SPECIFYING, DESIGNING, AND PROPORTIONING PAVING CONCRETE

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INTRODUCTION

This tech brief describes the process of developing concrete mixtures, which consists of three phases: specifying, designing, and proportioning. *Specifying* refers to the requirements placed in the contract documents with regards to the performance of the fresh and hardened concrete. *Designing* is the process of selecting mixture characteristics for the intended use and to meet the specification requirements. For pavement applications, these can include consideration of the fresh concrete properties for the given method of placement, the exposure conditions, and durability and strength requirements to meet the anticipated design life. Finally, *proportioning* entails the selection of proportions of available materials to produce economical concrete that meets the required specification parameters and design properties.

For most large-scale paving applications, concrete mixtures are most commonly placed using slipform pavers, which require a stiff mixture that readily fluidizes under vibration, yet remains rigid once the side slipform passes to provide a straight vertical edge (see figure 1). At the same time, most concrete pavement in the U.S. is exposed to harsh environmental conditions including freezing and thawing and the application of chemical deicers. In combination, these factors require stiff, air-entrained concrete mixtures that will withstand millions of heavy vehicle passes, resist wear from tires (including studded tires and chains in some locales), and remain durable under harsh climatic conditions for decades of service.

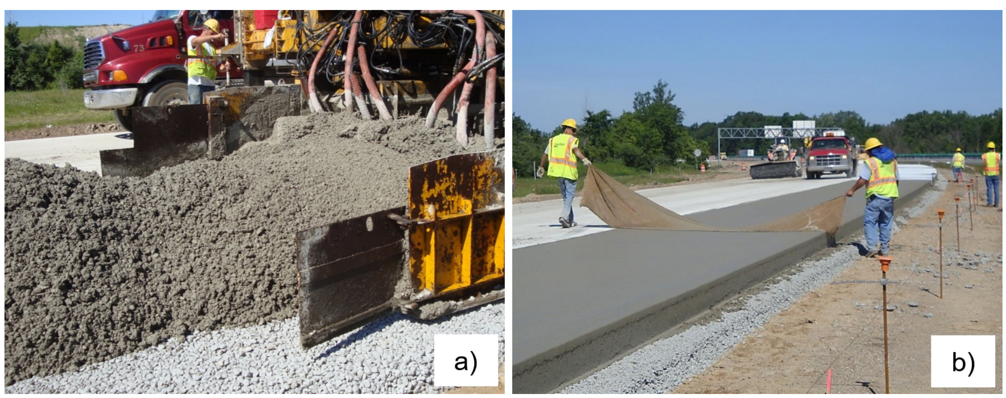

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Figure 1. Example of a stiff concrete slipform paving mixture that fluidizes readily under vibration (a) and then remains rigid after the paver has passed (b).

SPECIFYING PAVING CONCRETE

State highway agencies (SHAs) typically use a combination of specification types when specifying paving concrete, including (AASHTO 2003):

- Method Specifications – These require the contractor to produce and place a product using specified materials in definite proportions and the use of specific types of equipment and methods under the direction of the state highway agency (SHA).
- End-Result Specifications – These require the contractor to take the entire responsibility for producing and placing a product. The SHA is responsible for acceptance, rejection, or application of a price adjustment based on the level of compliance with the specifications.

- Quality Assurance Specifications – These require the contractor to conduct quality control and the SHA to perform acceptance activities throughout construction. Final acceptance is usually based on statistical sampling to measure the overall acceptability of key quality characteristics.
- Performance-Related Specifications – These are based on quality characteristics and life-cycle cost (LCC) relationships that are correlated to performance. Performance-related specifications are viewed as an improvement on quality assurance specifications because acceptance is related to pavement performance.
- Performance-Based Specifications – These are quality assurance specifications that describe the desired level of fundamental engineering properties that appear as input variables to primary performance prediction relationships including stress development, distress, or a combination of performance predictors such as traffic, environment, materials, etc.

Within each type of specification, certain characteristics of the concrete are evaluated that are believed to be related—directly or indirectly—to concrete pavement performance. Commonly used SHA concrete pavement specifications often include the following requirements:

- Materials approval – Detailed requirements are often specified for the concrete-making materials including aggregate, cementitious materials, admixtures, and water.
- Workability – Concrete workability is often specified using the slump test (AASHTO T 119).
- Air content – The total air content of fresh concrete is normally specified using the pressure method (AASHTO T 152).
- Strength – The concrete flexural (AASHTO T 97) or compressive strength (AASHTO T 22) are specified, commonly at 28 days. Strength testing may also be specified at earlier or later ages.
- Water-to-cementitious ratio (*w/cm*) – A maximum *w/cm* of 0.45 or less is commonly specified by SHA for concrete pavements that will be subject to freezing and thawing in the presence of chemical deicers or in severe sulfate exposure conditions.

In addition to the aforementioned characteristics, there are a few additional concrete materials tests that are being specified by some agencies, such as:

- Resistance to chloride ion penetration – The surface resistivity (AASHTO T 358) is appearing in some SHA specifications as an indicator of the concrete's resistance to chloride ion penetration.
- Drying shrinkage – Some agencies are specifying shrinkage limits based on ASTM C157.

It is recognized that the tests listed above have some limitations. For example, usefulness of the slump test as an indicator of workability has long been noted, as it does not characterize the ability of the concrete to be consolidated under vibration (Cook et al. 2013b). Similarly, the pressure meter (AASHTO T 152) provides an acceptable method to assess the total air content in a concrete mixture, but it does not assess the size and spacing of the entrained air voids that are essential to protect the concrete against freeze-thaw damage. Finally, indirect measurements of concrete permeability, such as surface resistivity (AASHTO T 358), fail to account for specimen geometry or pore solution conductivity, limiting their applicability.

Work is underway to address some of these limitations in the AASHTO performance-engineered mixture (PEM) specification (AASHTO PP 84) by assessing the following:

- Workability using either the Box Test (Cook et al. 2013b) or the V-Kelly Test (AASHTO TP 129).
- Concrete flexural (AASHTO T 97) and compressive strength (AASHTO T 22).
- Susceptibility to shrinkage, slab warping, and cracking resulting from volume change due to moisture loss (shrinkage) using ASTM C157 or AASHTO T 334 (restrained shrinkage ring test).
- Durability requirements for concrete placed in a freeze-thaw environment require that the *w/cm* be less than 0.45 and that either the air content be between 5 and 8 percent after placement as measured by the pressure meter (AASHTO T 152) or by the Super Air Meter (SAM) (AASHTO TP 118), or that the air content be greater than 4 percent after placement with a maximum SAM number (AASHTO TP 118) of 0.20. The performance specifications require that the mixture reaches critical saturation at 30 years, based on a calculated matrix saturation and apparent formation factor (FAPP) using AASHTO T 358 or TP 119.
- Joint damage due to chemical degradation from calcium chloride and magnesium chloride deicing chemicals is considered prescriptively by either using a minimum amount of supplementary cementitious materials (SCMs) to replace portland cement or providing a topical application of surface sealer. The performance specification is based on low temperature differential scanning calorimetry (LT-DSC) testing of the cementitious system for its susceptibility to the formation of calcium oxychloride using AASHTO T 365.
- Prescriptive requirements to improve the transport properties of concrete are based on using a maximum *w/cm* or FAPP derived from rapid chloride permeability (AASHTO T 277), surface resistivity (AASHTO T 358), or bulk resistivity (AASHTO TP 119) testing. The FAPP normalizes the results of these two tests for the given specimen geometries and assumed pore solution resistivity. This concept is extended to

the performance specification case with the main difference being the introduction of an assumed service life.

- Aggregate durability is considered for both resistance to freezing and thawing (based on SHA application of AASHTO T 161) and alkali-aggregate reactivity (based on guidance provided in AASHTO R 80). Both aggregate screening and mitigation strategies during mixture proportioning will be presented.

SELECTING MIXTURE CHARACTERISTICS (MIXTURE DESIGN)

Mixture design establishes the concrete properties based on the intended use, exposure conditions, and the required physical characteristics of the fresh and hardened concrete. The following sections describe the fresh concrete properties needed in the mixture for slipform paving, with table 1 providing a summary of the common test methods for those properties.

Table 1. Summary of test methods used to assess concrete properties.

Property	Test Method	Comment
Workability	AASHTO T 119: Slump test	Most commonly used measure of workability
	Box test	Newly developed test methods to assess concrete consolidation under vibration
	AASHTO TP 129 :VKelly test	Newly developed test methods to assess concrete consolidation under vibration
Air Content and Air-Void System Parameters	AASHTO T 152: Pressure meter	Most commonly used test for air content in fresh concrete
	AASHTO TP 118: SAM meter	Test based on pressure meter but uses sequential pressure to provide additional information related to air-void system characteristics
	ASTM C457: Microscopical evaluation of air voids	Measures air-void system parameters in hardened concrete as related to the susceptibility of the cement paste to damage by freezing and thawing
Strength	AASHTO T 97: Flexural strength	Conventional strength testing used as a common measure of concrete quality
	AASHTO T 22: Compressive strength	Conventional strength testing used as a common measure of concrete quality
Volume Change/Cracking Resistance	ASTM C157: Unrestrained drying shrinkage	Measures drying shrinkage of unrestrained concrete beams
	AASHTO T 334: Restrained shrinkage ring test	Measures cracking tendency of concrete cast around a ring
	AASHTO T 336: Coefficient of thermal expansion	Measures the concrete coefficient of thermal expansion
Chemical Deicer Resistance	AASHTO T 365: LT-DSC	Test method is currently being standardized
Transport Properties	AASHTO T 277: Rapid chloride penetrability	Electrical methods to determine concrete conductivity/resistivity from which the F factor can be determined
	AASHTO T 358 or TP 119: Concrete resistivity	Electrical methods to determine concrete conductivity/resistivity from which the F factor can be determined
Aggregate Durability	AASHTO T 161: Aggregate freeze-thaw resistance	Used by numerous SHA to assess aggregate freeze-thaw resistance
	AASHTO R 80: Alkali-aggregate reactivity	Protocols to determine aggregate reactivity and mitigation strategies

Maximum Water-to-Cementitious Ratio (w/cm)

The selection of the proper *w/cm* is a key parameter in any concrete mixture design as it strongly influences the strength and durability of the concrete mixture. Strength requirements are set by design, and the *w/cm* is established based on mixture testing and variability to ensure that the design strength is reliably achieved. Durability requirements are established based on the environment in which the concrete will serve. The two exposure conditions that can dictate the required *w/cm* for concrete pavements are freeze-thaw exposure and exposure to sulfates as summarized below (ACI 2016):

- Exposure to freezing
  - Class F0 – Concrete not exposed to freezing conditions. Does not influence *w/cm*.
  - Class F3 – Pavements that are subjected to freezing conditions are also expected to be near saturation at the time of freezing and subjected to deicer applications (Exposure Class F3). The maximum *w/cm* for Exposure Class F3 is 0.45 for plain jointed concrete pavement and may be lower for reinforced concrete pavement if corrosion is of concern.
- Exposure to external sulfates
  - Class S0 – Concrete not exposed to external sulfates. Does not influence *w/cm*.
  - Class S1 – Moderate exposure. The maximum *w/cm* is 0.50.
  - Class S2 – Severe exposure. The maximum *w/cm* is 0.45.
  - Class S3 – Very severe exposure. The maximum *w/cm* is 0.40.

The *w/cm* selected for design should be the lowest value needed to achieve the desired strength and meet expected exposure conditions (Kosmatka and Wilson 2016).

Air Content

In freeze-thaw environments, the concrete must be air entrained to protect the paste against freeze-thaw damage. For slipform paving concrete placed in a freeze-thaw environment, ACI (2016) recommends that the air content be based on the level of exposure (assume very severe [Exposure Class F3] as pavements in a freeze-thaw environment will almost always be exposed to moisture and deicers) and nominal maximum aggregate size. The recommended air content is as follows:

- Nominal maximum aggregate size of 0.5 to 0.75 inch (12 to 19 mm): 7 ± 1.5 percent.
- Nominal maximum aggregate size of 1.0 to 1.5 inch (25 to 37.5 mm): 6.5 ± 1.5 percent.

Slump

The concrete must be stiff so that the edges remain vertical without sloughing after the slipform paver passes. However, the concrete must also be readily consolidated under the influence of vibration resulting in minimal entrapped air as the material passes through the paver. The surface must also "close up" with minimal need for handwork, leaving a dense, uniform surface largely free of "bug holes" immediately behind the paver. Typical values for concrete slump are:

- Slipform paving: typically specified to be 0.5 to 1.5 inches (12 to 38 mm).
- Hand placement: typically in the range of 1 to 3 inches (25 to 75 mm).

Maximum Size of Aggregate

The nominal maximum aggregate size will largely be controlled by local aggregate availability and placement method. It is generally desirable to use the largest practical aggregate size available as this has a tendency to reduce the paste content while increasing economy and reducing shrinkage. Typically, for slipform paving, the practical limit is 1.5 to 2 inches (37.5 to 50 mm). In an attempt to address aggregate freeze-thaw deterioration, some SHA have specified the use of smaller aggregates (0.75 inch [19 mm] or less). Although this has been effective in addressing aggregate freeze-thaw deterioration, it has made it difficult to significantly reduce the cementitious materials content.

Strength

The strength of the concrete must be selected to meet both short-term and long-term needs. Often, strength is specified at 28 days, although it is also common to specify strength at earlier ages, even 24 hours or less, when early-opening requirements are in place. On the other hand, it may be desirable to specify strength at later ages, such as 56 days, for cases when high volumes of SCMs are being used and there is no pressure for opening the pavement to traffic.

Flexural strength (AASHTO T 97) is commonly specified as it relates directly to design, although a number of agencies use compressive strength (AASHTO T 22) for acceptance. The required flexural strength is largely controlled by design assumptions, with 550 to 650 lbf/in^2 (3.8 to 4.5 MPa) being within the typical range for many SHA specifications.

Other Requirements

In addition to the concrete properties listed above, other requirements may exist on the characteristics of the concrete, as described below.

Air-Void System Parameters

Although the total air content of fresh concrete is a common specification requirement, it is the properties of the entrained air-void system that actually impact the resistance of the concrete to freeze-thaw damage. As described by Van Dam (2019a), freeze-thaw durability is enhanced by having a well-dispersed network of microscopic air bubbles entrained throughout the paste at a size and spacing needed to relieve the build-up of stress that occurs as water in small pores freezes. For fresh concrete, AASHTO PP 84 specifies the use of the Super Air Meter (SAM, AASHTO TP 118), prescriptively specifying that the total air content be greater than 4 percent after placement with a maximum SAM number (AASHTO TP 118) of 0.20.

Although rare, some agencies have specified the spacing factor and/or specific surface for hardened concrete obtained in accordance with ASTM C457, *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*. The generally accepted maximum spacing factor and minimum specific surface for concrete with good resistance to freezing and thawing is 0.008 in (0.20 mm) and 600 in^2/in^3 (25 mm^2/mm^3), respectively (ACI 2016).

Transport Properties

The transport properties of paving concrete are rarely specified, yet are extremely important with regards to durability, whether it be resistance to freezing and thawing, sulfate attack, or chemical deicer attack. In addition to establishing a maximum *w/cm* values, some recent SHA specifications have introduced electrical methods (e.g., AASHTO T 277, AASHTO T 338, AASHTO TP 119) as an indirect means to assess permeability. AASHTO PP 84 goes a bit farther by using the results of these test methods to compute a required FAPP for specific conditions. Results from the rapid chloride penetration test and resistivity have been found to be highly correlated. For a chloride ion penetrability of "Low," the rapid chloride ion penetrability test yields 1000 to 2000 Coulombs passed whereas the resistivity test results are roughly between 20 and 10 k-ohm•cm. These values correspond to a FAPP of 2000 to 1000 (AASHTO PP 84).

Volume Stability

The volume stability of the hardened concrete is important for both short-term and long-term performance. The concrete's coefficient of thermal expansion (CTE), as assessed by AASHTO T 336, is an important structural design and mixture consideration and is therefore included in some specifications, particularly for continuously reinforced concrete pavements (CRCP). Less common is consideration of the drying shrinkage potential of the concrete, even though it impacts both the propensity for slabs to warp under a moisture gradient as well as crack when shrinkage is restrained. Drying shrinkage potential can be controlled by limiting the volume of the cement paste and/or specifying a maximum allowable drying shrinkage. One method specification approach is to limit paste volume to no more than 25 percent, whereas a performance approach is to reduce the 28-day shrinkage (ASTM C157) to 420 microstrain (AASHTO PP 84).

Aggregate Durability

Good quality, durable aggregates are required to achieve durable concrete. Many SHA specifications require that the aggregate be tested for durability characteristics specific to the SHA's own experience. Susceptibility to aggregate freeze-thaw deterioration is most commonly assessed using AASHTO T 161, often with SHA modifications reflecting local conditions and experience (Van Dam 2016b). A common acceptance limit for SHA using AASHTO T 161 is a minimum DF of 80. Recommendations for mitigating alkali-silica reactivity (ASR) and alkali-carbonate reactivity (ACR) are presented in AASHTO R 80.

MIXTURE PROPORTIONING

Mixture proportioning entails the selection of material proportions to produce economical concrete that meets the required specification parameters and design goals identified in the mixture design. Laboratory mixture proportioning is often used to develop an acceptable mix design, and this should be considered a reference point for field mix trials carried out to ensure the mixture is workable for the paving conditions. Adjustments, permitted by specification, may be required prior to full-scale paving (Tayabji, Fick, and Taylor 2012). The following criteria list the qualities of a properly proportioned concrete mixture (ACI 1991; Kosmatka and Wilson 2016):

- Good workability of the fresh concrete.
- Acceptable strength and durability of the hardened concrete.
- Economic and cost-effective mixture.
- Sustainable material selection and usage.

Several mixture proportioning methods are in use, the most widely being the absolute volume method detailed in ACI 211.1 (ACI 1991; Taylor et al. 2006). Other approaches to proportioning mixtures include proportioning from field data and proportioning from trial mixtures (see Kosmatka and Wilson 2016). One available mixture proportioning tool is the COMPASS Software, which provides guidelines to optimize job specific concrete mixtures (Transtec 2014). Another is an approach and software tool developed by Taylor et al. (2015b) in which the aggregate system and paste quality are established from which relative volumes of each are selected. However, Kosmatka and Wilson (2016) recommend using caution when using software tools as local material properties may not perform as predicted by computer models. The best way to determine constructability and performance is through laboratory field trials of concrete mixtures.

Detailed information on conducting mixture proportioning can be found in ACI 211.1 (ACI 1991), Taylor et al. (2006), and Kosmatka and Wilson (2016), including step-by-step processes that can be used to determine initial proportions. However, a few key mixture proportioning topics deserve more detailed discussion herein. These include aggregates, cementitious materials, water content, *w/cm*, workability, chemical admixtures, and durability.

Aggregates

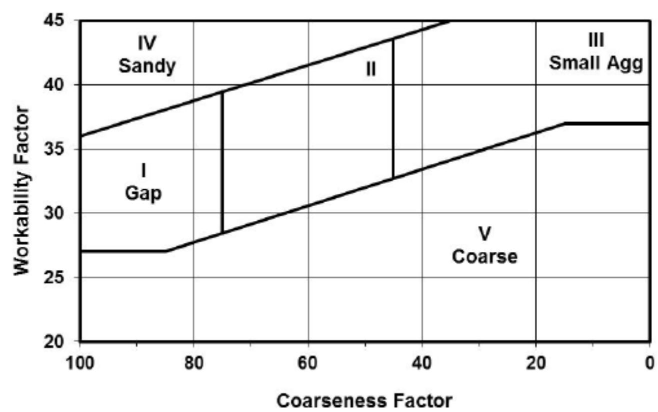
Aggregates used in concrete are most often derived from natural sources (either mined from gravel pits or quarried), although recycled and industrial byproduct materials are also used. The aggregates must be clean, hard, strong, and durable, and must be free of materials that will adversely affect the hydration of the cement and bonding of the hydrated cement to the aggregate particle (Kosmatka and Wilson 2016). Fine and coarse aggregates used in SHA paving concrete are typically specified in accordance with AASHTO M 6, *Standard Specification for Fine Aggregate for Hydraulic Cement Concrete* and AASHTO M 80, *Standard Specification for Coarse Aggregate for Hydraulic Cement Concrete*, respectively. Alternatively, some SHAs use ASTM C33, *Standard Specifications for Concrete Aggregates*. These specifications provide basic requirements for the aggregates to be used in concrete including permissible amounts of deleterious materials, physical properties with respect to soundness (AASHTO T 104) and abrasion (AASHTO T 96), and grading.

The effect of aggregate grading on concrete performance cannot be overstated (Taylor 2015). Ley, Cook, and Fick (2012) demonstrated that for a constant paste volume and *w/cm*, aggregate grading, nominal maximum size, and aggregate types all impact concrete strength, workability, and response to consolidation. When discussing aggregate grading, it is common to refer to an aggregate blend as being well-graded or gap-graded. Well-graded aggregates are distributed somewhat uniformly across sieve sizes whereas gap-graded aggregate typically exclude or have a very low percentage of aggregate retained on the intermediate sieve sizes. Well-graded aggregates are thought to be packed more densely in a mixture, leaving less void space that must be filled by paste. Recently, considerable efforts have been expended investigating improved aggregate packing to develop "optimized aggregate grading" that improves concrete workability while permitting a reduction in paste content (Cook et al. 2013b; Taylor et al. 2015b). The key is to carefully develop the aggregate proportions to ensure that the mixture workability is not compromised.

Taylor (2015) provides a good summary of aggregates blending for concrete paving mixture optimization.

Methods that have been investigated to improve aggregate grading include the coarseness factor chart, individual percent retained chart (8-18 curves), the 0.45 power curve, and most recently the "tarantula" curve, each of which is described below:

- The coarseness factor chart, developed by Shilstone (1990), uses the coarseness factor (CF) and workability factor (WF) to examine the distribution of coarse, intermediate, and fine aggregates in the combined grading. These factors are plotted on the modified coarseness factor chart (see figure 2 [Taylor 2015]), which features pre-defined zones associated with certain levels of workability (Shilstone 1990; Cook, Ghaeezadeh, and Ley 2013a; Taylor 2015). Zone II is the most desirable for slipform paving of concrete having 3/4 to 2 inch (19 to 50 mm) nominal maximum aggregate sizes.



Source: FHWA

Figure 2. Shilstone coarseness factor chart.

- The individual sieve percent retained chart (8-18), also developed by Shilstone (1990), plots percent retained for the combined gradation for each individual sieve size. This provides a deeper understanding of the distribution of the combined aggregate gradation for each sieve size. Previous experience has suggested the lower and upper limits of 8 and 18 percent, respectively, but there is limited research to justify these limits (Cook, Ghaeezadeh, and Ley 2013a).
- The 0.45 power curve plots the cumulative percent passing of the combined aggregate grading versus sieve size in millimeters, raised to the 0.45 power. A maximum density line is drawn from the origin to the nominal maximum size, and maximum and minimum percent passing limit lines are extended from the origin to one sieve size larger and smaller than the nominal maximum aggregate size, respectively (Taylor et al. 2006). Ley, Cook, and Fick (2012) and Cook, Ghaeezadeh, and Ley (2013a) suggest this

approach alone is not suitable for proportioning concrete mixtures for slipform paving.

- The tarantula curve (see figure 3) has been proposed by Cook et al. (2015) as a modification to the individual percent retained approach. This approach places limits on specific aggregate sizes for the combined gradation that were found to improve workability and resistance to segregation.

Cementitious Materials

Hydraulic Cements

For paving concrete, it is critically important to use cementitious materials that are suitable for the application, considering both the strength requirements and exposure conditions. The most commonly used hydraulic cements for pavement applications are portland cements (AASHTO M 85) and blended hydraulic cements (AASHTO M 240). The five types of AASHTO M 85 portland cement are:

- Type I – General-purpose portland cement, which is most commonly specified.
- Type II – Moderate sulfate resistance and moderate heat of hydration (MH) portland cement, which is used when pavement will be constructed on moderate sulfate-rich soils (categorized as S1 exposure according to ACI 2016).
- Type III – High early strength, which is used when high early strength gain is desired.
- Type IV – Low heat of hydration (rarely used in paving applications).
- Type V – High sulfate resistance specified when pavement will be constructed in an area with high sulfate-rich soils (categorized as S2 or S3 exposure according to ACI 2016).

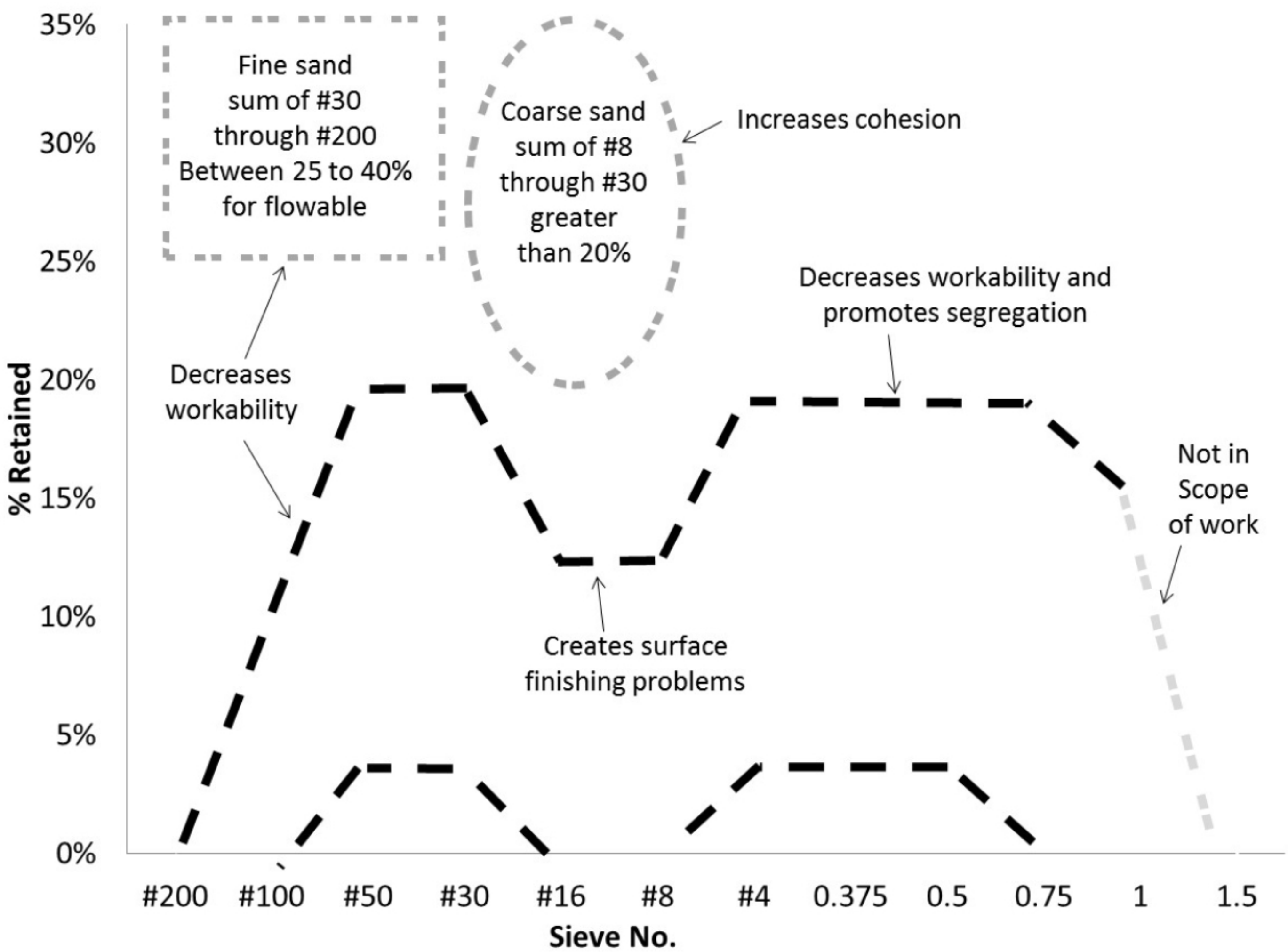


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Figure 3. An overview of the recommended aggregate gradation limits known as the Tarantula Curve.

Blended cements (AASHTO M 240) are interground or blended with SCMs, either a pozzolan or slag cement, or with limestone. A ternary combination of these materials is also permitted. These are classified as:

- Type IP(X) – Portland-pozzolan cement.
- Type IS(X) – Portland-slag cement.
- Type IL(X) – Portland-limestone cement.
- Type IT(AX)(BY) – Ternary blended cement.

The "X" and "Y" denote the nominal mass percent of SCM or limestone included in the blended cement. The "A" and "B" identify the type of ingredient present in the ternary blended cement, with P denoting pozzolan, S denoting slag cement, and L denoting limestone. For example, a Type IP(20) is a portland-pozzolan cement with 20 percent pozzolan, whereas A Type IT(L10)(P20) denotes a ternary blended cement with 10 percent limestone and 20 percent pozzolan.

Typical replacement rates for blended cements are 15 to 25 percent for Type IP(X), 30 to 50 percent for Type IS(X), and 10 to 12 percent for Type IL(X). The Type IT is a blend of two of the following (the percentages can vary greatly depending on the materials):

- 10 to 20 percent pozzolan.
- 15 to 30 percent slag.
- 5 to 10 percent limestone.

Blended cements can be further designated with (A), (MS) or (HS), (MH) or (LH), and (R), indicating air entraining, moderate or high sulfate resistance, moderate or low heat of hydration, or low reactivity with alkali-silica reactive aggregates, respectively. For example, a high-sulfate resistant, air entraining portland-slag cement with 40 percent slag is designated as a Type IS(40)(HS)(A).

In addition to AASHTO M 85 portland cement and AASHTO M 240 blended hydraulic cement, there are two performance hydraulic cements that are at times used in pavement construction: ASTM C1157, performance hydraulic cement and ASTM C1600, rapid hardening hydraulic cement. In contrast to the prescriptive nature of the cements discussed so far, performance hydraulic cement (ASTM C1157) must simply meet physical performance test requirements. Under this specification, six cement types are available:

- Type GU – General use.
- Type LH – Low heat of hydration.
- Type MH – Moderate heat of hydration.
- Type HE – High early strength.
- Type MS – Moderate sulfate-resistance.
- Type HS – High sulfate-resistance.

For example, Type MS and HS cements use ASTM C1012, *Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution* to ensure resistance to sulfate attack. In addition, as was true with AASHTO M 240 blended cement, these cements can also include the additional designation of (R) denoting low reactivity with alkali-reactive aggregates (i.e., Type GU-R for general use with low reactivity with alkali-silica reactive aggregates). This approach promotes development of composite portland cements (portland cement blended with multiple SCMs and/or limestone) as well as opening the door to non-portland cement-based hydraulic binders.

ASTM C1600 is for rapid hardening, high-early strength hydraulic cements that may be desirable for some applications such as accelerated paving. The specification classifies cements based on specific requirements for early compressive strength development, and includes the following four types of rapid hardening cement:

- Type URH – Ultra-rapid hardening.
- Type VRH – Very rapid hardening.
- Type MRH – medium rapid hardening.
- Type GRH – general rapid hardening.

Table 2 summarizes the different types of hydraulic cements and their general applications.

Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) are derived from industrial processes (co-products) or processed from natural sources. In concrete, SCMs can be used as an addition to or as a partial replacement of portland cement. They often reduce the cost of the concrete while contributing positively to the plastic and hardened properties, including increased workability, improved long-term strength, reduced permeability, increased resistance to ASR, and increased resistance to sulfate attack (Taylor et al. 2006; Kosmatka and Wilson 2016). In addition, if used to replace portland cement, SCMs can reduce the amount of CO2 associated with concrete production. Most SCMs also reduce the heat of hydration of concrete, which is a positive attribute for hot weather concreting and in reducing the risk of thermal-induced cracking but may delay concrete set during cold weather placements. Another potential negative is that the risk of unanticipated interactions between concrete making materials increases when some SCMs are used (Taylor et al. 2006). Therefore, the type and amount of SCM(s) should be tested in the job-mix concrete to ensure that the desired fresh and hardened mixture properties are obtained.

Table 2. Hydraulic cements (based on Tennis and Melander 2010 and ACI 2016).

Cement Specification	General Purpose	Moderate Heat of Hydration	High Early Strength	Low Heat of Hydration	Moderate Sulfate Resistance[1]	High Sulfate Resistance[2]
AASHTO M 85 Portland Cements	I	II(MH)	III	IV	II, II(MH)	V[3]
AASHTO M 240 Blended Cements	IP IS(<70) IL IT(P<S<70) IT(P≥S) IT(P≥L) IT(L<S<70)	IP(MH) IS(<70)(MH) IL(MH) IT(P<S<70)(MH) IT(P≥S)(MH) IT(P≥L)(MH) IT(L<S<70)(MH)	-	IP(LH) IL(LH) IT(P≥S)(LH) IT(P≥L)LH	IP (MS) IS(<70)(MS) IL(MS)[4] IT(P<S<70)(MS) IT(P≥S)(MS) IT(P≥L)(MS)[4] IT(L<S<70)(MS)[4]	IP (HS) IS(<70)(HS) IT(P<S<70)(HS) IT(P≥S)(HS) IT(P≥L)(HS)[4] IT(L<S<70)(HS)[4]
ASTM C1157 Performance Cements	GU	MH	HE	LH	MS	HS[3]
ASTM C1600 Rapid Hardening Cements	-	-	URH VRH MRH GRH	-	-	-

1 Moderate sulfate resistance for an S1 sulfate exposure based on ACI (2016).
2 High sulfate resistance for S2 and S3 sulfate exposure based on ACI (2016).
3 For S3 sulfate exposure, additional pozzolan or slag cement must be added (see ACI 2016).
4 Recent research (Hooton and Thomas 2016) has found that Type IL cements are nor more or less susceptible to sulfate attack than traditional portland cements.

Fly ash is the most commonly used SCM for paving applications, being obtained from the flue gases in coal-burning power plants. Specified under AASHTO M 240, fly ash is classified as either Class C fly ash or Class F fly ash. Class C fly ash has lower combined silica, alumina, and iron oxide content (< 70 percent), and generally has a higher calcium oxide content (10 to 30 percent) than Class F fly ash. This means that Class C fly ash is often self-cementing and will not greatly affect early strength gain when used at recommended dosages. On the other hand, Class C fly ash is not typically as effective as Class F fly ash in mitigating ASR and may actually decrease the concrete's resistance to sulfate attack.

Class F fly ash is typically pozzolanic, a term meaning it is not self-cementing but instead reacts with available sources of calcium oxide, such as is available during hydration of portland cement. This makes Class F fly ash much more effective at mitigating ASR or sulfate attack than Class C fly ash, but it does slow early strength gain.

Slag cement, specified under AASHTO M 302, is a common SCM in some areas of the U.S. but completely unavailable in others. Slag cement is produced when molten blast furnace slag is granulated and ground and is classified based on its reactivity in comparison to portland cement, with most states banning the use of the least reactive grade (Grade 80). It has both self-cementing and pozzolanic characteristics, and when used as a replacement for portland cement, does not significantly impact early strength gain at normal ambient temperatures, although it slows hydration at cooler temperatures. When used in sufficient quantities in conjunction with portland cement, slag cement can significantly improve the concrete's permeability as well as effectively mitigate ASR and sulfate attack.

There are a number of other SCMs that have been used in paving concrete, including a host of natural pozzolans (AASHTO M 295 Class N), such as volcanic ash, calcined clay, calcined shale, and metakaolin. In general, highly reactive SCMs such as metakaolin and silica fume (ASTM C1240) are used at relatively low replacement levels, although higher amounts of metakaolin may be used in some cases depending on the characteristics of the specific material.

In practice, SCMs are added to concrete in one of two ways. The first is they are added by the cement supplier to create blended hydraulic cement (AASHTO M 240), performance cement (ASTM C1157), or rapid hardening cement (ASTM C1600) as previously discussed. Providing the SCM pre-blended with the cement provides a greater level of quality control with less potential for unforeseen interactions but limits the concrete supplier's ability to adjust the SCM content to respond to changing mix designs or weather conditions. More commonly, SCMs are added by the concrete producer at the concrete plant. This practice provides greater flexibility in adjusting the SCM content on-site to address changing conditions but has a greater potential for problems due to improper batching and unforeseen interactions.

Replacement/addition rates for SCMs vary, but for paving concrete typically are as follows:

- Class C fly ash – 15 to 40 percent.
- Class F fly ash – 15 to 25 percent.
- Slag cement – 35 to 45 percent.
- Silica fume and metakaolin – 5 to 8 percent.
- Natural pozzolans – 15 to 25 percent.

Tables 3 and 4 summarize the impacts of common SCMs on the fresh and hardened properties of paving concrete.

Table 3. Impacts of common SCMs on fresh properties of paving concrete (modified from Taylor et al. 2006 and Kosmatka and Wilson 2016).

Property	Fly Ash Class F	Fly Ash Class C	Slag Cement	Silica Fume	Calcined Shale and Clay*	Metakaolin*
Water Demand	Reduces	Reduces	Reduces	Increases	No impact	Increases
Workability	Increases	Increases	Increases	Reduces	Increases	Reduces
Bleeding	Reduces	Reduces	May increase or lower	Reduces	No impact	Reduces
Set Time	Increases	May increase or lower	Increases	No impact	No impact	No impact
Air Content	Reduces	Reduces	No impact	Reduces	No impact	Reduces
Heat of Hydration	Reduces	May increase or lower	Reduces	No impact	Reduces	No impact

*Natural Pozzolans

Table 4. Impacts of common SCMs on hardened properties of paving concrete (modified from Taylor et al. 2006 and Kosmatka and Wilson 2016).

Property	Fly Ash Class F	Fly Ash Class C	Slag Cement	Silica Fume	Calcined Shale and Clay*	Metakaolin*
Early Strength	Reduces	No impact	May increase or lower	Increases	Reduces	Increases
Long-Term Strength	Increases	Increases	Increases	Increases	Increases	Increases
Abrasion Resistance	No impact	No impact	No impact	No impact	No impact	No impact
Drying Shrinkage	No impact	No impact	No impact	No impact	No impact	No impact
Permeability	Reduces	Reduces	Reduces	Reduces	Reduces	Reduces
Corrosion Resistance	Increases	Increases	Increases	Increases	Increases	Increases
Alkali-Silica Reactivity	Reduces	Reduces	Reduces	Reduces	Reduces	Reduces
Sulfate Resistance	Increases	May increase or lower	Increases	Increases	Increases	Increases
Freezing and Thawing	No impact	No impact	No impact	No impact	No impact	No impact
Deicer Chemical Attack Resistance	Increases	Increases	Increases	Increases	Increases	Increases

*Natural Pozzolans

Minimum Cementitious Materials Content

Many SHA specifications have a minimum cementitious materials contents requirement, with the intent of ensuring sufficient strength, good workability, and adequate durability. In recent years, the required minimum cementitious materials content requirements have been reduced by many SHAs as optimized aggregate gradings have been implemented because those gradations accommodate the use of reduced cementitious contents while maintaining workability and durability (Taylor et al. 2006; Cook et al. 2013b). Previous guidance that recommended a minimum cementitious content of 564 lbs/yd^3 (335 kg/m^3) for durability have been dropped, with new recommendations suggesting that high cementitious materials contents (in excess of 600 lbs/yd^3 [356 kg/m^3]) should be avoided as such mixtures have increased cost and higher risk of durability issues due to excessive drying shrinkage (Kosmatka and Wilson 2016).

Water Content

The water required in a concrete mixture is influenced by a number of factors including, but not limited to, the properties of the aggregate (i.e., gradation, shape, angularity, and texture), target slump, air content, *w/cm*, cementitious material type and content, admixtures, and environmental conditions during construction (Kosmatka and Wilson 2016). For example, an increase in cementitious material content or an increase in mixture temperatures will require additional water whereas the use of fly ash, water-reducing admixtures, or increased air content will decrease water demand. Guidance on initial water contents for mixture proportioning and additional details can be found in Kosmatka and Wilson (2016).

Water-to-Cementitious Materials Ratio

As previously discussed, the selection of the proper *w/cm* is a key parameter in any concrete mixture design as it strongly influences the strength and durability of the concrete mixture. As noted, the *w/cm* selected for proportioning should be the lowest value needed to achieve the desired strength and meet expected exposure conditions (Kosmatka and Wilson 2016). But even though a reduction in *w/cm* will improve strength and durability, using a *w/cm* much below 0.40 may have undesirable negative impacts including an increased risk of autogenous shrinkage, increased difficulty in entraining air into the mixture, and increased issues with workability (Tayabji, Fick, and Taylor 2012). Thus, a minimum *w/cm* of 0.40 is recommended for paving concrete, although some states have had success with *w/cm* as low as 0.37 (Taylor et al. 2006).

Chemical Admixtures

Admixtures are added to concrete mixtures to modify their fresh and hardened properties, such as air content, setting time, and water demand. It is important to note that the use of admixtures is not a replacement for proper mixture proportioning. Also, admixture compatibility should be verified through trial batches prior to production, or if constituent materials change during production (Taylor et al. 2006). Admixtures commonly used in paving concrete include:

- Air entraining – These are surfactants that work at the air-water interface during mixing to form stable, microscopic air bubbles that remain after the concrete hardens. Entrained air improves the workability of fresh concrete and helps protect it against damage from freezing and thawing.
- Water reducing – These are a category of admixtures used to reduce water demand while maintaining workability. The admixtures work at the surface of the cement particles, causing electrostatic repulsion, and in some cases steric hindrance (attached long chain admixture molecules physically separate cement grains), dispersing the cement grains and releasing water. Water reducing admixtures are used to increase workability and/or lower the *w/cm* of the mixture.
- Retarding – These admixtures retard setting times by inhibiting nucleation of certain crystalline hydration products, allowing more time to transport, place, consolidate, and finish the concrete. They are especially useful to slow concrete set during hot weather placements or to compensate for long transport times.
- Accelerating – These admixtures accelerate setting times by accelerating the hydration reactions for certain phases, increasing early strength gain which is useful in accelerating opening time to traffic, but often results in lower long-term strength and may negatively impact durability.

A summary of common chemical admixtures is presented in table 5.

Other chemical admixtures that may be encountered in concrete paving mixtures include shrinkage-reducing, alkali-silica inhibiting, hydration controlling, and workability retaining products. More detailed information on chemical admixtures is provided by Taylor et al. (2006), Kosmatka and Wilson (2016), and Van Dam (2019b).

Workability and Flowability

Achieving good workability in a concrete mixture is one of the key factors in achieving the desired outcomes of a hardened concrete mixture. Koehler and Fowler (2003) provide an in-depth summary of numerous concrete workability test methods. The slump test (AASHTO T 119) is the most commonly used method to assess workability, but, as noted earlier, is not always meaningful in determining the ability of a concrete mixture to consolidate under vibration without edge sloughing (Cook, Ghaeezadeh, and Ley 2014).

Table 5. Summary of common chemical admixtures used in paving concrete (Van Dam 2019b).

Admixture	Standard	Description	Comments
Air Entraining	AASHTO M 154 ASTM C260	Surfactants that entrain stable microscopic air bubbles in fresh concrete, which remain in the hardened concrete to protect it against freeze-thaw damage.	A wide variety of compounds are used to entrain air. Must ensure that the bubble size and spacing is sufficient to protect concrete against freeze-thaw damage.
Water-Reducing	AASHTO M 194 ASTM C494 Type A	Conventional WRAs can reduce water content by 5 to 10 percent.	Most conventional WRA disperse cement grains through electrostatic and steric repulsion. Can affect setting, with retardation more common as dosage increased. Can also be sensitive to temperature, and due to interactions with other mixture constituents, can result in flash setting or severe retardation.
Water-Reducing and Retarding	AASHTO M 194 ASTM C494 Type D	Conventional WRAs can reduce water content by 5 to 10 percent and retards setting.	Most conventional WRA disperse cement grains through electrostatic and steric repulsion. Can affect setting, with retardation more common as dosage increased. Can also be sensitive to temperature, and due to interactions with other mixture constituents, can result in flash setting or severe retardation.
Water-Reducing and Accelerating	AASHTO M 194 ASTM C494 Type E	Conventional WRAs can reduce water content by 5 to 10 percent and accelerates set.	Most conventional WRA disperse cement grains through electrostatic and steric repulsion. Can affect setting, with retardation more common as dosage increased. Can also be sensitive to temperature, and due to interactions with other mixture constituents, can result in flash setting or severe retardation.
Water-Reducing, Mid-Range	AASHTO M 194 ASTM C494 Type A and often Type F	Water reduction between 6 and 12 percent without retardation associated with high dosages of normal WRAs.	These bridge the gap between conventional WRAs and high-range WRAs. Depending on chemistry, they may entrain air.
Water-Reducing, High-Range	AASHTO M 194 ASTM C494 Type F	Water reduction between 12 and 40 percent without retardation. Not often used with paving grade concrete	Various compositions with the latest generation being based on polycarboxylate technology, resulting in improved long-term slump stability. Polycarboxylates have a tendency to entrain larger air bubbles and thus are often defoamed. This can impact air entrainment.
Water-Reducing, High-Range and retarding	AASHTO M 194 ASTM C494 Type G	Water reduction between 12 and 40 percent with retardation. Not often used with paving grade concrete	Various compositions with the latest generation being based on polycarboxylate technology, resulting in improved long-term slump stability. Polycarboxylates have a tendency to entrain larger air bubbles and thus are often defoamed. This can impact air entrainment.
Set-Retarding	AASHTO M 194 ASTM C494 Type B	Set-retarders are used to delay set, especially during hot weather and/or when delivery of concrete is delayed.	Various compounds are used that delay the hydration of the aluminate phase, calcium silicate phase, or both phases. Sensitive to temperature and other mixture constituents and thus must be evaluated for interactions.
Set-Accelerating	AASHTO M 194 ASTM C494 Type C	Set-accelerators are used to accelerate set, especially during cold weather and/or when rapid setting and strength gain are required for early-opening-to traffic.	The most common accelerator is calcium chloride although non-chloride accelerators are available. Calcium chloride accelerates the hydration of calcium silicate. The biggest drawback of calcium chloride is it increases the risk of chloride induced corrosion of embedded steel.

Two test methods have been advanced in AASHTO PP 84 to address this shortcoming. The Box Test was developed to evaluate the vibratory response of concrete, specifically for mixtures intended for slipform paving (Cook et al. 2013b; Cook, Ghaeezadeh, and Ley 2014). The test subjects fresh concrete placed in a 1 ft^3 (0.76 m^3) box to internal vibration and evaluates its consolidation response and its ability to hold an edge once the box form is removed. The Vibrating Kelly Ball Test (VKelly) also assesses the vibration response of stiff concrete mixtures intended for slipform paving (Taylor, Wang, and Wang 2015a). The VKelly test apparatus is a modification of the Kelly Ball apparatus, applying vibration to a fresh concrete mixture for a specified period of time. Van Dam (2016b) provides more information on the Box and VKelly tests.

Durability

Table 6 summarizes the most common durability-related distresses that affect concrete pavements. As discussed throughout this document, proper mixture proportioning needs to consider the long-term durability of the hardened concrete. Aggregates should be screened for susceptibility to ASR using the AASHTO PP 65 protocol and appropriate mitigation measures taken during the mixture proportioning process if aggregate susceptibility is observed. If the pavement is to be subjected to freezing conditions, aggregate susceptibility to freezing and thawing must also be considered as it can lead to the development of D-cracking. Furthermore, the susceptibility of the paste to freeze-thaw damage must be addressed by entraining air into the concrete and using a sufficiently low *w/cm*. Similarly, exposure to external sulfates can be very damaging and also requires the selection of a sufficiently low *w/cm* as well as sulfate-resistant cementitious materials. Van Dam (2016a; 2016b; 2019a) and ACI (2016) provide more detailed information on concrete durability.

Mixture Review

While it is expected that laboratory results will be similar to field results, inherent material variability, production inconsistencies, and changing environmental conditions will likely require field adjustments prior to or during concrete mixture production. If it is anticipated that construction will span more than one season (e.g., construction may span hotter summer months and cooler fall and winter months), it is advisable to develop and have approved multiple concrete mixtures that are each suited to specific climatic conditions expected to be encountered throughout the construction process.

CONCLUDING REMARKS

Three phases typically occur in the development of a concrete mixture: specifying, designing, and proportioning. Specifying refers to the requirements contained in the contract documents with regards to performance requirements for the fresh and hardened concrete. Mixture design is the process of selecting mixture characteristics for the intended use and to meet the specification requirements. Finally, mixture proportioning entails the selection of proportions of available materials to produce economical concrete that meets the required specification parameters, design properties, and considers material sustainability. This Tech Brief describes each phase, providing succinct guidance while providing sources for more detailed information.

Table 6. Summary of common durability-related distresses affecting concrete pavements (Van Dam 2016a).

Type of MRD	Observed Distress	Cause	Time of Appearance
Freeze-Thaw Deterioration of Hardened Cement Paste	Crazing or surface scaling, or joint spalling or deterioration. Generally initiates near joints or cracks; possible internal disruption of concrete matrix.	Deterioration of HCP due to repeated freeze-thaw cycles in a saturated state. Entrained air-void system insufficient to protect HCP from damage.	1-10 years
Deicer Scaling/ Deterioration	Crazing or surface scaling with possible alteration of the concrete pore system or the HCP, leading to staining at joints and cracks, followed by joint deterioration.	Deicing chemicals amplify freeze-thaw deterioration by increasing the level of saturation and pressures generated; may interact chemically with HCP (Sutter et al. 2006; Jones et al. 2013).	1-5 years
Freeze-Thaw Deterioration of Aggregate	Cracking parallel to joints and cracks, followed by spalling; may be accompanied by surface staining.	Freezing and thawing of susceptible coarse aggregates results in fracturing or excessive dilation of aggregate.	10-25 years
Alkali-Silica Reactivity (ASR)	Pattern cracking at joints and often over entire slab surface. Exudate often accompanies cracking. May have expansion-related distresses (joint closure, spalling, blowups).	Reaction between alkalis in the pore solution and reactive silica in aggregate results in formation of an expansive gel and degradation of the aggregate particle.	5-25 years
Alkali-Carbonate Reactivity (ACR)	Map cracking over entire slab area and accompanying expansion-related distresses (joint closure, spalling, blowups).	Aggressive expansive reaction between alkalis in pore solution and certain dolomitic aggregates which commonly involves dedolomitization and brucite formation.	5-15 years
External Sulfate Attack	Fine cracking near joints and slab edges or map cracking over entire slab area, ultimately resulting in joint or surface deterioration.	Formation of ettringite, gypsum, or thaumasite that occurs when external sources of sulfate (e.g., groundwater, deicing chemicals) react with aluminate phases in HCP.	1-10 years
Internal Sulfate Attack	Fine cracking near joints and slab edges or map cracking over entire slab area. Evidence of expansion-related distress (joint closure, spalling, blowups).	Delayed ettringite formation (DEF) from high early-age curing temperatures that results in either expansive disruption in the paste phase	1-5 years
Corrosion of Embedded Steel	Spalling, cracking, and deterioration at areas above or surrounding embedded steel.	Chloride ions penetrate concrete, facilitating corrosion of embedded steel. Increased volume of corrosion products causes distress.	3-20 years

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