will also meet the performance criteria of the owner to provide sufficient strength, durability, wear resistance, skid resistance, and dimensional and shape stability while achieving economy and sustainability. These properties are interrelated. For instance, placeability and finishability are important to the integrity of the top 1/8 in. (3 mm) of the slab surface, thus affecting resistance to freezing and thawing as well as wear resistance. To achieve all these goals, the optimal combination of materials and proportions should be provided.

The dilemma of mixture design and proportioning involves conflicting combinations of benefits and disadvantages as materials and proportions are varied. Reduction of water content will increase strength and durability while reducing shrinkage and edge slump. It may, however, negatively impact finishability and smoothness, which refers to the undulation of the concrete surface elevation, not the surface texture or skid resistance, and could reduce the ability to entrain air, thereby reducing durability. Raising the air content will improve finishability, but lower strength. Use of locally available aggregate

may be less expensive, but gap-graded or poorly-shaped material may negatively impact finishability, smoothness, and edge slump. Increased water content may increase workability and finishability, but decreases strength and durability. Material incompatibilities will further complicate the issue. The intent of this guide is to find a way through these issues and produce successful mixture designs.

Mixture design criteria taken into consideration in this guide include:

- a) Slump
- b) Air content
- c) Strength
- d) Resistance to freezing and thawing
- e) Sulfate attack
- f) Alkali-silica reaction
- g) Modulus of elasticity
- h) Thermal expansion and contraction
- i) Shrinkage
- j) Warping
- k) Curling
- l) Abrasion resistance
- m) Setting time
- n) Permeability
- o) Corrosion resistance of reinforcing steel

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

Abs	= absorption of an aggregate	$HRWRA_{adj}$	= adjustment of water requirement for use of high-range water-reducing admixture
AEA_{adj}	= adjustment of water requirement for use of air-entraining admixture	k	= regression factor
DRD_{avg}	= dry-rodded density of combined CA and IA aggregate	M_{admix}	= mass of admixture
DRD_{CA}	= dry-rodded density of coarse aggregate	$M_{admix\ water}$	= mass of water in admixture
DRD_{FA}	= dry-rodded density of fine aggregate	$M_{AEA\ water}$	= mass of water in air-entraining admixture
DRD_{IA}	= dry-rodded density of intermediate aggregate	M_{agg}	= mass of total aggregate
f_c	= compressive strength	$M_{base\ water}$	= mass of base water
f'_c	= specified compressive strength of concrete	$M_{batch\ water}$	= mass of batch water
f'_{cr}	= required average compressive strength of concrete used as the basis for selection of concrete proportions	M_{CAadj}	= mass of coarse aggregate shape water adjustment
$Fly\ ash_{adj}$	= adjustment of water requirement for use of fly ash	$M_{CA,OD}$	= mass of oven-dry coarse aggregate
G_{admix}	= specific gravity of admixture	$M_{CA,SSD}$	= mass of saturated surface-dry coarse aggregate
$G_{CA,OD}$	= oven-dry specific gravity of coarse aggregate	M_{cem}	= mass of portland cement
$G_{CA,SSD}$	= saturated surface-dry specific gravity of coarse aggregate	M_{cm}	= mass of cementitious material
G_{cem}	= specific gravity of cement	M_{FAadj}	= mass of fine aggregate shape water adjustment
G_{cm}	= specific gravity of cementitious material	$M_{FA,OD}$	= mass of oven-dry fine aggregate
$G_{FA,OD}$	= oven-dry specific gravity of fine aggregate	$M_{FA,SSD}$	= mass of saturated surface-dry fine aggregate
$G_{FA,SSD}$	= saturated surface-dry specific gravity of fine aggregate	$M_{fly\ ash}$	= mass of fly ash
$G_{fly\ ash}$	= specific gravity of fly ash	$M_{fly\ ashadj}$	= mass of fly ash water adjustment
$G_{IA,OD}$	= oven-dry specific gravity of intermediate aggregate	$M_{IA,OD}$	= mass of oven-dry intermediate aggregate
$G_{IA,SSD}$	= saturated surface-dry specific gravity of intermediate aggregate	$M_{IA,SSD}$	= mass of saturated surface-dry intermediate aggregate
G_w	= specific gravity of water	M_{SFadj}	= mass of silica fume water adjustment
		M_{slag}	= mass of slag cement
		$M_{slagadj}$	= mass of slag cement water adjustment
		M_{TCM}	= mass of total cementitious materials
		M_{water}	= mass of total design water
		$M_{WRA\ water}$	= mass of water in water-reducing admixture
		MC	= moisture content, aggregate
		N	= number of test results in a data set
		RD_{fiber}	= relative density of fibers
		S	= standard deviation of f'_c
		SCM_{adj}	= adjustment of water requirement for use of SCM
		$Slag_{adj}$	= adjustment of water requirement for use of slag cement
		V	= absolute volume of a component
		V_{admix}	= absolute volume of admixture
		V_{air}	= absolute volume of air
		$V_{CA,OD}$	= absolute volume of oven-dry coarse aggregate
		V_{cm}	= absolute volume of cementitious material
		$V_{FA,OD}$	= absolute volume of oven-dry fine aggregate
		$V_{FAvoid\ content}$	= absolute volume of fine aggregate void content
		V_{fiber}	= absolute volume of fibers
		$V_{fly\ ash}$	= absolute volume of fly ash
		$V_{IA,OD}$	= absolute volume of oven-dry intermediate aggregate
		V_p	= absolute volume of paste
		w	= water content
		WRA_{adj}	= adjustment of water requirement for use of WRA
		wt	= weight
		ρ_{water}	= density of water

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," <https://www.concrete.org/publications/terminology>

www.concrete.org/store/productdetail.aspx?ItemID=CT13. Definitions provided herein complement that source.

mass (weight)—this usage is provided as an aid to understanding for users of the U.S. customary system in which “mass” refers to pounds mass, but is often erroneously called “weight”, which is mass multiplied by the acceleration of gravity.

stress ratio—ratio of maximum applied flexural stress to modulus of rupture.

vibrator trails—localized areas of segregation characterized as mortar-rich and often with a compromised air-void system.

CHAPTER 3—BASIC PROPERTIES

3.1—Desired properties

This section presents concrete behavior that is desired during production, construction, and service life as related to specific concrete mixture properties and components. Regarding production and construction, a major factor to be considered is workability. In this document, workability includes ease of mixing, transporting, placing, screeding and consolidating, finishing, and texturing. Hardened concrete performance properties of interest include strength, durability, skid resistance, smoothness, and dimensional and shape stability (resistance to excessive warping, curling, or both). Desired properties are addressed in the mixture design phase either by being specified in the contract documents, or by a decision made by the contractor/producer. If the property is specified, then the contractor/producer should work within the specification, but may elect to further enhance the property in the mixture design. If the property is not specified, the contractor/producer may still choose to add requirements/additives for the mixture.

3.2—Workability

3.2.1 *Effects of concrete components*

3.2.1.1 *Effects of water*—A major factor affecting the workability of a concrete mixture is water content. Increasing the water content will increase the flow and compactability of the mixture, but will usually also reduce strength while increasing segregation, bleeding, and permeability (Mindess et al. 2003). Workability decreases with time as water from the mixture evaporates, is absorbed by the aggregate, and reacts with cementitious materials during the initial chemical reactions. Increases in ambient temperatures will accelerate these effects because higher temperatures increase both the evaporation and hydration rates (Mindess et al. 2003).

3.2.1.2 *Effects of aggregate*—Effects on all aspects of workability are related to aggregate particle shape and surface texture, nominal maximum size, and grading. The more rounded and smooth the aggregate, the lower the water requirement; thus, rounded river gravels and sands would be preferred in this regard. The particle shape of the fine aggregate is especially important to finishability. Increased finishability will result in less hand manipulation of the surface, producing a smoother-riding pavement, as discussed in 3.2.5 and 3.6. Regarding ease of mixing, more rounded and smoother aggregate may shorten mixing time. Also, as

aggregate becomes flatter, more elongated, or both (failing a 3:1 shape ratio requirement per ASTM D4791), issues arise regarding increased paste content. In some specifications, the recommended maximum limit of flat and elongated aggregate is 15 to 20 percent. Cubical or well-rounded particles are more mobile under vibration and flow more easily around dowel baskets, chairs, and reinforcement. Angular aggregate, such as manufactured sand, can sometimes cause the surface of the concrete to tear as the mixture moves through the paver.

A more well-graded aggregate has been shown to decrease segregation, which can cause honeycombing. For traditionally-graded mixtures, it is recommended that when coarse aggregate graded from No. 4 to 1-1/2 in. (4.75 to 38 mm) is specified, the coarse aggregates should be furnished in at least two separate sizes, with the separation at the 3/4 in. (19 mm) sieve. For No. 4 to 2 in. (4.75 to 50 mm) material, the separation should be at the 1 in. (25 mm) size. Such separation is not necessary when the specified nominal maximum size of coarse aggregate is 1 in. (25 mm) or less (MoDOT 2011). A more well-graded aggregate has been shown to increase finishability and smoothness. Being well graded, the larger particles will not lock with others because of less direct contact under vibration and finishing. Tearing of the concrete surface through the paver is associated with gap-graded mixtures, which are typically deficient in the No. 8 to No. 30 (2.36 to 0.59 mm) sizes. Coarser fine aggregates are recommended to reduce the occurrence of shrinkage cracking and joint raveling. Mixtures that are too sandy or where the fine aggregate is too fine may appear sticky.

Whether to use the traditional two-aggregate blend (coarse and fine), or to optimize the grading with three or more aggregate products, is driven by the benefits of a well-graded combined aggregate. These benefits can include the following:

- a) Enhanced finishability, leading to higher smoothness incentives
- b) Less day-to-day variability, leading to less intermittent problems of edge slump, segregation, and strength variation
- c) Less shrinkage cracking
- d) Less joint raveling

For example, MoDOT allows a 50 lb/yd³ (23 kg/m³) reduction in cement content if an optimized grading is used (MoDOT 2011).

However, potential constraints of using more than two aggregates to optimize grading should also be considered. These constraints could include, but are not limited to, economics, available stockpile space at the plant site, increased time needed for the plant to measure a batch, and increased water demand or paste content if the additional aggregate source contains deleterious materials or undesirable particle shapes. The cost of bringing in a third or fourth aggregate or blending two fine aggregates is often offset by a cement reduction or higher smoothness bonus, or less penalties for excessive cracking (USAF 1997).

The largest nominal maximum size (NMS) consistent with workability should be used to minimize shrinkage cracking and provide the most economical concrete. For aggregate systems, however, the choice of a large NMS is often

overruled by such factors as availability (for example, a 3/4 in. [19 mm] NMS may be the most readily available coarse aggregate), potential for segregation, desirability for smoothness pay factor incentive, enhancement of flexural strength, and potential for freezing-and-thawing deterioration of aggregate.

NMS of the aggregate affects production and construction operations. As with particle shape, smaller NMS will result in shorter mixing times. Slipform pavers generally have problems with placing and consolidating aggregate with NMS of 2 in. (50 mm) and greater. Tearing of the concrete surface through the paver is associated with larger NMS aggregate. As NMS decreases, there are fewer low spots produced under the finishing pan and, as NMS and the proportion of coarse aggregate increases, the potential for segregation in stockpiles or mixtures increases.

3.2.1.3 Effects of cement—Although less important to workability than other components' properties, the characteristics of the cement may also affect workability. For example, the increased specific surface area caused by cement fineness associated with Type III cements means they will have a lower workability at a given water-cementitious materials ratio (w/cm) than a Type I cement (Mindess et al. 2003).

3.2.1.4 Effects of supplementary cementitious materials—The workability of concrete is usually enhanced by the inclusion of fly ash or slag cement for several reasons. First, the specific gravity of fly ash and slag cement is typically lower than portland cement, so a 1:1 mass substitution of supplementary cementitious materials (SCMs) for cement will result in an increase in paste volume, thus increasing plasticity and cohesiveness of the mixture. If fly ash is added to increase the total cementitious content, the increase in fines can compensate for aggregate deficiency in the smaller particles—for example, coarse sand. Second, the rounded fly ash particle shape and the nature of the slag cement usually allows for a reduction in water content (ACI 211.1; Richardson 2015). The water demand can be lowered by as much as 3 to 5 percent (PCA EB001; ACPA 2003a). Although fly ash and slag cement both improve workability, fly ash has the greater effect. In hot weather, however, some fly ashes may cause early stiffening and loss of workability of the mixture, as discussed in 3.8 and 4.3. Silica fume will markedly increase the water requirement and stickiness at dosages above 5 percent by mass of cement because of the high surface area. Silica fume is not typically used in concrete for pavements, as discussed in 4.3 and 5.4. Bleeding may be reduced when SCMs with finer particles are used, especially if water demand has been lowered. Slipform low-slump mixtures with higher fines contents may not bleed, and necessitate prompt curing practices, special curing methods after finishing, or use of finishing aids.

3.2.1.5 Effects of air—Entrained air increases the paste volume while acting as a lubricant to improve the workability of concrete (Scanlon 1994). Entrained air is particularly effective in improving the workability of lean mixtures with a low cement content that otherwise might be harsh and difficult to work, and of mixtures with angular and poorly-graded aggregates (PCA EB001). Excessive amounts of entrained



Fig. 3.2.4a—Slipform paver (courtesy of GOMACO Corp.).

air, however, can make a mixture sticky and difficult to finish, may reduce concrete strength, and may increase permeability. Allowable upper limits are a function of many factors, but typically are in terms of 8.0 to 9.5 percent (ACI 211.1).

3.2.1.6 Effects of water-reducing admixtures—Water-reducing admixtures (WRAs) are used to increase workability, reduce water demand, or both, although the rate of slump loss may not be reduced, depending on the chemistry of the admixture (PCA EB001).

3.2.1.7 Effects of set-modifying admixtures—Set-retarding admixtures reduce the early rate of hardening and permit concrete to be handled and vibrated longer (Scanlon 1994; ACI 212.3R).

3.2.2 Ability to be mixed—The concrete mixture should be able to be mixed successfully with the mixing equipment intended for the project. Successful mixing entails production of a batch that is uniform throughout and achievable in a minimum amount of time. Occurrences of cement balls, clumps of fibers, rocky portions, and so forth, should be minimized. Smaller-sized rounded aggregate mixtures may not break down fiber bags as easily as other mixtures. Thus, fiber balls may appear more often. The variety of mixers that may potentially be used in a given project should be taken into consideration.

3.2.3 Transportability—Transportability is the concrete's ability to be transported from the mixer to the delivery vehicle and into the forms successfully and without harmful segregation. The mode of transportation should be considered, along with haul distance. Paving concrete for highways is hauled in dump trucks, agitator trucks, or transit truck mixers. Care should be taken to minimize segregation. Low-slump mixtures suitable for slipform paving may resist segregation, but mixtures intended for form-and-place paving may require greater slumps, which may lead to a greater risk of segregation.

3.2.4 Placeability—Placeability is the concrete's ability to be conveyed from the delivery vehicle into forms without harmful segregation. Placeability is affected by slump, which is a measure of fluidity. Slump is commonly specified in the contract documents with the inclusion of minimum/

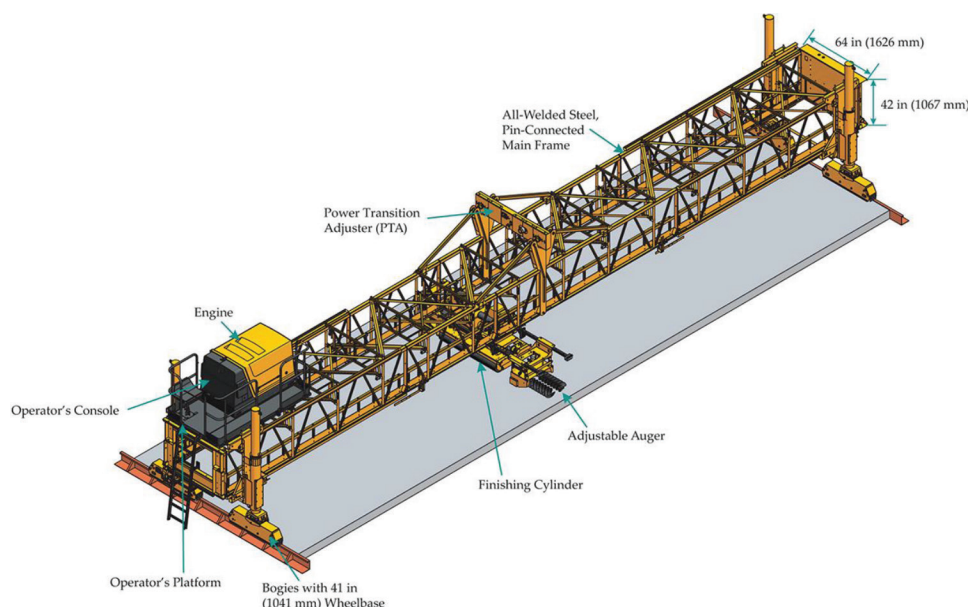


Fig. 3.2.4b—Bridge deck paver (courtesy of GOMACO Corp.).

maximum requirements. The contractor/producer then selects a slump within the specified limits as a function of placement methods. Placeability is affected by characteristics of the mixture, such as grading, particle shape, and proportions of the combined aggregate; amount and characteristics of cement and other cementitious materials; presence of entrained air and chemical admixtures; and slump of the mixture (ACI 211.1). On some paving projects, concrete is placed by pumping, which may necessitate extra care in proportioning. The mixture should be matched to the type of paving equipment. Pavers can be classified as heavy or light. Slipform pavers and some fixed (side) form pavers are heavy; other fixed form pavers, bridge truss pavers, and vibratory screeds or tube rollers would be considered relatively light. Heavy pavers (Fig. 3.2.4a) can accommodate stiffer mixtures.

Bridge deck pavers (Fig. 3.2.4b) are sometimes used for paving areas too constrained for slipform pavers. Vibrators on bridge deck pavers may allow higher vibration frequencies than desired, leading to air-void system disruption.

Lighter pavers may require more handwork, thus needing a different mortar content than slipform pavers. Vibratory screeds, vibratory roller screeds, and laser-guided screeds (Fig. 3.2.4c, 3.2.4d, and 3.2.4e) provide little or no consolidation, but can be used successfully under certain conditions such as higher-slump concrete or thinner overlays.

Internal vibration may be necessary for low-slump mixtures. Required manual strike-off, vibration, and bull floating behind the screed may bring excessive mortar to the surface and reduce entrained air near the surface. A somewhat higher slump mixture should be used when pulling slipform pavers onto and off headers to facilitate hand consolidation and finishing operations (Kohn and Tayabji 2003).

Concrete that is placed on the subgrade or base in front of the paving machine by a belt placer will be moved laterally by the machine's auger or hydraulic plow-pan (Fig. 3.2.4f).



Fig. 3.2.4c—Vibratory truss screed.

If the concrete is dumped in front of the paver by trucks, it will be moved by both the augers and possibly by the vibrators. This may lead to a loss of entrained air that may warrant increasing the initial air content. The mixture should also be resistant to segregation by these actions.

3.2.5 Ability to be screeded and consolidated—Paving concrete is spread, screeded, and consolidated by a variety of equipment types and methods such as vibratory screeds, vibratory roller screeds, laser-guided screeds, and hand screeding for small sections. Slipform and fixed-form paving equipment includes placer-spreaders and pavers (screed finishers). If the mixture is too stiff, lighter devices may tend to ride up and over the placed concrete. Surface-type screeds, such as vibratory and vibratory-roller screeds and hand strike-off, usually require a more workable mixture, typically slumps of 5 to 6 in. (125 to 150 mm). There is an interaction between the mixture stiffness and the paving equipment. For stiffer mixtures, the screed lift should be increased to enhance consolidation; less screed lift is needed for

sary for more fluid mixtures because of the tendency to surge under the screed, which results in a high surface behind it. Sometimes the paver is equipped with a tamper bar to aid in consolidation and finishing of low-slump paving mixtures. However, this action may create a mortar-rich surface that could scale or craze. To avoid problems associated with a tamper bar, mixtures that are inconsistent regarding workability should be avoided.



Fig. 3.2.4d—Vibratory roller screed (Taylor et al. 2007).

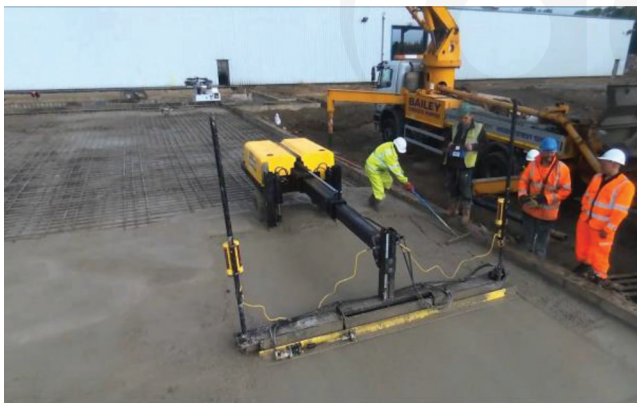


Fig. 3.2.4e—Laser-guided screed.

Concrete pavers typically consolidate the concrete by making use of vibrators. Desired density of the mixture should be achieved without undue segregation and loss of entrained air. Regarding proper vibration energy imparted to the mixture, there is a functional relationship between mixture characteristics, paver speed, pavement thickness, and head of concrete. Equipment characteristics such as vibrator rotor force, vibrator frequency and amplitude, and vibrator spacing are also interrelated with the mixture, paving operation, and slab characteristics. Thus, the mixture characteristics (such as dense-graded versus gap-graded aggregate) will affect the equipment settings and operational variables (Tayabji et al. 2012). With mechanical paving machines using gang-mounted internal vibrators, overvibration caused by excessive vibrator frequency or incorrect paver speed can result in vibrator trails resulting in localized areas of segregation characterized as mortar-rich, often with a compromised air-void system. The trails provide a plane of weakness that can result in longitudinal cracking. Additionally, trails may be low in entrained air, resulting in freezing-and-thawing damage. With surface-type screeds, overvibration could cause the coarse aggregate to sink deeper, forcing more paste to the surface, reducing abrasion resistance, potentially causing crazing and scaling, and resulting in a less durable surface. The mixture characteristics also affect the desirable vibrator frequency and spacing, which should be set correctly to achieve proper overlap of influence zones. Gaps in the zones can lead to voids in the finished pavement.

The mixture characteristics should be such that well-formed slipformed edges are achievable, but have sufficient strength and stability when freshly cast to resist edge slump (Voigt et al. 2010). A well-graded material has been shown to decrease the tendency for excessive edge slump because of increased particle-to-particle contact. Edge slump can be reduced by increasing coarse aggregate content, decreasing water content, decreasing mortar content, and using manufactured fine aggregate (Kohn and Tayabji 2003). The mixture's ability to be consolidated around all embedments and dowel types and styles, including round, elliptical, and plate dowels, should be considered.

3.2.6 Finishability—The mixture should be able to be finished successfully primarily by the action of the finishing

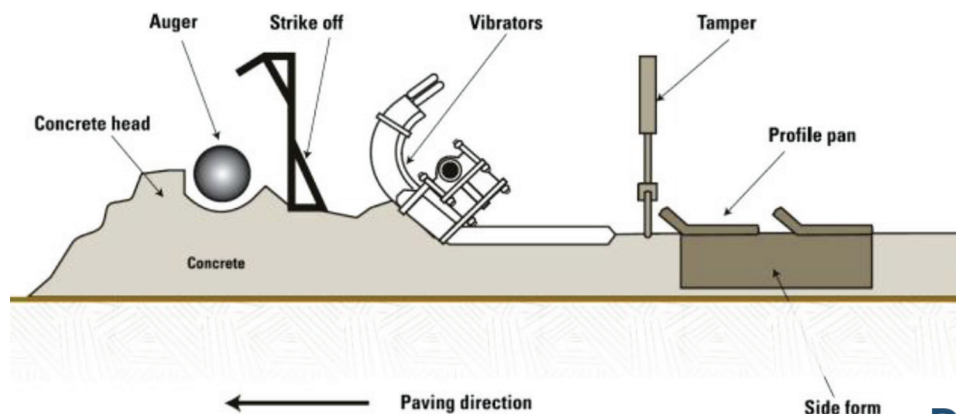


Fig. 3.2.4f—Components of typical slipform paver (Taylor et al. 2007).

equipment such as screed, strike-off plate, tamper bar, profile pan, side forms, and longitudinal mechanical floats with little or no handwork. A surface that is difficult to close may be suffering from insufficient paste or mortar or premature stiffening due to possible material incompatibility (Kohn and Tayabji 2003). Excessive working of the surface may result in a weak, nondurable surface. After screeding, or being extruded by the paving machine, the concrete surface may have to be smoothed with a bull float or a scraping straightedge. The mixture should allow all edges, tooled joints, and isolation joints to be rounded to the specified radius. For a given type of finishing equipment, the mixture should be optimized in its response to the finishing equipment. Surface depressions resulting from poor response under the pan can lead to excessive hand-working and lower durability from loss of air and perhaps an excessive w/cm at the slab surface. Longitudinal mechanical floats may pool slurry on the low edge, indicating a possible incorrect mixture (Tayabji et al. 2012). Various placing methods may dictate different mixture characteristics. Slipform pavers, fixed-form finishing equipment such as screed-finishers and finisher-floats, laser-guided screeds, vibratory roller screeds on forms, vibrating screeds on forms, and occasional handwork will call for different slumps that vary from 1 to 6 in. (25 to 150 mm). Additionally, specifications will most likely place restrictions on slump.

Mixtures containing fly ash tend to be stickier and thus more difficult to finish where high air or high fines contents are prevalent. Slag cement concrete may appear sticky, but attempting to remedy the problem with added water may lead to other problems, such as aggregate segregation at the surface, leading to reduced freezing-and-thawing resistance. Slight increases in coarse aggregate content can eliminate the stickiness issue. In mixtures containing fly ash or slag cement, bleed water at the slab surface may not form (Kohn and Tayabji 2003).

3.2.7 Ability to be textured—Surface texturing of the slab is performed on concrete that is either in the plastic or hardened state. Types of texturing associated with the plastic state are turf drag, burlap drag, brooming, and tining. Diamond grinding and diamond grooving are applied to concrete in the hardened state. The mixture should be able to respond well to the specified texturing methods. The paving train may include texturing equipment, such as a burlap drag behind the paver, a separate tining machine, or both. Burlap and artificial turf drag provides microtexture, whereas macrotexture is imparted by tining or diamond grooving. Microtexture is associated primarily with the mortar, and in the case of tining, the mortar fraction is the wearing surface; thus, the fine aggregate needs to be resistant to polishing and the mortar should be durable. The concrete characteristics will affect the operation of the tining machine. The w/cm should be low enough for the mortar to be durable, and the mixture not too wet, which would result in slumped or closed-up tining serrations or attenuated broom texture, but not too dry, which would result in rough, torn, poorly defined serration shapes; insufficient serration depths; or both. In terms of aggregate grading and mortar volume, the

mixture should be consistent batch-to-batch to achieve the desired surface consistently and to prevent the texture from excessive depth variance.

3.3—Strength

3.3.1 Flexural strength—Concrete pavements are designed against failure from either fatigue cracking or pumping at the joints. Thus, strength requirements are typically included in the contract documents. The contractor/producer may, however, require a greater strength or a greater strength gain rate to meet desired construction operations and schedules, to assure compliance in meeting minimum specified strengths, to avoid penalties for noncompliance, or to earn incentives. The characteristics of the mixture have much to do with both fatigue and erosion modes of failure. Although loads applied to pavements produce both compressive and tensile stresses, tensile stresses are more critical because heavy loads will induce stresses that may be a significant percentage of the concrete flexural strength, whereas compressive stresses remain relatively small in relation to the compressive strength. Thus, the mixture's flexural strength, or modulus of rupture (MOR), is the primary consideration in mixture design. The concrete should have sufficient strength to provide a sufficiently low stress ratio to prolong fatigue life. As flexural strength increases, the slab thickness requirement decreases. Strength is often used as a pay incentive in end-result (performance) types of specifications.

A negative result of specifying and rewarding higher flexural strength levels is that excessive strength at 28 days from high cement contents and low w/cm tend to produce concrete that increases stiffness, thereby increasing risk of cracking at early ages. Curling stresses increase due to an increased modulus of elasticity, and the ability to dissipate stresses through creep relaxation is diminished. ACI 360R cautions the designer to be careful in choosing a target strength, w/cm , or both. Additionally, higher compressive strength can decrease load-carrying capacity because of increased curling stresses (Walker and Holland 1999) and can increase stress concentration at flaws, which increases brittleness and severity of corner breaks (Ruiz et al. 2005). Some design professionals advocate specifying a modest strength, such as 650 to 700 psi (4.5 to 4.8 MPa) flexural strength (Ruiz et al. 2005), which will force thicker slabs and reduce shrinkage, warping, curling, and brittleness problems.

A major factor impacting the flexural strength of concrete is the paste-aggregate bond. The bond is affected by aggregate surface texture; unit stress at the interface of the paste and the aggregate; paste strength; and flaws at the interface that include interfering coatings, encrustations, dust, trapped bleed water, shrinkage cracks, and locally high w/cm created due to uneven mixing.

Rougher aggregate enhances bond. As particles become more angular and as nominal size aggregate (NMS) decreases, the unit stress at the interface decreases and strength increases. At constant w/cm , more angular fine aggregates have been shown to increase flexural strength. However, the resulting increased water demand and the constant slump may offset the strength gain. Cleaner aggregate

gate, in terms of both coatings and dust content, enhances flexural strength. Any characteristic of the aggregate that would lower the water demand will result in less bleed water and a lower w/cm , both of which increase bond strength.

Concrete strength is diminished by increasing air content. To achieve adequate strength, the air content should be as low as allowable while still achieving durability. A sufficient air-void system is essential for durability. In terms of bond strength, although a certain level of entrained air may be necessary for durability reasons, incompatibilities between cementitious materials and admixtures may cause the air bubbles to accumulate around aggregate particles, disrupting the bond strength (Kohn and Tayabji 2003).

Other aspects of a mixture can enhance strength. The most important is the use of as low a w/cm as practical, as discussed further in 5.4.4, perhaps accomplished by water-reducing admixtures. The specific mineralogy of certain aggregates can increase flexural strength. Optimized gradings have been shown to increase strength because less mortar is necessary to fill void space, and typically water demand is less. Finer cementitious and inert materials such as some mineral components and portland-limestone cements tend to lower bleed water and improve paste-aggregate bond strength (Shannon et al. 2015). Finally, the lower the deleterious material content, the less chance of strength being negatively impacted. Specifications limit the amount of weak and abrasion-prone aggregates such as soft chert and sandstone, shale, and highly plastic materials that can contribute to water demand. These include clay lumps, clay dust, and clay coatings.

Under certain circumstances, consideration should be given to designing for 56- or 90-day strengths instead of 28-day strength targets because of the delay in application of traffic for certain facilities. This would better use the slower strength-gaining characteristics of SCMs. The effect and timing of curing becomes more critical with slower strength-gaining mixtures. Using more fly ash and slag cement and less portland cement will generally result in lower early strengths but higher later-age strengths. At very late ages (6 months and beyond), this strength differential can be significant.

3.3.2 Compressive strength—The factors that affect compressive strength are similar to those that affect flexural strength, but some are not as important to compressive strength as they are to flexural strength. Factors that affect the bond between the aggregate and the paste tend to affect flexural strength more than compressive strength, such as aggregate surface properties, the aggregate-paste interfacial zone, and unit stress at the aggregate surface. Thus, for pavements, these factors should be viewed with an increased emphasis, as opposed to applications where compressive strength is the strength of interest. Thus, inadvertent changes in grading, aggregate source (mineralogy), w/cm , aggregate cleanliness, and deleterious material content could lead to unconservative assurance of flexural strength being achieved if compressive strength is used for quality control. Subtle changes in the mixture constituents may not significantly affect compressive strength, but can impact flexural strength, so caution should be used when using compressive strength as a crite-

rior for acceptance (Richardson and Whitwell 2015). Use of compressive strength in place of flexural strength for quality control is discussed more fully in Chapter 5.

3.3.3 Early strength—Acceleration of strength gain may be desired for fast-track construction, early opening to traffic, cold weather, or patching. Higher early strength can be achieved by provision of a lower w/cm (0.33 to 0.43), Type III cement, silica fume, accelerators, water-reducing admixtures (WRAs), high-range water-reducing admixtures (HRWRAs), and greater cement contents if necessary. Rapid-setting hydraulic cement and several proprietary cements can also be used.

Recommendations (Tayabji et al. 2012) have been made that additional cement can be used for achieving earlier strengths, such as 100 to 150 lb/yd³ (59 to 88 kg/m³) Type I or II (ACI 302.1R). Cement contents of 700 to 800 lb/yd³ (413 to 472 kg/m³) are recommended by ACI 325.11R. A survey (Van Dam et al. 2005) of state department of transportation early opening to traffic (EOT) mixtures reported cement contents of 658 to 900 lb/yd³ (392 to 534 kg/m³) for 6- to 8-hour EOT mixtures and 564 to 846 lb/yd³ (335 to 502 kg/m³) for 20- to 24-hour EOT mixtures. It is now recognized, however, that there is an optimal amount of cement that leads to maximum strength. Beyond that, strength will not increase and may actually decrease. Enhancing early strength may be at the expense of durability and long-term strength. It is difficult to achieve an adequate air-void system in mixtures containing high cement contents, low w/cm , and multiple admixtures, especially with Type III cement. A lower-quality paste may be produced because of lower homogeneity and more microcracking. These types of mixtures have resulted in freezing-and-thawing deterioration and deicer scaling (Van Dam et al. 2005). Greater cement contents will result in higher paste contents and a greater potential for shrinkage and cracking. In general, paste is also more permeable than aggregate, so increasing cement content may increase permeability, although a greater cement content that leads to a lower w/cm may offset the increased permeability to a certain extent. Designers should strive toward achieving both early strength and acceptable durability by reasonably reducing the w/cm and increasing the aggregate volume, such as through aggregate grading optimization (Van Dam et al. 2005). Types I and II cements have been used, but usually require an accelerator and a lower w/cm . Type III cement is also used; however, it may be advisable to check with users of a specific source of Type III cement that have experience with its strength-gaining characteristics. Additionally, use of finer cement such as Type III may result in a greater water demand and early setting (ACI 325.11R). Class F fly ash, slag cement, and excessive air content can reduce early strength.

It is common to use w/cm less than 0.40 for 6- to 8-hour EOT mixtures, while somewhat higher w/cm have been successful for 20- to 24-hour EOTs. The use of w/cm less than 0.40 increases the risk of autogenous shrinkage.

The use of Type A and E WRAs can enhance early strengths by lowering the quantity of water required for placing and finishing operations, especially if Type I or II cement is used. In mixtures with low w/cm and containing Type III

cement, the use of Type F HRWRA may be warranted. Accelerators, typically Types C and E, are used and are almost a necessity in 6- to 8-hour EOT mixtures (Van Dam et al. 2005). Calcium chloride is common; however, if steel is present, consideration should be given to use of a nonchloride accelerator such as calcium nitrate because of corrosion concerns (ACI 318; ACI 201.2R). Calcium chloride may also increase drying shrinkage and negatively impact the microstructure; the latter has been linked to reduced freezing-and-thawing resistance (Van Dam et al. 2005).

Typical strength-based opening criteria are as follows: 250 psi (1.7 MPa) flexural strength and 3000 psi (13.8 MPa) compressive strength for 6- to 8-hour mixtures, and 300 to 600 psi (2.1 to 4.2 MPa) flexural strength and 2500 to 3500 psi (17 to 24 MPa) compressive strength for 20- to 24-hour mixtures (Van Dam et al. 2005). The FAA (2009a) requires that construction equipment such as pavers are permitted to ride on the edge of new slabs if the MOR is equal to or greater than 400 psi (2.8 MPa). The flexural strength should be up to 550 psi (3.8 MPa) if hauling equipment is allowed to ride on new slabs.

Strength and setting time testing should be performed using a range of probable temperatures to assess the sensitivity of the mixture to temperature, enabling contingency plans for adjusting the mixture as necessary in the field. The use of maturity testing can facilitate both the mixture proportioning process and field monitoring of the placement to determine that opening strength has been achieved.

3.4—Durability

3.4.1 Freezing and thawing, deicer salt attack, sulfate, and alkali-aggregate reactions—Pavement slabs experience a variety of conditions that can cause the pavement to fail prematurely. Freezing-and-thawing damage and deicer salt attack are durability issues normally attributed to specific climate regions. The local pavement environment in which the slab resides should be taken into account during the mixture design phase of the operation. Although open-graded bases may be beneficial in reducing trapped water that can be a source of moisture contributing to freezing-and-thawing deterioration, the open texture of the base may cause other problems, as discussed in 3.7.3. Thus, the burden of frost resistance must be borne by the concrete mixture. Additionally, it is important to note whether pavement slabs in certain geologic areas have the potential for sulfate exposure and attack and whether the aggregate being used in the paving mixture has alkali-silica reaction (ASR) or alkali-carbonate reaction (ACR) potential so that an appropriate mixture design can be developed to guard against these durability issues. Both the paste and the aggregate impact the level of durability that the slab will exhibit. These four types of durability issues are typically addressed by the designer/specifier by prescriptive specification of durable paving materials, both aggregates and paste. Alternately, sometimes end-result performance specifications will require specific limits on such properties as freezing-and-thawing resistance or chloride ion penetration from deicers or saltwater spray (ACI 201.2R). Durability

is considered to be enhanced by use of mixtures that do not bleed excessively and have relatively low permeability because of reduced avenues of water penetration. Lower permeability can be accomplished by optimizing materials, reducing the w/cm , and lowering paste content.

Successful achievement of a target air content and variations in air content have been associated with changes in aggregate grading; recommendations include use of a more well-graded total aggregate and reducing variation in the No. 30 through No. 100 (0.59 through 0.15 mm) sieve size materials. Additionally, a more angular and rocky mixture will require the vibrators to run at a higher frequency, possibly reducing air content.

3.4.1.1 Freezing-and-thawing deterioration—To maximize resistance to freezing and thawing, attention should be paid to both the paste and the coarse aggregate (ACI 201.2R). The paste should be of low permeability as indicated by the rapid chloride ion permeability test (RCPT) (ASTM C1202) (Taylor et al. 2007), although the interpretation of the RCPT results should consider effects of the mixture constituents. Low w/cm and a good air-void system are critical. SCMs will help create a denser, less permeable paste. For properly air-entrained concrete, there is no significant change in freezing-and-thawing resistance of mixtures containing SCMs. Even though larger nominal size aggregate (NMS) mixtures require less water, the larger the NMS, the greater the local w/cm in the paste-aggregate interfacial transition zone, which leads to weaker and more permeable concrete (Mehta and Monteiro 2006). Paving machine vibrator trails can be associated with oversanded mixtures, poor total gradings, incorrect vibrator settings, and vibratory spacing. The trails will be composed of more paste and possibly a lower entrained-air content. This can lead to reduced durability because of the increased chances of cracking and less freezing-and-thawing resistance where vibrator trails exist.

The coarse aggregate should be sound at the NMS that is contemplated for use—that is, smaller than the critical size for aggregate freezing-and-thawing deterioration. There are many limestones, dolomites, and siliceous gravels that are subject to this problem, which is primarily the result of a deficient internal voluminous, yet fine, pore system in the coarse aggregate (ACI 201.2R). Therefore, freezing and thawing of damage-prone NMS should be reduced.

3.4.1.2 Scaling—Good scaling resistance is discussed in ACI 201.2R and comes from sufficient air content, a proper air-void system, and a reasonably low w/cm at the surface of the concrete. The mixture should be sufficiently workable and contain enough paste so that excessive efforts do not need to be made to bring paste to the surface for finishing. Mixtures prone to excessive bleeding will contribute to the likelihood of scaling. Some water-reducing admixtures (WRAs) and high-range water-reducing admixtures (HRWRAs) may entrain coarse air bubbles, which do not enhance scaling resistance. Specifications sometimes limit the use of SCMs (for example, fly ash and slag cement) because of concerns about scaling. Deicers have sometimes been found to cause greater surface mortar loss (scaling) when fly ash is used, especially at higher proportions (Rao

and Stehly 2011). Typical limits on recommended fly ash contents are discussed herein. Some laboratory studies have indicated increased scaling due to the substitution of slag cement or fly ash for portland cement, but field studies show that the use of slag cement has little effect as long as sufficient curing and drying time has been provided prior to freezing weather and the application of chemical deicers (Bouzoubaa et al. 2001; Naik et al. 2003). Because of increased potential for deicer scaling from deicer salts, ACI 318 limits SCM contents (Taylor et al. 2007). In Table 26.4.2.2(b) of ACI 318-14 are the maximum allowable limits of cement replacement for fly ash (25 percent), slag cement (50 percent), silica fume (10 percent), and total SCM (50 percent). As noted in 5.4.5.1, machine-finished high-quality concrete with a minimum of handwork with SCM contents exceeding these limits has been shown to be scaling-resistant.

3.4.1.3 Alkali aggregate reactivity—ASR or ACR is discussed in ACI 201.2R and occurs when certain aggregates react adversely to alkalis in the cement and other mixture materials or environment, plus water, to form an expansive gel on each particle that, combined with water, can cause expansive stresses. These stresses can result in polygonal (map) and other types of cracking, surface disruptions, linear expansion, and disintegration. The more common ASR can occur with reactive siliceous aggregates.

ASR-resistant mixtures are ones where ASR-prone aggregates are avoided, minimized, or the deleterious reactions are mitigated. Mitigation measures include partial cement replacement with SCMs such as low-CaO-content fly ash, slag cement or natural pozzolans, lithium-based ASR-mitigating admixtures, and low-alkali cement (less than 0.6 percent total alkalis). A detailed presentation of FHWA and AASHTO protocols are presented in 4.1.1.2. ACI 201.2R indicates that there are conflicting specifications regarding the importance of the alkali contribution of fly ash and recommended minimum cement replacement levels. Combinations of high alkali and calcium oxide contents in pozzolans are considered potentially harmful; thus, it is recommended that the pozzolan be evaluated. It may not be advisable to specify a maximum limit on alkali content of the cement because the higher alkali content would be advantageous to offset low hydration rates during cool weather or when SCMs are used (Tayabji et al. 2012). Greater cement replacement levels may be desired for certain fly ashes, but this may conflict with cool-weather concreting, where fly ash replacement is normally kept to lower levels to assist in attaining adequate early strength (Rao and Stehly 2011). Finer fly ashes tend to mitigate ASR more effectively. Modest replacement of cement with slag cement (30 to 40 percent) has often been found to be quite effective in providing effective ASR resistance without contributing to significant cool-weather concrete issues. The U.S. military uses 40 to 50 percent slag (USACE 2012).

Some dolomitic aggregates are susceptible to alkali-carbonate reactivity (ACR). Unlike ASR, there are no known mitigation strategies for ACR-susceptible aggregates and they should not be used. Section 4.1.2 should be consulted regarding AAR testing.

3.4.1.4 Sulfate attack—Sulfate in soil, groundwater, and saltwater can attack concrete paste. Sulfate attack is discussed in ACI 201.2R. Use of a sulfate-resistant cementitious system, including cements that are low in calcium aluminate, appropriate SCMs used as partial cement replacement, or both, along with attention to maximum w/cm , are the usual mitigation strategies. While Type II and Type V cements are generally preferred for concrete mixtures that will be exposed to sulfates, equivalent or greater sulfate resistance may be possible even with Type I cement when appropriate SCM replacement is incorporated. Slag cement is especially effective in this role, as greater replacement rates are possible without significant performance side effects. Both fly ash and slag cement have been shown to mitigate sulfate attack through reduction of free lime content during the pozzolanic reaction, reduction in permeability, and the dilution effect of reduction of total tricalcium aluminate (C_3A) content. Finer fly ashes tend to mitigate sulfate more effectively. Fly ashes with a high (greater than 10 percent) calcium oxide (CaO) or C_3A contents (typically found in Class C fly ashes) should be avoided (Rao and Stehly 2011). Sulfate detection and mitigation testing is discussed in 5.3.2. Mitigation strategies are included in 5.4.4.1.

3.4.1.5 Deleterious materials—Excessive deleterious materials, including shale, clay balls, and soft chert, can cause durability-related problems such as popouts, pitting, and staining. The deleterious content should not exceed local agency specified limits. In place of local jurisdictions, for airfields, Kohn and Tayabji (2003) refer to ASTM C33/C33M for civilian projects and USACE (2012) for military projects. The American Concrete Pavement Association (ACPA 2004) cautions that mixtures from portable central mixing plants can be more susceptible to clay balls because stockpiles are more likely to be placed directly on the ground, thus increasing the chance of contamination of the aggregate from the underlying soil. Excessive vibration may float lighter (deleterious) materials to the surface and increase the occurrence of popouts and pitting, even if the deleterious material content is within specification limits.

3.4.2 Abrasion resistance—Abrasion resistance usually is not explicitly specified for pavements, although abrasion should be kept in mind when selecting materials and proportions to prevent excessive wear under certain conditions, such as with parking lots at trucking facilities where the exterior pavement may be subjected to forklift traffic with hard rubber wheels and with bins being pushed across the surface, or abrasion from snow plows, studded tires, and tire chain wear. Abrasion-resistant aggregate, such as granite, traprock, and dolomitic limestone, and stronger paste are the usual components that should be used to achieve acceptable abrasion resistance. Surface hardness controls abrasion resistance. Although greater paste content generally lowers abrasion resistance, the required cementitious material content may need to be higher than for internal strength alone to reduce w/cm at the pavement surface, thus increasing abrasion resistance of the paste (Farny 2001). Well-graded aggregate and harder fine aggregate

in the larger particle sizes contribute to abrasion resistance (ACI 201.2R).

A lower fine aggregate content should be used in low-slump concrete (less than 1 in. [25 mm]) because this concrete does not normally bleed or segregate. Decreased fine aggregate contents can improve resistance to abrasion of concrete that exhibits little bleeding and segregation. Surface marring and worn-away mortar have been associated with oversanded mixtures.

At equal compressive strengths, mixtures containing SCMs generally exhibit equivalent abrasion resistance to those without SCMs. At greater SCM contents, however, strengths may not be equal and abrasion resistance may suffer. Abrasion resistance problems and scaling sometimes have been associated with concrete mixtures using higher SCM replacement rates and the use of deicer salts (3.4.1.2) or excessive vibrator energy during construction.

3.4.3 Joint spalling and raveling—Material raveling from joints can be a result of a variety of mixture-related causes. Mismatching the timing of sawing and type of sawing equipment with the mixture can result in pulling aggregate from the joint. Excessive joint spalling during service has been attributed to improper air-void systems and gap-graded aggregates, as discussed in 3.4.4 and 3.7.3 (Lafrenz 2001). A more well-graded aggregate performs better than a gap- or poorly-graded aggregate because of better constructability (USAF 1997). Air-void clustering (3.3.1) can cause poor aggregate-paste bond, which may result in aggregate dislodgement during sawing, grinding, and grooving (Tayabji et al. 2012).

Required concrete strengths for the commencement of sawing operations increase for harder aggregates to prevent raveling. Required compressive strengths range from a minimum of 260 psi (1.8 MPa) for soft, rounded coarse aggregate to 1010 psi (7.0 MPa) for hard, crushed coarse aggregate (Okomato et al. 1994). Blades should be matched to the coarse aggregate type. For softer aggregates, silicon carbide or carborundum dry-saw blades are effective, but ACI 325.11R recommends wet-saw diamond blades for hard aggregates. Harder aggregates cause faster saw blade wear and increase the tendency of the blade to ride up, thus making the saw cuts shallower (Kohn and Tayabji 2003). Harder aggregates may also increase the risk of aggregates being loosened under the action of sawing, particularly if sawing is too early, an incorrect blade is used, or the machine is not well-maintained.

3.4.4 Foreign object damage—Foreign object damage (FOD) is sometimes listed as a separate issue in airfield specifications. FOD results from objects being sucked into aircraft engines. Typical FOD results from joint cracking spalls, ASR, or freezing-and-thawing damage (Tayabji and Anderson 2007). The mixture designer should therefore try to minimize the possibility of FODs. A common problem in airfields is the issue of sliver spalling at the joints. It has been suggested that tight control of the aggregate grading using the 0.45 power curve helps to reduce the risk of this

occurring (Lafrenz 2001). Raveling at joints and deleterious materials are discussed in 3.4.1.5 and 3.4.3.

3.4.5 Calibration hardstands and power check pads—Some agencies have specifications for special applications such as calibration hardstands and power check pads. Special attention needs to be paid to the mineralogical type of aggregate used in these instances. For calibration hardstands, aggregates that contain iron oxides or iron-rich materials that have magnetic properties should be avoided. Examples include magnetite in granites, high-iron materials in trap rock, pyrite in limestone, and free iron or iron oxide in slag aggregate.

For concrete exposed to extended jet engine blast (power check pads), igneous rocks with low silica content and a large ferromagnesian mineral content or slag would be useful. Limestone and dolomite are acceptable. Aggregates high in silica such as chert, quartz, sandstone, and granite should be avoided (UFC 2004).

3.5—Skid resistance

Skid resistance is often included in contract documents. Both macrotexture and microtexture of the slab surface are important to skid resistance. Macrotexture is achieved primarily in the texturing operation, whereas microtexture is more a function of the mineralogy of the aggregate. As particles become more angular and rough, the skid resistance increases. Crushed aggregate with rough surfaces usually offers better skid resistance than rounded, smooth aggregate. Crushed silica-based aggregates often have better skid resistance retention than crushed limestones because of less polishing potential, although this is source dependent. Skid resistance requirements may necessitate the use of certain coarse aggregates with a greater acid-insoluble content (such as silica) or a natural siliceous sand as opposed to a manufactured fine aggregate made from a softer material. Angular polishing-resistant natural sands promote skid resistance even if soft limestone is used as the coarse aggregate. Some specifications limit the amount of pure limestone materials to avoid polishing.

3.6—Smoothness

Smoothness refers to the undulation of the concrete surface elevation, not the surface texture or skid resistance. Smoothness is commonly specified for certain kinds of projects, such as highways. Typically, smoothness is measured with a profilograph or a profilometer. The response of the screed to the mixture impacts smoothness; thus, the mixture should be matched to the paving equipment to achieve good smoothness numbers. More workable concrete results in enhanced smoothness.

Surface bumps and rough-riding pavements have been attributed to nonuniform concrete, possibly caused by aggregate grading and moisture content changes leading to wet and dry batches. Bumps caused by reinforcement ripple (restraint of newly-placed concrete settlement by reinforcement) can be addressed by changing to a more well-graded aggregate. Smoothness is also addressed in 3.4.1.2.

3.7—Dimensional and shape stability

3.7.1 Cracking—Cracks in pavement slabs can be the result of a variety of factors. Thermal volume changes and restrained drying shrinkage can induce prominent forces that can generate excessive axial and bending movements, resulting in stresses that exceed the tensile strength of the slab. Thermal volume changes are primarily a function of the aggregate type whereas shrinkage is dependent on paste content and characteristics as well as aggregate characteristics, such as size, gradation, and modulus of elasticity (MOE). Cracking results primarily from excessive axial or bending stresses. Harmful axial, in-plane stresses are produced in the slab as it is restrained from shortening due to drying shrinking, cooling, or both. Restraint may be caused by friction at the base. Bending stresses are caused by upward or downward curvatures of the slab, or both. Such curvatures are due to differential temperature through the thickness of the slab and due to differential shrinkage strains between the top and bottom of the slab, termed “curling” and “warping”, respectively.

Shrinkage limits are usually not specified directly for pavements, and neither are several of the factors that contribute to curling and warping, such as MOE of the aggregate, minimum nominal maximum size (NMS), or coefficient of thermal expansion (CTE). The contractor/producer may, however, elect to choose mixture proportions and materials to minimize risk of cracking.

3.7.2 Thermal volume change—Axial and bending movement from changes in temperature is directly related to the CTE of the concrete. The CTE of the aggregate has a large impact on the concrete’s CTE. The aggregate CTE is usually lower than the paste CTE. As aggregate volume increases, the impact of aggregate CTE on concrete CTE increases. Large differences between aggregate and paste CTE may lead to stress, which can lower durability. Greater concrete CTE has been linked to less resistance to temperature changes (Van Dam et al. 2005). The aggregate’s CTE is primarily a function of the mineralogical makeup of the aggregate. Pure limestones typically have a much lower CTE than silica-based gravels and, therefore, pavement made with pure limestone coarse aggregate will not exhibit as large an expansion, contraction, and curling as those made with siliceous gravels, and joint spacing can be longer. For bonded concrete overlays, problems will be reduced if the CTE of the overlay can be matched to that of the base slab (Taylor et al. 2007). High-CTE aggregate can potentially be a problem with continuously reinforced pavements as well as jointed pavements.

3.7.3 Shrinkage—Axial and bending movement from drying is directly related to the shrinkage characteristics of the mixture, which is a function of the paste content and characteristics, and the restraint from the aggregate. As nominal maximum size (NMS) decreases, paste requirements increase, increasing the potential for shrinkage. Use of 3/4 in. (19 mm) NMS under conditions where 1-1/2 in. (38 mm) NMS could have been used will increase concrete shrinkage approximately 25 percent because of the greater water demand. In addition to the water demand effect, aggregate

generally acts to control (reduce) shrinkage by restraining the shrinkage of the cement paste. Larger NMS aggregate offers more restraint. To minimize shrinkage of the cement paste, the concrete should contain the maximum practical amount of incompressible, clean aggregate. Additionally, the harder the aggregate, the greater the restraint of paste shrinkage tendencies. Higher cement contents contribute to drying, autogenous, and plastic surface shrinkage (Van Dam et al. 2005).

Coarser fine aggregates, as indicated by a greater fineness modulus (FM), have been shown to reduce volumetric shrinkage. It is desirable to reduce the percent passing the No. 50 and No. 100 (0.30 and 0.15 mm) sieve sizes of normalweight fine aggregates, especially if SCMs, finer portland cements, or greater cementitious material contents are used. Very fine sands (as indicated by a low FM) can lead to excessive water demand, shrinkage, and early cracking even though the fine aggregate may meet ASTM C33/C33M grading requirements. Some sources recommend or specify a coarser-than-typical fine aggregate FM of 2.5 to 3.4 (Kohn and Tayabji 2003; USACE 2012).

A well-graded material has been shown to decrease paste content and, in turn, suffer less shrinkage. ACI 302.1R limits the recommended percent passing on the No. 30 and No. 50 (0.59 and 0.30 mm) sieves. ACI 302.1R recognizes, however, that too little fines content could result in an increased chance of bleeding, and that the limitations on water content become increasingly important.

Regarding open-graded drainage bases, there is evidence that the mortar fraction from the fresh concrete will intrude into the base, thus increasing the bond between the base and the slab, which would restrain the panel, setting up a situation of uncontrolled shrinkage cracking if timely joint sawing is not carried out (Kohn and Tayabji 2003). Poorly-graded aggregates that are prone to exhibit excessive segregation under the action of vibration may exacerbate the problem (Lafrenz 2001).

ACI 360R lists six materials-related adverse factors that relate to shrinkage: high slump, small NMS, cement with high shrinkage characteristics, dirty or contaminated aggregate, inherently shrinkage-prone aggregate, and certain water-reducing admixtures (WRAs) and high-range water-reducing admixtures (HRWRAs) that contribute to shrinkage.

3.7.4 Plastic shrinkage cracking—Plastic shrinkage cracks are surface cracks that form when the slab surface evaporation rate exceeds the bleedwater rate, resulting in surface shrinkage and cracking. Higher cement contents and low w/cm can increase the potential for plastic shrinkage cracking (Van Dam et al. 2005). Gap-graded mixtures may require more paste that could lead to an increased risk of plastic shrinkage cracks (PCA EB001; Taylor et al. 2007; ACPA 2003c).

During high evaporation conditions, delayed set due to SCM substitution for cement may increase the probability of plastic shrinkage cracking. SCMs that tend to reduce bleeding may further aggravate plastic shrinkage cracking. Lower water demand contributions of SCMs may be benefi-

cial, however, if proper curing is provided (Rao and Stehly 2011).

3.7.5 Joint spacing—During the pavement design, transverse contraction joint spacing is specified. The spacing is a function of allowable joint opening and the likelihood of midpanel cracks, which are somewhat a function of concrete characteristics: MOE, CTE, coefficient of shrinkage, and density. These properties primarily are dependent on the aggregate's MOE, CTE, specific gravity, and the mixture's shrinkage tendency. Joint spacing can be increased as mixture shrinkage tendency decreases (NMS increases, water content decreases, aggregate volume increases). Joint spacing can also be increased as the thermal contraction tendency decreases (CTE of the aggregate decreases) and curling stress decreases (MOE decreases).

3.7.6 Load transfer—Longer panel lengths mean wider joint openings, so unless load transfer features such as dowels are used, enhanced aggregate interlock will be necessary at the joints for adequate load transfer. Therefore, use of a larger NMS, a more angular coarse aggregate particle shape, and more abrasion-resistant coarse aggregate will contribute to better load transfer. Abrasion-resistant coarse aggregate, such as a siliceous gravel with lower Los Angeles Abrasion (LAA) will suffer lower loss of aggregate interlock with repeated loadings. There is an offsetting set of circumstances (abrasion resistance versus shape) regarding evaluation of crushed limestone versus hard river gravel (Taylor et al. 2007; Ruiz et al. 2005; ACI 201.2R). For greater truck traffic volumes, dowels are necessary for effective load transfer. When dowel bar inserters are used, dowel misalignment has been attributed to gap-graded mixtures.

3.8—Time of setting

Proper setting time of the concrete is desired to prevent problems of delayed sawing and texturing and early-age cracking. Setting time is affected by many factors, such as fineness and chemistry of the cement, type and amount of SCMs, amount of cement and water, w/cm , various admixtures, and temperature.

If fly ash or slag cement is substituted for cement, the time of setting typically will be extended, but this will be dependent on temperature conditions, SCM and portland cement characteristics, and percentage of SCM replacement. At 73°F (23°C), mixtures with greater than 25 percent slag cement may extend set 1 to 3 hours; at 85°F (29°C), the effect on set time is negligible (ACPA 2003a). Reduction of substitution levels of SCMs may be warranted in cooler weather unless the SCM is being used to mitigate alkali-silica reaction (ASR), sulfate attack, or both.

Setting delays caused by SCMs can lead to problems with texturing and joint sawing. Retardation may also contribute to plastic shrinkage cracking and cracking before sawing (Hanna et al. 2010). Early-age cracking has sometimes been traced to material incompatibility and associated delayed set, but it can also be driven by any influence that results in delayed set, including normal SCM interaction. To avoid early-age cracking, it is recommended to reduce fly ash or slag cement in cool weather conditions if it will not compro-

mise the ASR and sulfate resistance of the concrete (for example, SCM content should be a 30 percent maximum for temperatures less than 55°F [15°C]) (Tayabji et al. 2012). A consequence of delayed set is cracking; shorter sawing windows increase the risk of uncontrolled cracking (Kohn and Tayabji 2003). Whenever such influences tend to delay setting and joint sawing, special attention should be given to timely and effective curing so that early shrinkage is minimized. It is not uncommon in some cases that incompatibility may cause slump loss and early stiffening, which may complicate consolidation in the pavement. Caution should be used in attempting to overvibrate a mixture exhibiting early stiffening, as this can lead to a loss of entrained air. With increasing emphasis on SCM use in paving concrete, incompatibility of materials has been more frequently experienced and the potential warrants caution. Such incompatibility is most commonly associated with Class C fly ash, but may also be influenced by higher temperatures and certain water-reducing admixtures. It is driven by insufficient levels of calcium sulfate, or gypsum (which is contributed entirely by the portland or blended cement), in the fresh concrete mixture for the specific materials combination and conditions. Related performance trends are typically slump loss, set retardation, and poor early strength gain. In extreme cases, flash set is possible. These issues are more likely or more extreme in hot weather. Evaluation of incompatibility potential should be done with trials at the highest envisioned project temperatures. Mitigation of such tendencies may include reduced fly ash replacement; reduced water-reducing admixture dosage; or changing the type of fly ash, water-reducing admixture, or both. The composition and dosage of various water reducers can exacerbate problems with early stiffening, delayed set, slow strength gain, or all of these.

3.9—Basic properties and considerations

Overall economic comparisons of alternate mixtures entail material as well as construction costs. Concrete material costs are a function of component unit costs and proportions. Natural, unprocessed aggregates such as gravel are usually less expensive than crushed aggregates. There are also cost savings in the use of SCMs as a replacement of the more expensive portland cement. Additionally, reductions of total cementitious content may be possible with good quality control and consistency of strength performance (low strength standard deviations). Well-graded aggregates may require less paste in the mixture, which would lead to a more economical design. However, there is a trade-off when comparing the cost of bringing in a third aggregate versus the cost of extra cementitious materials in the traditional two-aggregate mixtures. There are economic advantages of optimized gradations regarding increased smoothness incentives, fewer construction problems, and lower life-cycle costs (ACI 365.1R).

3.10—Sustainability

Regarding mixture design, sustainability usually refers to using concrete products that produce a smaller carbon footprint over the pavement's life cycle. This typically entails

using concrete that contains less portland cement clinker by using reduced total cementitious content, increasing the percent cement replaced with supplementary cementitious materials (SCMs), and increasing durability to achieve longer pavement life (Van Dam and Taylor 2009). The use of ASTM C595/C595M blended cements, including portland-limestone cement, is an excellent way to reduce the portland cement clinker content of the cementitious materials. The materials used in making paving concrete have a significant impact on the sustainability of the pavement. The cementitious materials have the largest environmental impact, emphasizing the need to use the appropriate amount of cementing materials, reducing unwarranted cement through good mixture design and the use of SCMs, as well as recycled and industrial by-product materials used as aggregate. Slag cement and fly ash are the SCMs most commonly used in pavements in the United States. It is possible, but not common, to consider the use of silica fume, metakaolin, and ultra-fine fly ash for special applications, although careful attention will be required to control the risk of early-age cracking.

Manufacturing portland cement is an energy-intensive process that involves heating large quantities of finely ground rocks and minerals to very high temperatures to produce clinker that is then interground with gypsum to a fine powder. The carbon dioxide (CO₂) burden is high because the process includes decomposing calcium carbonate (CaCO₃) rock into calcium oxide (CaO) and CO₂. Roughly half of the CO₂ generated in clinker production comes from this source, and the proportion is increasing as manufacturers make their process more energy efficient (Van Dam and Taylor 2009). Although it is estimated that the global impact of cement manufacturing on the release of CO₂ is approximately 4.5 percent (Tayabji et al. 2012), the burdens can be reduced by any combination of the following:

- a) Reduction of the energy and greenhouse gas emissions associated with portland cement clinker production
- b) Reduction of the amount of portland cement clinker in the cement
- c) Reduction of the amount of cement in the concrete mixture
- d) Use of less concrete in a pavement over the life cycle

Portland-limestone cements (ASTM C595/C595M Type IL), which can have up to 15 percent pure limestone interground with the clinker, improve concrete mixture sustainability by lowering the clinker content and the CO₂ footprint and energy content of the cement without detracting from performance or adding to mixture costs. They can be used similarly to ordinary portland cements, in combination with other cementitious materials and admixtures, without operational distinction (Cost et al. 2013a).

Most SCMs used in the United States are by-products from other industries (for example, fly ash is produced from the burning of coal to produce electricity and slag cement is a by-product of pig iron production) that beneficially react with portland cement to enhance the performance of concrete. The effective use of SCMs not only reduces the amount of portland cement required, it also reduces the need to dispose of what otherwise would be industrial waste.

There is increased interest in recycling concrete and other construction waste for use as aggregates in paving concrete and supporting layers. This is beneficial because it reduces the demand for virgin aggregates and reduces the need to place the waste materials into landfills. If recycled materials are used in concrete, the mixtures have to be proportioned and tested in the laboratory to ensure that setting times and strengths are satisfactory. Consideration should also be given to why the original pavement failed. Recycled concrete aggregate containing alkali-reactive aggregates or those prone to freezing-and-thawing damage may not be advisable for use in paving concrete unless the distress is mitigated in the new concrete.

The amount of mixture water in paving concrete is primarily governed by the *w/cm* and paste requirement of the aggregate system, and the type and dosage of the chemical admixtures in use. The presence of SCMs will normally reduce the amount of water needed for a given cementitious content. Therefore, choosing a good aggregate system, reducing the cementitious content (within limits), and using water-reducing admixtures will help to reduce the amount of water required to achieve a given workability.

Ideally, a concrete paving mixture will use an optimized combined aggregate grading that minimizes the voids and the paste requirement, resulting in minimal cement and water required. Aggregates should be resistant to the environment and not prone to freezing-and-thawing damage, alkali-silica reaction (ASR), or alkali-carbonate reaction (ACR). The quality of the paste, including the cement type, SCMs, *w/cm*, and air-void system, should be selected based on the environment to which the mixture will be exposed (ACI 201.2R).

3.11—Innovative methods and materials

3.11.1 Innovative methods—Several innovative methods for concrete pavement mixture design and for aggregate grading characterization are in the process of being developed. Recently, the established concept of considering the total aggregate gradation as represented on the individual percent retained curve has been enhanced by use of the so-called tarantula curve (Ley and Cook 2014). Although not widely adopted yet, the concept is being evaluated by industry (Taylor and Fick 2015). Regarding mixture proportioning, a new method has been developed by the Concrete Pavement Tech Center (Taylor et al. 2015) based on the work of Koehler and Fowler (2006). As experience is gained, these methods may become more established in the industry.

3.11.2 Innovative materials—Many promising materials for use in concrete pavement mixtures are being advanced. Several are discussed in this guide: portland-limestone cement (3.3.1, 3.10, 4.4, and 4.5) and lightweight aggregate (4.1.2). Others include various powder additives for enhancing the properties or mitigating problems of high-volume fly ash mixtures (Bentz 2010; Bentz et al. 2010; Richardson et al. 2015). As these technologies mature, their use may become more commonplace.

CHAPTER 4—MATERIALS

4.1—Aggregate

4.1.1 General—Aggregate properties as they relate to desired concrete behavior are presented in [Chapter 3](#). Aggregate should be examined for the potential of freezing and thawing deterioration and alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR) behavior.

4.1.1.1 Testing freezing-and-thawing resistance of aggregate—There are many test methods that address freezing-and-thawing deterioration, such as [ASTM C666/C666M](#). The method involves the testing of concrete; however, it is commonly used as an aggregate durability test by using a durable paste, leaving only the aggregate durability as a variable. ASTM C666/C666M is considered one of the primary test methods in use; however, it is important to know which option (Procedure A or B) is being specified by the agency because the results are different. Unfortunately, testing time for ASTM C666/C666M is 2 to 3 months and equipment is expensive. Numerous tests of aggregate by itself have been used by a variety of agencies to screen or help predict the possibility of proneness to freezing-and-thawing behavior ([Richardson and Lusher 2014](#)). Local agency test methods and specifications should be reviewed. Mitigation primarily consists of reducing the aggregate nominal maximum size (NMS) to less than the critical size for freezing-and-thawing behavior, as determined by testing.

4.1.1.2 Testing alkali-aggregate reactivity—For alkali-aggregate reactive (AAR) aggregate, [AASHTO PP 65](#), based on FHWA protocols ([Thomas et al. 2008](#)), provides a detailed procedure to identify and mitigate reactive aggregates and their harmful behavior. [ASTM C1778](#) is similar to AASHTO PP 65. The process involves two major steps: the first is to determine whether the aggregate is reactive and, if so, whether it is of the ACR or ASR variety. If it is ACR, use of the aggregate should be avoided. If it is ASR, Step 2 includes methods to deal with the aggregate. Two alternate methods are offered to determine preventative measures by: 1) testing cement replacement levels using various supplementary cementitious materials (SCMs) or by varying lithium nitrate admixture levels; or 2) following a prescriptive method that involves determination of level of reactivity, level of risk, level of required prevention (based on the type of structure and acceptable risk), and level of SCMs or maximum allowable alkali content of the concrete.

Determination of whether the aggregate is reactive or not can involve examining past histories of the aggregate, which includes viewing existing structures, searching for mixture design information, and coring the structures for verification purposes. Despite all this effort, the value of the history of the aggregate hinges on the characteristics of the cement used in the past versus what is being proposed: these should match. If not, testing will be required anyway. Petrographic examination ([ASTM C295/C295M](#)) is also recommended. Expansion testing, however, will offer a more definitive answer, but is somewhat demanding in effort and time. [ASTM C1260](#) mortar-bar expansion testing should be used for screening purposes. If expansion is greater than or equal

to 0.10 percent at 14 days, either [ASTM C1293](#) can be used for verification (1-year duration), or the AASHTO method allows moving right into mitigation strategies without having to resort to ASTM C1293. Expansion exceeding 0.04 percent at 1 year in the ASTM C1293 test is considered potentially reactive. ASTM C1293 is considered a better predictor, but the long test duration is an issue. Once mitigation is indicated, either the 14-day [ASTM C1567](#) (a modified form of ASTM C1260) or a 2-year ASTM C1293 can be used with varying types and replacement levels of SCMs or lithium nitrate being evaluated. Some agencies choose to modify the test duration for either ASTM C1260, ASTM C1567, or both. The FAA uses 28 days and the military uses less than 0.08 percent expansion at 28 days for ASTM C1260 and ASTM C1567 ([USACE 2012](#)).

Alternately, instead of direct mitigation testing, a series of tables can be used in the AASHTO PP 65 prescriptive method to arrive at recommended SCM or limited alkali loading treatments. The prescriptive method includes the concepts of the importance of the level of aggregate reactivity (nonreactive to very highly reactive), ASR risk (six levels based on level of reactivity and structure size and exposure conditions: dry, humid, buried, exposed to alkali), and level of required prevention (six levels based on level of risk and classification of structure—that is, severity of consequences to ASR damage). Knowledge of the required prevention level steers the designer into allowable levels of alkali of the concrete (four levels), minimum percentages of low-CaO content fly ash (15 to 40 percent), or both; slag cement (25 to 65 percent); or silica fume (minimum 7 percent). There are choices to be made regarding the mixture throughout the process; thus, the designer needs to be aware of and familiar with the AASHTO procedure protocols, which should be consulted if applicable.

4.1.2 Internal curing—Internal curing (IC) refers to the inclusion of prewetted lightweight aggregate (LWA) in the mixture that functions as a source of moisture for increasing hydration of the cementitious materials. The substitution of a portion of normalweight aggregate with saturated LWA can reduce cracking from autogenous shrinkage and mitigate plastic shrinkage cracking ([Henkensiefken et al. 2010](#)). Conclusions from a report by [Rao and Darter \(2013\)](#) indicate that effects of IC could potentially include a 5 percent reduction in unit weight, 5 percent reduction in modulus of elasticity (MOE), 5 percent increase in flexural strength, 5 to 10 percent reduction in coefficient of thermal expansion (CTE), and a reduction in shrinkage, all of which could lead to improved fatigue resistance and better control of shrinkage crack (joint) openings. A 10 percent reduction in permeability is typical and could lead to enhanced joint deterioration resistance. Reduction in upward curling would be beneficial but has not been fully documented yet for pavements. A cumulative effect of the preceding benefits could lead to longer service lives. Saturation is mandatory and will require constant stockpile wetting, turning, and monitoring. Increased materials and handling costs would have to be compared to either reduced design thickness or decreased service life cost. If not used, additional laboratory testing will be required. Proper-

tions can be established by procedures as presented in [ASTM C1761/C1761M](#). Additionally, the ESCSI has guidelines for proportioning the LWA portion of the mixture's fine aggregate content ([ESCSI 2012](#); [Delatte et al. 2007](#); [ACI \(308-213\)R](#); [Rao and Darter 2013](#)).

IC is a relatively new development and shows promise. It has been used in structural applications; however, for pavements, it has been limited to applied research and demonstration projects. The most recent summary published by Rao and Darter (2013) of all known IC pavement projects include one freeway, one off-ramp, one intermodal terminal, and some residential and collector streets, all in the Dallas/Ft. Worth, TX, area. The pavement ages were relatively young, 1 to 8 years old. IC concrete is not considered as a state-of-the-practice for routine paving mixture design and has only been used on a few concrete paving projects in the United States. Thus, proportioning concepts of internal curing for pavements are not included in this guide.

4.2—Portland cement

The effects of portland cement on mixture and slab performance are discussed in 3.2, 3.3, 3.4, 3.8, and 3.10. The w/cm is the primary factor that controls strength and permeability. Typically, [ASTM C150/C150M](#) Types I and II are used in paving mixtures in the United States. Some cements are marketed with a combined type classification, such as Type I/II, indicating that the cement meets the requirements of the indicated types and is being offered as suitable for use when either type is desired ([ASTM C150/C150M](#)). Type II cement is a moderate sulfate-resistant, moderate heat-of-hydration portland cement. The finer Type III cement is used for increasing reaction rates for fast-track construction, patching, or for cooler weather. The choice of type of cement impacts strength-gain rates. Finer cements tend to react more quickly, but often increase water demand, thus resulting in greater shrinkage potential ([Taylor et al. 2007](#)).

The availability of a given cement type in a particular geographic location should be verified before it is specified for use on a project.

4.3—Supplementary cementitious materials

4.3.1 General—Supplementary cementitious materials (SCMs) such as fly ash, slag cement, and natural pozzolans can be blended at the cement plant to create [ASTM C595/C595M](#) blended cements or added separately at the concrete plant. Blended cements are discussed in 4.4. Silica fume, a common SCM used for high-performance concrete applications, is not normally used in paving because of loss of workability and cost ([Taylor et al. 2007](#)). It has been suggested that only fly ash and slag cement be used in paving applications ([Tayabji et al. 2012](#)), although natural pozzolans have been used. Certain military specifications, however, allow the use of silica fume in overseas projects. Silica fume is only allowed on Department of Defense (DOD) projects outside the continental United States where Class F fly ash and slag cement are not available. Silica fume should conform to [ASTM C1240](#) and the optional testing for reactivity with cement alkalis should also be completed. Silica

fume can be provided either as a dry, densified bulk material or as a slurry. Typical silica fume contents range from 7 to 10 percent unless a prescribed amount is required to mitigate alkali-silica reactivity (ASR). For military airfield pavement construction, a high-range-water reducer ([ASTM C494/C494M](#), Type F or G) is allowed when silica fume is used. It is recommended that a knowledgeable admixture manufacturer's representative be on site for the first 4 days of concrete production and placement when silica fume mixtures are used ([USACE 2012](#)). The use of natural pozzolans, such as metakaolin, is not common in pavements constructed in the United States ([UFC 2004](#); [Delatte 2008](#)) due to a relatively abundant supply of acceptable fly ash and slag cement. Yet, in many other countries around the world, almost all concrete pavements are made with blended cements containing natural pozzolans. More information can be found in [ACI 232.2R](#).

The benefits of SCM replacements of portland cement during construction are improved workability (including finishability if fine aggregates are harsh), lower vibrator energy requirements, lower water demand, and reduction in temperature rise. Benefits post-construction include increased long-term strength, reduced permeability, increased resistance to sulfate attack, mitigation of excessive expansion due to ASR, delayed set time, reduced thermal stresses in early-age concrete, and reduced cost. The [FAA \(2009a\)](#) allows the use of slag cement and fly ash at the contractor's discretion ([Rao and Stehly 2011](#)). The delayed set and reduced shrinkage aspects common of mixtures containing SCMs can reduce frictional drag stresses in slabs built on high-friction bases. At 25 percent and higher replacement rates, however, Class F fly ash may not gain strength quickly enough to allow joint sawing before shrinkage cracking commences ([Tayabji et al. 2012](#)).

Both Class F and C fly ashes are pozzolanic, while Class C may also be slightly cementitious due to its normally higher calcium content ([ACI 232.2R](#)). Class C ash may have higher aluminate and alkali contents, however, and may be more prone to premature stiffening and thermal cracking while being less sulfate resistant and less beneficial in controlling ASR. In most cases, it is not recommended that a Class C fly ash be used in mixtures designed to combat ASR, and it is not permitted to be used to mitigate sulfate attack, as it has the potential to make the concrete even more susceptible to this chemical attack ([ACI 201.2R](#)). Other issues include problems with finishing, rapid set, poor strength gain, reduced air content, increased risk of incompatibility, and increased potential for scaling. Class F fly ash is considered the more effective fly ash for controlling heat, ASR, and sulfate attack ([Kohn and Tayabji 2003](#); [Rao and Stehly 2011](#)), and slag cement may be equally or even more effective. Class C fly ash will usually delay setting time, although it has been known to cause severe acceleration. Because of the spherical shape of fly ash particles, mixtures that use it as a partial replacement of portland cement generally have a slightly lower water demand.

4.3.2 Testing for compatibility of cementitious materials, admixtures, and temperature—The compatibility of concrete

mixture components can take the form of unusual stiffening and setting, cracking, poor early strength gain, and inadequate air-void systems. Regarding the first three issues, to be compatible, mixtures need to strike the right balance of sulfate and aluminate, and calcium and silicates. The planned sources of portland cement, fly ash, slag cement, and admixtures should be subjected to a compatibility evaluation, especially if the cement source or chemical admixtures to be used are unfamiliar, Class C fly ash replacement of cement is to be used, or both. It is important to include some higher-than-expected admixture dosages and SCM replacement rates, and to test the mixtures at the highest field concrete temperature expected. Because it may be necessary to evaluate various combinations and proportions, laboratory testing of paste or mortar of the same proportions as those of parallel concrete mixtures but without aggregates may be a convenient and time-saving approach, rather than actual concrete mixtures. Such testing also allows rapid comparative evaluation of different candidate admixtures, SCMs, or cements. Specific tests that may be useful include isothermal calorimetry (ASTM C1679) or semi-adiabatic calorimetry, mortar cube strength testing (ASTM C109/C109M), mini-slump testing or various setting time tests, or simple thermal profile testing. Repeated tests with added sources of calcium sulfate can easily confirm any apparent incompatibility tendencies in initial mixtures (Cost and Knight 2007; Roberts and Taylor 2007; Cost and Gardiner 2009; Richardson et al. 2015).

Cements from different sources that all meet specifications may have subtle differences that can affect the concrete mixture performance significantly. The same can be said for SCMs and admixtures. Thus, once materials have been proven to be compatible, the job specifications should prohibit source changes unless compatibility of the changed source is verified.

4.3.3 Matching fly ash to project requirements—A compatibility evaluation of the actual project materials and proportions (portland cement, SCMs, and admixtures) should be done (4.3.2). The prequalification exercise should begin with a review of the mill certifications of the cementitious materials with an eye toward the goals of the design (for example, ASR mitigation, early strength, and sulfate resistance), and incompatibility issues.

In choosing a fly ash replacement level, the effect on other properties should be considered. For instance, if a high replacement level is required to combat ASR, lower early strengths may be the result; thus, offsetting strategies will have to be employed, such as use of an accelerator, lower w/cm , or choice of a finer fly ash with a low loss on ignition (LOI). The particle size distribution of fly ash is important to reactivity and water demand. Particles smaller than 10 μm are considered pozzolanic; particles greater than 45 μm (No. 325 sieve) are not. Also, particles smaller than 45 μm (No. 325 sieve) are effective in reducing water demand. ASTM C618 places a maximum limit of 34 percent retained on the 45 μm (No. 325 sieve) size. There is usually no particle size distribution given in specifications or mill reports (Rao and Stehly 2011).

Rao and Stehly (2011) present a method for working through the process of choosing a replacement level of fly ash. The interactions between ASR reactivity, deicers, cement alkali content, requirements for early opening strength, weather during placement, characteristics of the fly ash, and recommended curing regime are considered. The steps are shown in Fig. 4.3.3. Recent research has cast doubt on the link between potassium acetate deicers and ASR, but the rest of the fly ash implementation evaluation methodology is still very useful.

Recommended testing includes slump, air content, concrete setting time, bleeding, strength, air voids, rapid freezing and thawing, scaling resistance, and ASR potential, as appropriate. The final choice of fly ash replacement level should be based on the following:

- a) Maximum fly ash content that exceeds strength requirement
- b) Maximum fly ash content that has acceptable setting time
- c) Maximum fly ash content that still provides adequate freezing and thawing and scaling durability
- d) Minimum fly ash content that limits 14-day mortar bar expansion below 0.1 percent when tested in a non-deicer environment

Risk of sulfate attack is discussed in 5.3.2 and mitigation strategies are presented in 5.4.4.1.

4.3.4 Matching other SCMs to project requirements—A process of optimizing slag cement replacement levels would be similar, except that typical rates are notably higher. Increasing use of systems containing multiple SCMs is being reported, and may offer certain advantages in many areas. These combinations may include multiple separately-batched components or blended cements with additionally batched components.

4.4—Blended cement

Many blended cements are used in pavement construction interchangeably with ASTM C150/C150M Type I or Type II cements, depending on the type and amount of supplementary cementitious material (SCM) used. Blended cements are produced by intergrinding or blending two or more fine materials, such as portland cement and one or more SCMs, limestone, or both. Blended cements specified under ASTM C595/C595M are classified as portland-slag cement (Type IS), portland-pozzolan cement (Type IP), portland-limestone cement (Type IL), and ternary blended cement (Type IT). Type IT contains any combination of two additional materials (slag cement, pozzolan, and limestone). The use of blended cements, rather than adding separate cementitious components at the concrete plant, can potentially help prevent incompatibility problems because the cement manufacturer is able to optimize calcium sulfate content more effectively for the specific combination of materials (Taylor et al. 2007). Type IL portland-limestone cements may contain 5 to 15 percent interground limestone and are manufactured to perform similarly to Type I and II portland cements manufactured at the same plant. They also interact favorably with typical SCMs due to secondary hydration reactions.

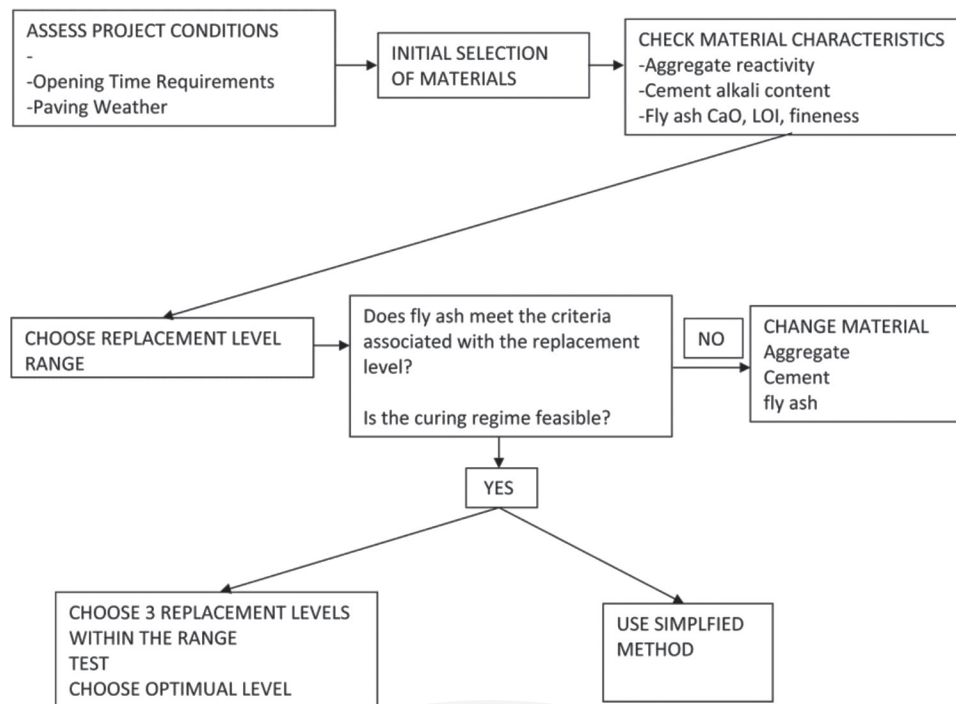


Fig. 4.3.3—Fly ash replacement flowchart.

carboaluminates (Cost et al. 2013b). Long-term durability has been researched (Thomas and Hooton 2010).

4.5—Water

4.5.1 General—Water should be free of substances that would interfere with the hydration of the cementitious materials. Normally, potable water is considered acceptable by default. Nonpotable water should be tested for deleterious effects on the strength and setting characteristics of the mixture, as per ACI 318.

4.5.2 Testing—Nonpotable water should be tested in accordance with ASTM C1602/C1602M, which involves testing concrete or mortar for strength and setting time problems. Optionally, limits on chloride, sulfate, alkalis, and total solids may be specified. Concrete mixer and plant wash water and stormwater runoff should be tested for density to determine frequencies of testing.

4.6—Chemical admixtures

4.6.1 General—Chemical admixtures for paving include water reducers, retarders, accelerators, air-entrainers, and viscosity modifiers. Adding chemical admixtures may help concrete mixture designers achieve desired concrete properties more efficiently or economically than adjusting other ingredients or mixture proportions. Admixtures are also used to maintain specific properties during concreting operations or under unusual conditions (ACI 212.3R). However, admixtures should not be used as a substitute for good concrete practice. They should be used to enhance good concrete, not to fix bad concrete. Chemical admixtures may have unintended side effects that need to be accommodated. An admixture's effectiveness depends on many mixture factors, including cementitious materials properties, water content,

aggregate properties, concrete materials proportions, mixing time and intensity, and temperature. In the case of multiple admixtures in the same mixture, incompatibility issues can be avoided by use of admixtures from the same manufacturer (Kohn and Tayabji 2003) with related experienced-based guidance. The following items present the use of admixtures that are commonly used in pavement mixtures.

4.6.2 Water-reducing admixtures—Water-reducing admixtures (WRAs) are used in paving concrete for a variety of reasons, including increasing strength by reducing the water necessary to achieve the desired slump, and improving workability, especially for fixed-form paving and areas of handwork. Strength can be increased up to 10 percent for concrete of equal w/cm , cement content, or slump (Taylor et al. 2007). Normal WRAs, ASTM C494/C494M Type A and water-reducing and retarding admixtures, Type D, in the past have been the predominant types of WRAs used in paving concrete. However, mid-range water-reducing admixtures (MRWRA) have gained wide acceptance in the concrete industry. Although MRWRA is not a category in ASTM C494/C494M, this type of admixture can meet ASTM C494/C494M Type A, B, and D, or Type F, depending on the dosage rate. High-range water-reducing admixtures (HRWRAs) Type F and G are not normally used in paving because of the difficulty in controlling the low slump required for slip-form paving and because of potential higher cost, and are prohibited in certain specifications (USAF 1997). HRWRAs are typically used in high-volume fiber concretes and are used to provide workability in low- w/cm high-early-strength mixtures. HRWRA (polycarboxylate) technology has been used on some airport and highway paving projects. With all low-slump concrete mixtures, knowing the moisture conditions (content) of the aggregate is important. When dealing

with low-slump concrete using HRWRAs, the moisture content of the aggregate is even more critical.

WRAs can accelerate aluminate reactions in the cementitious system, aggravating the potential for incompatibility-related behaviors (related discussion in 4.3.2). In mixtures that already have marginal cementitious material sulfate systems, WRAs containing lignosulfonate, triethanolamine, or both, may result in early stiffening (Kohn and Tayabji 2003). Retardation effects associated with certain WRAs (notably Type D but occasionally others) may be somewhat variable with changes in concrete temperature and may complicate finishing and joint sawing or increase the likelihood of plastic shrinkage cracking and the severity of drying shrinkage cracking if the concrete surface is not protected from premature drying. Lastly, studies suggest that some WRAs may negatively influence the characteristics of the air-void system (Attiogbe et al. 1992; Freeman 2012).

4.6.3 Retarding admixtures—Retarders (Types B and D) extend the dormancy period, and heat generation may be delayed, extended, or both, yet ultimate strength is usually increased. Retarders can be useful for avoiding problems associated with long transport times. Bleeding rate and bleeding capacity are increased. In hot weather, excessive retardation can result in slab cracking due to drying and shrinkage that occurs before the slab has gained enough strength to allow the initiation of joint sawing (Kohn and Tayabji 2003).

4.6.4 Accelerating admixtures—Accelerators (Types C and E) shorten the dormancy period, therefore setting occurs earlier, along with a steeper hydration curve and more rapid release of heat of hydration. Therefore, accelerators permit earlier finishing, earlier removal of forms, earlier opening to traffic, and reduction of time of protection against freezing, but all things equal, will have lower ultimate strength. Accelerators are useful for situations involving fast-track construction, such as intersection rehabilitation, patching, and cold weather. Accelerators have been recommended to prevent early-age cracking in cold weather. An excess may cause cracking before finishing or sawing is complete. Calcium chloride is the most common accelerator, but there are issues of reinforcement corrosion and durability problems. Many specifications and guidelines prohibit or limit its use (Tayabji and Anderson 2007; USACE 2012). ACI 302.1R recommends exclusion of admixtures with intentionally-added chlorides for conventional reinforced concrete in moist environments exposed to deicing salt or saltwater mist. Calcium nitrate is the most common nonchloride accelerator.

4.6.5 Air-entraining admixtures—Entrained air is commonly provided to improve durability when concrete is exposed to repeated cycles of freezing and thawing under saturated conditions. Air entrainment also improves concrete workability. Good control of air content is critical to quality and requires frequent air content testing and admixture dosage adjustment, if necessary. Excessive air content is a common cause of strength problems. Related but less frequent issues include air void clustering, coalescence, or both, characterized by air void concentrations around aggregate particle edges, which can contribute to

poor paste-aggregate bond and cause low strength and loss of durability. Some nonvinsol agents may cause air bubbles to cluster around aggregate particles when the mixture is retempered (Kozikowski et al. 2005), typically after late water addition—for example, holding back water during batching, then adding at the job site (Tayabji et al. 2012). An air-void system can be improved by increasing slump, using a more well-graded aggregate, increasing mixing time up to 150 seconds, and introducing all the aggregate materials together on the belt feed (ACPA 2003b). Low-slump mixtures make entrainment of air more difficult (Kohn and Tayabji 2003).

When using SCMs, air-entraining dosages typically need to be increased. This is dependent on the particular SCM type, source, class, type of air-entraining admixture, the mixture temperature, and other conditions. There have been cases reported where dosage rates were unaffected or even reduced in the presence of the fly ash (ACI 211.1). Fly ash sources that contain significant carbon content may require significantly higher dosages, and air control becomes problematic when the carbon content is variable. Loss on ignition (LOI), as an indication of carbon content, should be monitored and more frequent air tests performed when variable LOI sources are used. The foam index test can be useful for checking each fly ash delivery. Fly ash with LOI values of 4 percent or more will be less able to achieve a proper air-void system (Tayabji et al. 2012).

4.6.6 Other admixtures—Viscosity-modifying admixtures and rheology-controlling admixtures can be used to enhance the extrusion properties of slipform concrete mixtures.

4.6.7 Dosage—Care should be taken when choosing admixture dosage. Typically, dosage is expressed in terms of fl oz/100 lb (mL/100 kg) total cementitious materials (TCMs). Setting and early stiffening problems have been reported on projects where dosage recommendations were based on cement weight, but field dosages were calculated based on total cementitious weight. Changing conditions through the day or season may mean that admixture dosages have to be adjusted often.

4.7—Fibers

Fibers are used in concrete pavements to improve flexural toughness in applications such as bonded and unbonded concrete overlays and thin concrete pavement designs, and have been recommended as a possible solution to plastic shrinkage cracking. When using fibers, extra water should not be added to compensate for apparent reduction in workability, rather, chemical admixtures or mixture adjustments should be considered (Farny 2001). The most common fibers used in paving have been plastic, typically polypropylene, and either microsynthetic or macrosynthetic. Microsynthetic fibers have been available since the late 1970s; they are relatively thin denier fibers, typically 3/4 in. (19 mm) in length or shorter and used at dosage rates of 0.75 to 1.5 lb/yd³ (0.4 to 0.9 kg/m³). Macrosynthetic fibers have been used since the late 1990s; they are larger denier fibers typically 1-1/2 to 2-1/4 in. (38 to 57 mm) long and used at dosage rates of 3.0 to 7.5 lb/yd³ (1.8 to 4.4 kg/m³). The geometry

of the macrosynthetic fibers, plus improvements in concrete mixture proportioning and admixtures, has allowed them to be used at higher dosages than microsynthetic fibers. In addition to the benefits of microsynthetic fibers (plastic shrinkage cracking reduction), higher volumes (up to 7.5 lb/yd³ [4.4 kg/m³]) of macrosynthetic fibers have been reported to reduce curling, reduce joint edge spalling, increase abrasion resistance, and allow longer joint spacing (Walker and Holland 2007; Holland et al. 2008). Anti-static material applied to certain types of fibers can sometimes cause an increase in air content (ACI 211.1). Steel fibers have also been used in concrete pavement applications (ACI 544.1R).

4.8—Summary

Table 4.8 is a summary of the effects of material characteristics on the desired properties of the concrete mixture.

CHAPTER 5—MIXTURE PROPORTIONING

5.1—Mixture design

Mixture design involves choosing the performance parameters that are most important, and then choosing the materials and proportions to meet the design goals. The mixture designer should decide the level of desirability for certain parameters that are important to the success of the mixture. Recommended optimization criteria to be considered might include:

- a) Flexural strength
- b) Compressive strength
- c) Early strength
- d) Workability (ability to be mixed, transported, screeded, consolidated, finished, and textured)
- e) Scaling resistance
- f) Resistance to freezing and thawing
- g) Abrasion resistance
- h) Sulfate resistance
- i) Alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR) resistance
- j) Reduction of warping
- k) Reduction of curling
- l) Smoothness
- m) Joint spacing
- n) Sustainability
- o) Cost

5.1.1 Approaches to achieving desired properties—The two general approaches to achieving the desired properties of the mixture are through materials/methods specifications or performance specifications. The more traditional materials specifications are presented throughout this document. A listing of the test methods sometimes used in performance specifications is shown in Table 5.1.1.

5.1.2 Weather conditions—The rate of cement hydration roughly doubles for every change of 20°F (7°C). Beyond approximately 90°F (32°C), the quality of hydration product can be significantly reduced. Conversely, low temperatures will slow rates of setting and strength development.

During weather conditions with high evaporative influences due to low humidity, wind, and high temperature, typical problems may include rapid slump loss, reduced air

content, premature stiffening, plastic shrinkage cracking, and thermal cracking. To remedy these issues, the designer should consider use of retarders and slag cement or Class F fly ash and avoid the use of Class C fly ash with high aluminate content, increasing air-entraining admixture dosage, and avoid use of cement or fly ash with an excessively high temperature (150 to 180°F [66 to 82°C]).

During cold weather, consideration may be given to using higher cement contents, less slag cement or fly ash, Type III cement, and adjusting air-entraining admixture dosage to account for lower temperature effects on dosage efficiency and possibly an accelerator if allowed by the specifications (Kohn and Tayabji 2003), unless mildly ASR-prone aggregates are present.

5.2—Proportioning methods

The mixture proportioning method presented in this guide is based on the ACI 211.1 absolute volume method, geared specifically toward paving mixtures. Regarding the subject of grading, the typical two-aggregate situation is presented. As an option, several total grading methods of aggregate grading optimization are offered. Other mixture design methods were reviewed, and some concepts from these methods were incorporated into this guide (Transtec Group, Inc. 2010).

5.3—Preliminary testing

5.3.1 Testing for freezing and thawing and alkali-aggregate reactivity—Section 4.1.2 should be reviewed for assessing potential problems of aggregate freezing-and-thawing deterioration and aggregate alkali-aggregate reactivity (AAR).

5.3.2 Testing for sulfate attack conditions—In areas of suspected sulfate attack conditions, the soil or groundwater should be tested via ASTM C1580 to determine the level of sulfate present. A method for extraction of sulfate from soil is given in ACI 201.2R. If greater than 0.10 percent by weight of the soil or 150 ppm in the water, the condition is potentially harmful and allowance should be made in the mixture design. Specific remedies are presented in 5.4.4.1. Verification of mitigation effectiveness may be required by use of ASTM C1012/C1012M, which may take up to 18 months. A maximum expansion of 0.01 percent is recommended. Table 5.3.2 is derived from ACI 201.2R and ACI 318, and shows exposure levels. Sulfate exposure classes are S0, S1, S2, and S3. Condition S0 is for conditions where the soluble sulfate exposure is too low for concern. The other classes are for concrete in direct contact with sulfates in soil or water. More detailed information on recommended cement types and Bogue-calculated cement compound contents are discussed in ACI 201.2R.

5.4—Proportioning procedure

The proportioning procedure follows the steps outlined in ACI 211.1 and is discussed in the following sections.

5.4.1 Acquiring required information—Once the goals of the mixture design are established, as discussed in 5.1, how they can be met are decided upon. Materials available to the project should be reviewed and matched to the mixture design goals. At that point, the mixture proportioning steps are initiated.