CP ROAD MAP
shaping the future of **concrete pavement**

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ROAD MAP TRACK 1

PROJECT TITLE
Performance Engineered Mixtures for Concrete Pavements

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Moving Advancements into Practice (MAP) Briefs describe innovative research and promising technologies that can be used now to enhance concrete paving practices. The **April** 2017 MAP Brief provides information relevant to Track 1 of the CP Road Map: Materials and Mixes for Concrete Pavements.

This MAP Brief is available at www.cproadmap.org/publications/MAPbriefMarch2017.pdf.

"Moving Advancements into Practice"
MAP Brief April 2017
Best practices and promising technologies that can be used now to enhance concrete paving

Performance Engineered Mixtures (PEM) for Concrete Pavements

Introduction

Concrete pavements are designed to perform for decades under harsh service conditions. Owners invest in them because of their ability to provide a safe, low-maintenance, long-life solution to a full range of needs, from low-volume secondary roads to the highest volume interstate applications in the country. With recent advancements in testing technologies, it is now possible to more directly measure the key properties of concrete paving mixtures that relate to performance and design them to perform with increased reliability in all climatic regions.

This tech brief will explain how concrete paving mixtures can be engineered to meet performance requirements and how to incorporate key performance parameters into a robust specification and quality process.

Why performance-engineered mixtures are needed

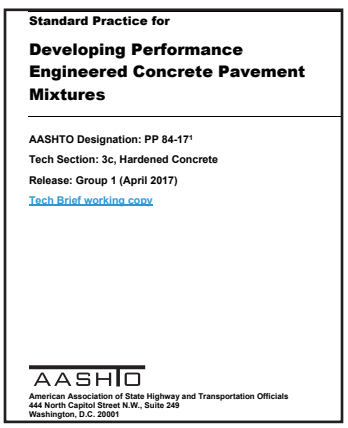
Concrete paving specifications have not kept pace with advancements in concrete science and innovations in testing technologies.

Current specifications are still largely based on strength, slump, and air content and have been for over 50 years. While these are important parameters, there are other parameters that are not being measured that are equally or more important. Mixtures have become more complex with a growing range of chemical admixtures and supplementary cementitious materials (SCMs). Traffic is increasing, more aggressive winter maintenance practices are the norm, and demands are growing for systems to be built more quickly, less expensively, and with increased longevity.

Many local specifications are predominantly prescriptive, thus limiting the potential for innovation and not necessarily addressing current materials, environments, or construction methodologies.

Recognizing the need to advance concrete paving specifications, the Federal Highway Administration (FHWA), the American Concrete Paving Association, the Portland Cement Association and other industry partners, and member states of the National Concrete Consortium (NCC) are collaborating with the research and technical community to modernize the specifications for paving mixtures. This partnership formally began in April of 2015 at the spring meeting of the NCC with the formation of an Expert Task Group that included seven champion states (Indiana, Iowa, Minnesota, Michigan, Nebraska, South Dakota, Wisconsin, the Illinois Tollway, and Manitoba). FHWA's shared vision was to have a provisional American Association of State Highway and Transportation Officials (AASHTO) specification by 2017. This vision has become a reality.

In April of 2017, AASHTO will publish PP 84-17, Developing Performance Engineering Concrete Pavement Mixtures (figure 1). The focus now shifts from this first step to technical education of agencies and industry on how to apply the PEM specification within an integrated framework that provides for innovation and local optimization.


Standard Practice for

Developing Performance Engineered Concrete Pavement Mixtures

AASHTO Designation: PP 84-17[1]
Tech Section: 3c, Hardened Concrete
Release: Group 1 (April 2017)
Tech Brief working copy

AASHTO
American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001

Figure 1. AASHTO PP 84-17 specification

Overview of PEM mixture requirements

Identified Properties Controlling Concrete Mixture Performance

The following six mixture properties are addressed in section 6 of the specification:

- **Aggregate Stability**—including alkali aggregate reaction and D-cracking
- **Fluid Transport Properties**—The ability to resist passage of water and aggressive fluids
- **Cold Weather**—The ability to resist freezing and thawing and the effects of deicing salts
- **Shrinkage**—As it affects random cracking as well as warping
- **Strength**—The ability to carry static, dynamic, and fatigue loads
- **Workability**—As it affects the constructability of the system, and the observation that the efforts to overcome poor workability can impact durability

The PEM specification is structured around the recommendations of the expert task group concerning the critical parameters that determine concrete paving mixture performance.

The concept is to implement these requirements in the following order:

- Mixture qualification—Material and mixture properties for local conditions
- Mixture verification—At the project level
- Mixture quality control and acceptance

Table 1 summarizes section 6 of AASHTO PP84-17 as it relates to concrete mixture performance.

For each of the above six mixture properties, PP-84-17 provides a range of options from prescriptive methods to performance measures. The intent is to provide state highway agenices (SHAs) flexibility in their approach to addressing the desired performance measure.

As SHAs gain experience and confidence in the performance of PEM mixtures, it is expected that specifications will become more performance based and allow for the innovation that is needed to increase performance. The inclusion of performance measures increases the importance of quality control (Q/C), as the acceptance criteria are predicted on a well-designed and executed quality program.

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Table 1. Summary of AASHTO PP84-17 specification

AASHTO PP84-17 test summary						Where is the test used?		
Mixture parameter	Traditional acceptance criteria	Property	Specification reference	Specified test	Selection details	Mixture qualification	Acceptance	Special notes
Aggregate stability	√	D-cracking	6.7.1	T161, ASTM C1646		√	—	
		Alkali aggregate reactivity	6.7.2	R80		√	—	
Transport properties		Water to cementitious materials (w/cm) ratio	6.6.1.1	_	Choose only one	√	√	The required maximum water to cementitious ratio is selected based on freeze–thaw conditions
		Formation factor	6.6.1.2	Table 1		√	√	Based on freeze–thaw conditions; other criteria could be selected
		Ionic penetration, F factor	6.6.2.1	Appendix X2		√	√	Determined using guidance provided in Appendix X2
Durability of hydrated cement paste for freeze-thaw durability		Water to cementitious materials (w/cm) ratio	6.5.1.1	—	Choose either 6.5.1.1 or 6.5.2.1	√	√	
	√	Fresh air content	6.5.1.2	T152, T196, TP118	Choose only one	√	√	
		Fresh air content/SAM	6.5.1.3	T152, T196, TP118		√	√	
		Time to critical saturation	6.5.2.1	"Bucket Test"		√	—	Variation controlled with mixture proportion observation or F factor and porosity measures
		Deicing salt damage	6.5.3.1	35% SCMs	Choose only one	√	√	Are calcium or magnesium chloride used
		Deicing salt damage	6.5.3.2	M224		√	√	Are calcium or magnesium chloride used; use specified sealers
		Calcium oxychloride limit	6.5.4.1	T 365-17		—	—	Are calcium or magnesium chloride used
Reducing unwanted slab warping and cracking due to shrinkage		Volume of paste (25%)	6.4.1.1	—	Choose only one	√	—	
		Unrestrained volume change	6.4.1.2	ASTM C157		√	—	Curing conditions
		Unrestrained volume change	6.4.2.1	ASTM C157		√	—	
		Restrained shrinkage	6.4.2.2	T 334		√	—	
		Restrained shrinkage	6.4.2.3	TP 363-17 (Dual Ring)		√	—	
		Probability of cracking	6.4.2.4	Appendix X1		√		Variation controlled with mixture proportion observation or F factor and porosity measures.
		Quality control check	Commentary			—	√	
Concrete strength	√	Flexural strength	6.3.1	T 97	Choose either or both	√	√	
		Compressive strength	6.3.2	T 22		√	√	
Workability	Slump	Box rest	6.8.1	Appendix 3	Choose one		—	
		V-Kelly test	6.8.2	Appendix 4			—	

Where will PEM mixtures be beneficial?

The PEM specification is applicable to all states. It gives agencies the flexibility to customize their specification for a specific climatic zone, whether cold, humid, or arid (figure 2) and to measure key parameters related to performance.

When considering the exposure conditions for a pavement, it is important to understand the impact of winter maintenance practices. In 2016, Clear Roads completed the second year of a multi-year project to systematically gather, compile, and analyze a range of data from SHAs related to their winter operations (figure 3).

All SHAs were invited to participate in a survey to collect information about their winter resources, materials and costs for the winter season from July 1, 2015 to June 30, 2016.

The results of this survey are very informative relative to the national use of deicing and anti-icing material. Of the 26 states responding to this portion of the survey:

- 26 reported using dry sodium chloride
- 9 reported using dry calcium chloride
- 2 reported using dry magnesium chloride
- 24 reported using sodium chloride brine
- 13 reported using calcium chloride brine
- 14 reported using magnesium chloride brine

While much of the southern U.S. is associated with mild, cool winters, all climatic regions except region 3 are subject to ice and snow events, requiring significant quantities of both dry and liquid deicing materials to provide safety during storm events. In fact, the northeast of region 2 has some of heaviest uses of deicers in the U.S. due to freezing rain.

Key PEM requirements—Why are they important?

PEMs are designed to address six properties that are critical to the performance of the concrete pavement.

1. Aggregate stability

Ideally aggregates are clean, hard, strong, and durable and will contribute positively to the economy, constructability, and long-term performance of the concrete pavement. Unfortunately, a number of mechanisms can affect the stability of certain aggregates in concrete, particularly when the concrete is subjected to a harsh environment that includes extreme heat with moisture conditions, freezing and thawing under saturated conditions, and being exposed to chemical deicers.

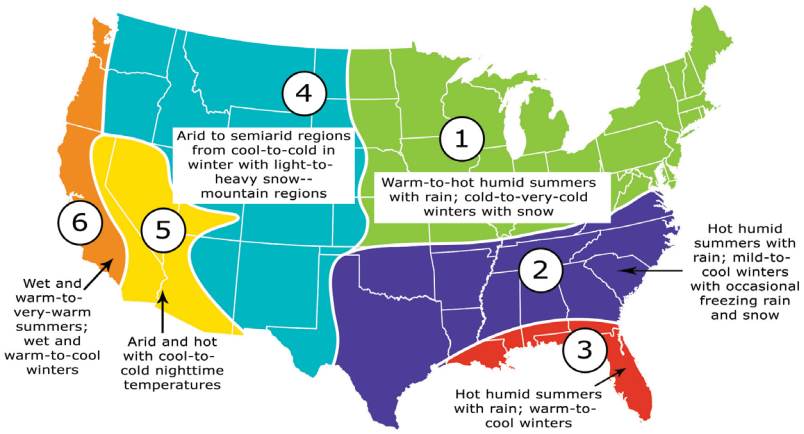

Figure 2. PEMs can be customized for different U.S. weather regions

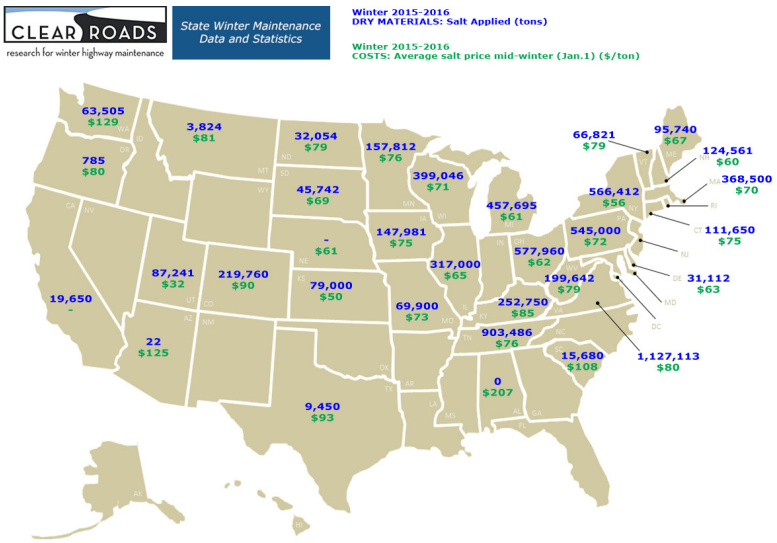

Figure 3. Reported salt usage by state (reprinted with permission from Clear Roads, more info at clearroads.org/winter-maintenance-survey)

D-Cracking

Aggregates that are typically identified as being D-cracking susceptible either fracture and/or dilate as they freeze, resulting in cracking of the surrounding mortar. The most effective means of preventing aggregate freeze-thaw deterioration is by prohibiting the use of susceptible aggregate by specifying that coarse aggregates pass certain freeze-thaw requirements often established by individual SHAs.

Alkali-silica reactivity (ASR)

Most highway agencies in the U.S. have reported instances of alkali-silica reactivity (ASR). ASR is a result of a chemical reaction between the hydroxyl ions of alkalis in the pore solution from the hydrated cement and certain siliceous rocks and minerals that are present in some aggregates.

ASR of most reactive aggregates can be mitigated with the use of SCMs. Application of AASHTO PP 65 is recommended to screen aggregate sources for susceptibility to ASR, as well as provide mitigation strategies.

Alkali-carbonate reactivity (ACR)

Alkali-carbonate reactivity (ACR) is not as common as ASR, but is extremely damaging, resulting in significant expansion and rapid failure of concrete structures. ACR results from a chemical reaction between the hydroxyl ions of alkalis in the pore solution and mineral components of certain carbonate rocks. There is no known strategy that can be employed to mitigate ACR other than identifying ACR susceptible aggregates and avoiding their use in concrete. AASHTO PP 65 provides a protocol to identify ACR susceptible aggregates.

2. Fluid transport properties

In general, the word "transport" is used to describe how fluids move through concrete. Nearly all durability-related distresses involve the transport of fluids, including water and other substances into the concrete. By measuring the transport properties of concrete, a prediction can be made about the material's resistance to potential types of deterioration, such as chloride penetration, sulfate attack, carbonation, ASR, and damage due to freezing and thawing in a saturated state.

Capillary pores form in the cement paste, providing a means for fluids to enter the concrete. The capillary pore volume and interconnectivity are related to the water-to-cementitious materials ratio (w/cm), and the degree to which the paste has hydrated, both decreasing as the w/cm decreases and the degree of hydration increases.

Measurement and control of transport properties has long been a challenge. They are fundamentally controlled by the connectivity of capillary pores within the hydrated cementitious paste, including the interfacial zone around the aggregate particles. It is known that transport properties are controlled through the following methods:

- Reduce w/cm below 0.45, which will reduce both the volume and connectivity of capillary pores. Care must be taken not to reduce the w/cm substantially below 0.40 as this can lead to undesirable autogenous shrinkage.
- Use high-quality SCMs at a proper dosage, as this will react with calcium hydroxide to form calcium silicate hydrate, hence improving long-term transport performance. (See discussion on concrete strength)
- Manage time and temperature, because cement hydration requires both heat and the presence of moisture to progress sufficiently to reduce transport to acceptable levels. This is of particular concern for late season placements in cold climates where not enough time and temperature are available to sufficiently hydrate the cement to prevent damage from freezing and thawing.

A number of test methods have been used to directly or indirectly assess transport properties, all with different strengths and weaknesses. The largest technical barrier has been that all of the methods are sensitive to the moisture state of the sample at the time of testing as well as the degree of hydration of the mixture, both of which are difficult to measure and control.

An electrical method commonly used in specifications is the rapid chloride penetrability test (RCPT) in which the electrical current passed through a sample under a 60V potential is monitored over 6 hours.

An approach based on measuring the resistivity across a sample has shown good correlation with the RCPT and is more cost effective. The basis of the method is that electrical conduction is significantly greater through fluid-filled pores than it is through solids. Therefore, the higher the resistivity, the lower the volume and connectivity of the pore system.

All electrical methods are affected by the following factors:

- Moisture state
- Temperature
- Sample geometry
- Curing conditions
- Ionic concentration of the pore solution
- Volume and connectivity of the pore system

The first four can be experimentally controlled through standardization of testing, and the pore solution chemistry can be determined either by measurement or by knowing the chemistry of the cementitious system and calculating conductivity using available software tools. The remaining parameter, volume and connectivity of the pore system, can be expressed in a single parameter known as the formation (F) factor. The F factor is a fundamental property of the cement paste and is defined as the ratio of the resistivity of a concrete sample to the conductivity, or resistivity, of the pore solution in the sample. The F factor can be used to characterize the pore structure of concrete since it is a constant value that is only dependent on the pore volume and connectivity.

3. Cold weather resistance

Freeze-thaw durability

Concrete is most at risk for freeze-thaw damage when it is at or close to being saturated. The critical saturation point ranges from 78-91%; however, it is normally considered to be approximately 85%. At this saturation level damage occurs in just a few F-T cycles (figure 4). To protect concrete from F-T damage, an air entraining admixture (AEA) is added while the concrete is mixing. An AEA helps stabilize air voids that are spherical and typically between 0.0005 in. and 0.05 in. in diameter. After the concrete hardens, these voids can reduce damage from freezing while larger entrapped air voids present from the mixing process do not. The entrained air will slow the rate of saturation because it is harder to fill larger air bubbles than it is to fill small capillaries. Likewise decreasing w/cm will slow saturation because capillary pores are smaller and less likely to be connected, thereby slowing water penetration in to the system.

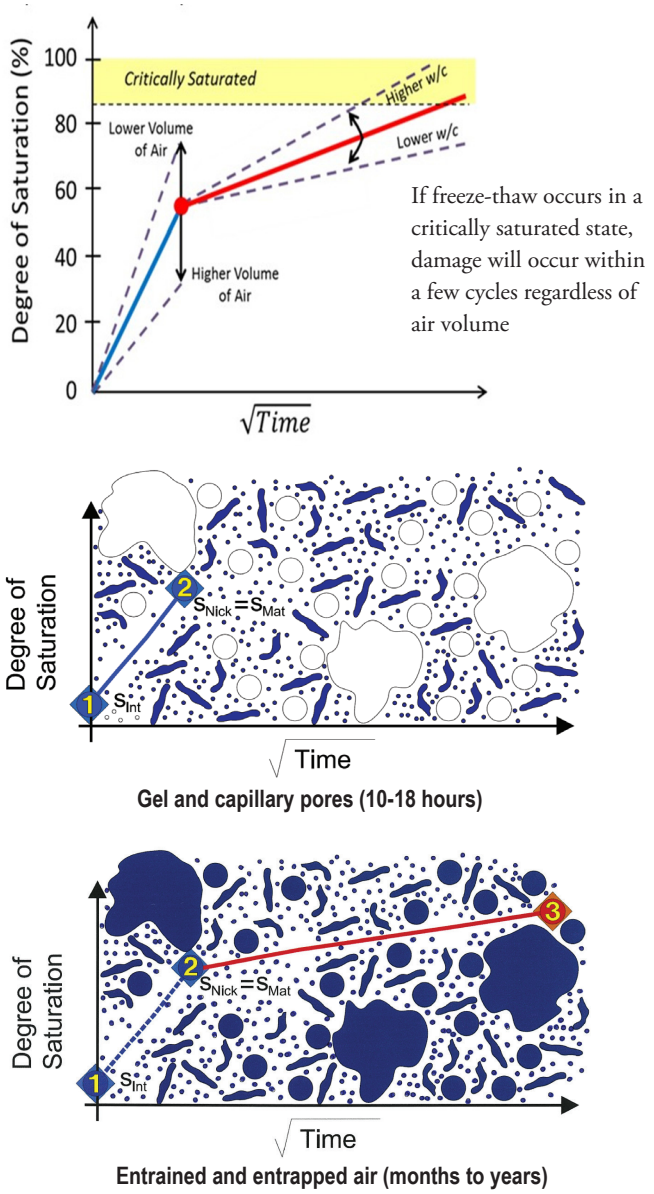

Figure 4.Degree of saturation vs time (illustrations courtesy of Jason Weiss, middle and bottom adapted from Tokan)

Measuring the Air Void System in Plastic Concrete

The desirable air-void system consists of small and well-dispersed bubbles. This is why bubble size and spacing are the two most important parameters in determining the effectiveness or quality of the air-void system. Because these two parameters cannot be directly measured in fresh concrete, most specifications only require a certain volume of total air in the concrete.

Figure 5. Photo of SAM (Ley 2015)

Recent research at Oklahoma State University has led to the development of a new testing device that is able to measure the quality of the air-void system in fresh concrete. This device, the Super Air Meter (SAM), is shown in figure 5 and described by AASHTO TP 118. The device and sample preparation have many similarities to the AASHTO T 152 (ASTM C231) pressure meter, but the SAM test method uses higher pressures and a larger number of pressure events to determine the volume and quality of the air-void system in fresh concrete. The test takes less than 10 minutes to run, and the meter provides both the air content as determined by AASHTO T 152 (ASTM C231) and a new measurement called the SAM number that correlates with the bubble spacing, known as the spacing factor.

Protection of the hydrated cement paste (HCP) from chemical deicers

It is known that chemical reactions (paste softening) can occur between various deicers and a number of phases in hydrated cement paste (HCP), including reactions with the tricalcium aluminate phase to form Friedel's salt. Yet the primary mechanism thought to be responsible for chemical deicer attack is a phase change that occurs in the presence of water, in which the calcium hydroxide present in typical HCP reacts with calcium chloride ($CaCl_2$) to form calcium oxychloride.

The source of $CaCl_2$ can be from $CaCl_2$-based deicers and reactions with magnesium chloride deicers and HCP. The phase change to calcium oxychloride is highly expansive, with the resulting damage to the HCP likely due to crystallization pressures. Figure 6 shows the effect of this expansive reaction on cylinders of mortar soaked in solutions of 17% $CaCl_2$ and 15% $MgCl_2$ at4.4°C (40°F) (i.e., above freezing).

Recommendations for addressing chemical deicer distress are (1) reduce the amount of calcium hydroxide present in the HCP, or (2) decrease the ingress of salt solution into the concrete. The use of SCMs will reduce the amount of remnant calcium hydroxide in the HCP as well as decrease the permeability of the concrete. The ability of SCMs to reduce calcium hydroxide is partially due to dilution, in which the portland cement is replaced by SCMs, and partially by the consumption of calcium hydroxide through the reaction that occurs with certain SCMs (e.g., low-calcium fly ash, slag cement, and silica fume). Reducing calcium hydroxide results directly in a reduction in the formation of calcium oxychloride, as illustrated in figure 7.

Figure 6. Expansion in Mortar Specimens Soaked in (a) 17% CaCl2 and (b) 15% MgCl2 for 150 days at 40°F. Note: specimens were never frozen (Source: South Dakota Department of Transportation)

4. Reducing Unwanted Slab Warping and Cracking Due to Shrinkage

With today's modern concrete paving technologies, including use of concrete mixtures with improved workability, stringless paving, and real-time smoothness measurements, the opportunity exists to construct the smoothest concrete pavements in history. Yet, a trend has been observed on some projects where concrete pavement roughness increased within months of construction and continued to increase over time even in the absence of distress (e.g. cracking, spalling, faulting, etc.). Data indicate that long-term slab warping is influencing some pavement roughness measurements.

Shrinkage

The development of long-term slab curvature is influenced by the drying shrinkage characteristics of the concrete. As the top of the slab dries and undergoes cycles of wetting and drying, the bottom of the slab remains near or at saturation. As illustrated in figure 8, concrete shrinks as it dries. Upon rewetting, it gains back some of this shrinkage (known as recoverable shrinkage), yet some of the shrinkage is permanently lost (irreversible shrinkage).

Equally important, as illustrated in figure 9, as concrete undergoes cycles of wetting and drying, the irreversible shrinkage continues to accrue, with small increments of irreversible shrinkage added at each drying cycle. Under these conditions, the surface continues to accrue increments of irreversible shrinkage until the ultimate shrinkage for the ambient conditions is reached.

Temperature Curling and Moisture Warping

For concrete pavements, curling is defined as curvature induced in the concrete pavement slab as a result of a temperature gradient, in which the surface of the slab has a temperature that is different from that at the bottom. If the top of the slab is warmer (daytime conditions), a downward curvature will develop as the top expands relative to the bottom. The opposite occurs at night when the slab surface is cooler than the bottom and the slab develops upward curl. Temperature curling is not significantly affected by the mixture.

Warping, on the other hand, is curvature in the slab that is induced due to a moisture gradient. After the slab is cast, the surface begins to dry and eventually undergoes wetting and drying cycles depending on the local environment. The bottom of the slab often remains near or at saturation. As a result, the warping induced curvature is almost always upward.

Figure 10 illustrates these two similar, but separate phenomena.

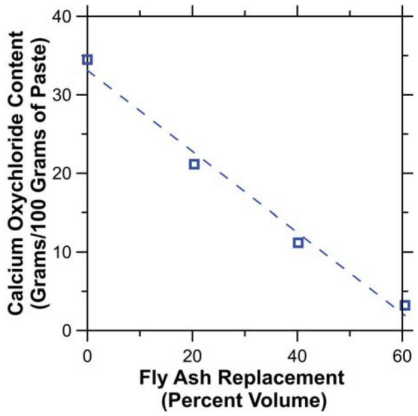

Figure 7. Average CAOXY Contents for a Wide Range of Binders as a Function of Fly Ash (SCM) Replacement

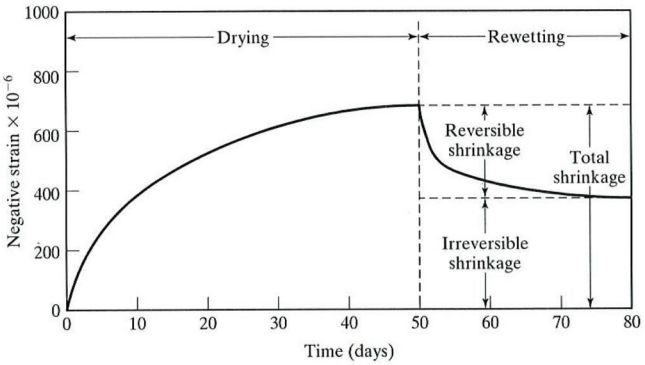

Figure 8. Components of drying shrinkage (Mindess, Young, and Darwin 2008)

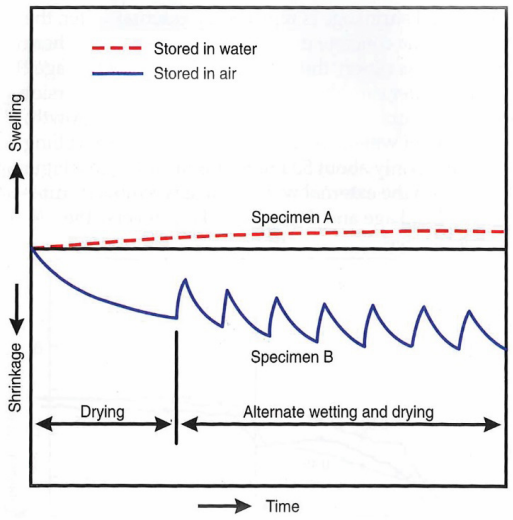

Figure 9. Long-term shrinkage under alternate wetting and drying (Kosmatka and Wilson 2011)

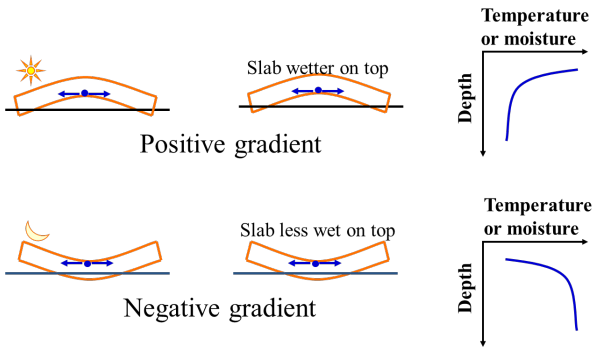

Figure 10. Illustration of curvature due to temperature curling and moisture warping (Mack 2009)

Mixture considerations for mitigation of these effects

The key material property influencing water-related volume changes of concrete is the nature and volume of the pores within the HCP, which in turn is controlled by the volume of cementitious materials and mix water present.

For a given w/cm, reducing the cementitious materials content by increasing the aggregate volume will reduce the ultimate shrinkage of the concrete, not only through reduction in the volume of HCP but also because aggregates provide internal restraint of the shrinkage.

Many of the recommendations addressed by the key PEM requirements will be beneficial to mitigating moisture warping and cracking. These include the following:

- Optimize aggregate gradation and paste content
- Good air system
- Low permeability
- Adequate curing

5. Concrete Strength

The strength of the paving mixture remains an important design parameter. However, strength alone does not ensure good performance of the pavement in service. The paving mixture must obtain the design strength requirement, but also be workable and durable in the local environment.

Aggregates

The gradation, volume, shape, and texture of aggregates make major contributions to the workability, paste content required, and mechanical properties of a concrete mixture.

The aggregate gradation plays a major role in the constructability of a slipformed pavement. For example, if the aggregate gradation contains high amounts on any given sieve size, it negatively impacts the ability of a mixture to be consolidated under vibration and finished. Also, the material on the #8 through the #30 sieves plays an important role in the cohesion of the concrete or the ability for it to hold an edge. Mixtures lacking these sieve sizes are at greater risk of edge slumping and possibly segregation.

There are a number of approaches to selecting an aggregate gradation (Shilstone, Power 0.45 Curve, etc.). One of the most promising recent methodologies is the "Tarantula Curve," plotted using the amount of material retained on individual sieves (figure 11). Systems within this envelope can be close to a theoretical maximum density yet still allow good workability and finishing characteristics. More information can be found at www.optimizedgraded.com.

Paste Content

In principle, the more aggregate that can be put into a mixture, the lower the amount of HCP required. This is beneficial because paste is generally the most expensive component. It also generates heat and is the component that is most prone to mechanisms that effect durability.

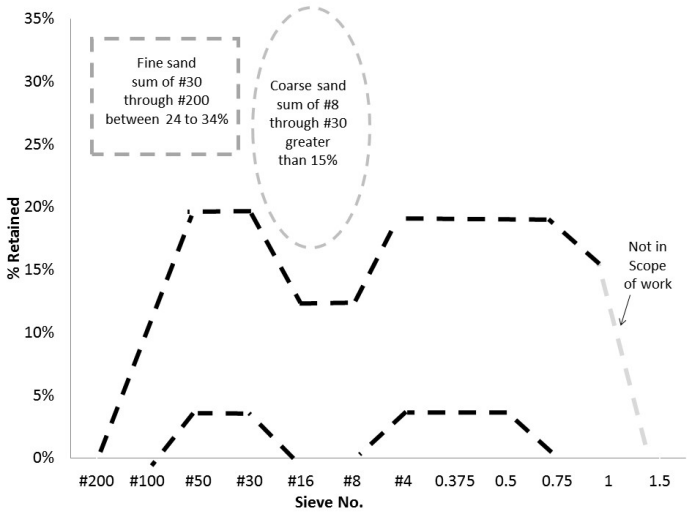

Figure 11. Tarantula curve (source: Tyler Ley)

For a concrete mixture to be workable and meet hardened performance requirements, it should contain a minimum amount of HCP sufficient to fill all of the voids between aggregate particles. An additional amount is also required to separate the aggregates slightly and act as a lubricant to make the mixture workable. Excess paste beyond this amount provides no measurable benefit and may reduce performance in terms of permeability, cracking tendency, and even strength.

Water-Cement Ratio

As discussed under Transport Properties, there are two types of pores in concrete that are important for mass transport: capillary pores and gel pores. The capillary pore volume is related to w/cm (decreases when decreasing the w/cm), and decreases as the system hydrates. Adding excess water to a mix will make it more workable but may compromise other properties. Typically, a good range of w/cm for paving grade concrete is between 0.40 and 0.45.

SCMs

When used in conjunction with portland cement, SCMs can enhance the properties of concrete through hydraulic or pozzolanic activity or both. Fly ash is the most widely used SCM in concrete. The benefits it provides to concrete include the following:

- Less water is normally required to achieve workability.
- Rates of strength gain may be slowed, but later strengths are increased, because fly ash reaction rates are initially slower but continue longer.
- Heat of hydration is reduced.
- Resistance to alkali-silica reaction and sulfate attack may be improved when the appropriate ash and substitution rate are used.
- Permeability is reduced; consequently, resistance to chloride ion penetration is improved.
- Reduction in calcium oxychloride formation when properly proportioned.

6. Workability

The workability requirements of a concrete mixture can change depending on the application. The unique construction process of slipformed paving requires the workability of a mixture to be flowable enough under vibration for consolidation but still able to hold an edge after the vibration has stopped and the side forms are removed. This property of concrete is called thixotropy and is controlled by the paste properties of a mixture and the aggregate volume and gradation.

Two new tests have been developed that better represent how a low-slump mixture will respond to vibration. Both the Box Test and V-Kelly tests are significant advancements from the slump test, which became an ASTM Standard in 1922. While the slump test may have some utility as a Q/C tool, it is broadly recognized that the slump test is not very meaningful for predicting workability of concrete paving mixtures.

Box Test

This test investigates the concrete's response to vibration and its ability to hold an edge after the vibration is stopped and the side forms are removed. Unconsolidated concrete is placed in a 1 ft^3 collapsible wood form and vibrated in a consistent manner. Next, the wood forms are removed and the sides of the concrete are inspected for excessive voids. If the sides have excessive voids, the mixture did not consolidate under the vibration and is not satisfactory. Also, the edges of the concrete can be inspected for edge slumping. Illustration of the Box Test is shown in figure 12.

V-Kelly Test

The Kelly ball test—the basis of the V-Kelly test —was developed in the 1950s in the United States as a fast alternative method to the slump test. The test was formerly standardized in ASTM C360-92, Standard Test Method for Ball Penetration in Freshly Mixed Hydraulic Cement Concrete (1992). However, it was discontinued in 1999 due to lack of use and has never been widely used outside the United States. In 2014, California Test 533 brought it back again as a modification of ASTM C360. However, the test was not able to give valuable information when testing low-slump concrete.

To overcome this shortcoming, the test was modified by Iowa State University through the addition of a vibrator attached to the Kelly ball. The ball is trimmed to maintain the original weight of 30 lbs. This enhancement enables the V-Kelly test apparatus to be used on low slump mixtures for assessing a mixture's response to vibration (workability) (figure 13).

Quality Control

These new test procedures, applied in conjunction with the PP-84 specification, give owners the opportunity to better specify and assess the quality of their concrete pavements. Contractors and suppliers can also use these tools to better guide their quality control operations and produce a more consistent high-quality mix. PP-84 is a provisional specification and will continue to develop over the next few years to reflect additional information learned during implementation and performance monitoring of projects. A critical part of successfully using the recommended approach to the PEM specification is the contractor's Q/C plan. A future MAP brief will provide a more detailed overview of the contractor's critical role in fully achieving the optimal outcomes from the PEM specification.

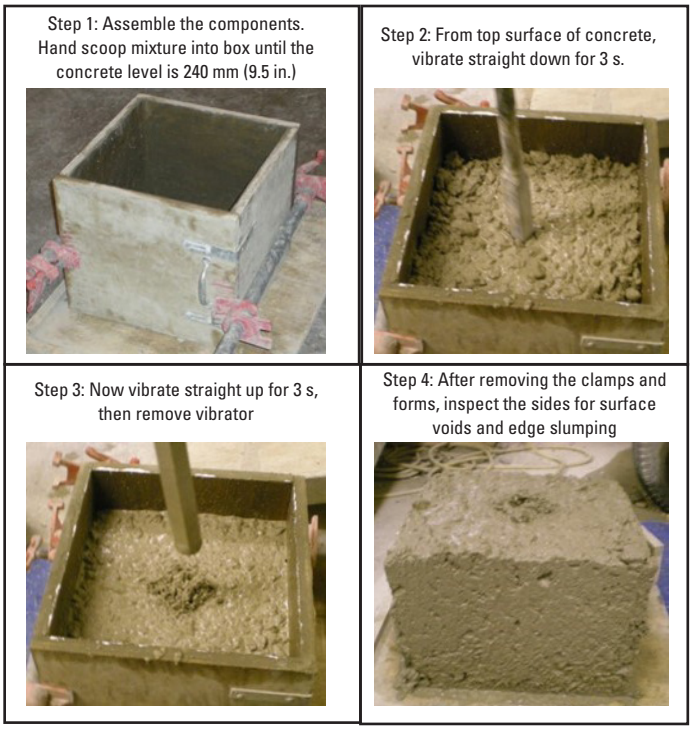

Figure 12. Four steps of the Box Test (source: Oklahoma Transportation Center, Cook et al. 2013)

Figure 13. Ongoing V-Kelly test

For more information

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