Tech Brief

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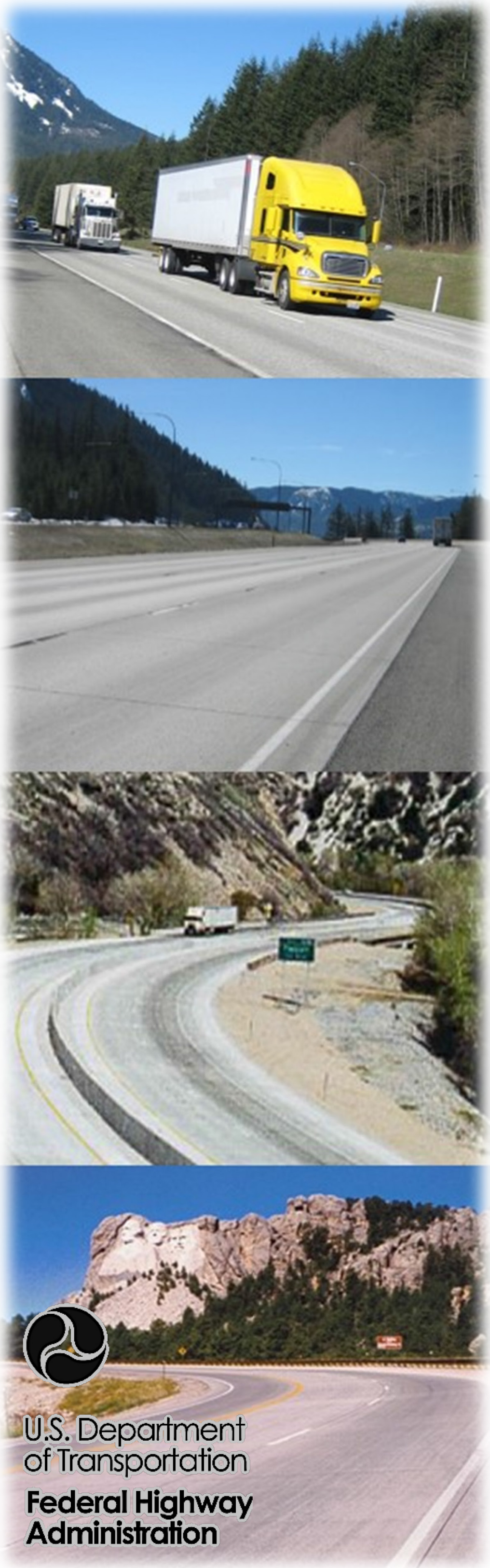
ENSURING DURABILITY OF CONCRETE PAVING MIXTURES
PART II: TEST METHODS



U.S. Department of Transportation
Federal Highway Administration

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INTRODUCTION AND BACKGROUND

In its simplest form, hydraulic cement concrete (hereafter referred to simply as concrete) is composed of aggregates bound together by a hydrated cement paste (HCP). The structural performance of a concrete pavement is addressed through consideration of the system's response to repeated loading, factoring in material properties, support conditions, slab geometry, load transfer, and climatic impacts. The assumption inherent in pavement structural design is that if the concrete possesses the required mechanical properties (e.g., strength, stiffness), the pavement will achieve design expectations as long as the concrete is durable.

Unfortunately, durability is not an intrinsic material property of concrete. Instead it is a set of material properties that are required for the concrete to resist the particular environment in which it serves (TRB 2013). For example, a concrete placed in a mild, dry environment may remain wholly intact for decades yet that same concrete may rapidly disintegrate if exposed to chemical deicers in a wet, freeze-thaw environment. Both the environment and materials must be considered together to specify and construct durable concrete pavements.

A companion Tech Brief (*Ensuring Durability of Concrete Paving Mixtures-Part I: Mechanisms and Mitigation*) describes the mechanisms responsible for materials-related distress (MRD) that can compromise the durability of concrete and outlines strategies to improve the durability of concrete paving mixtures. This Tech Brief builds on that Tech Brief, presenting approaches for testing constituent materials and concrete mixtures to assess resistance to various types of MRDs.

No test, or combination of tests, directly measures the durability of concrete. Instead, multiple tests are employed on both the constituent materials and on the concrete itself to make an assessment of whether the concrete will be durable in a specific environment. Commonly used durability-related test methods, summarized in table 1, can be used to test constituent materials and project specific mixtures during the mix design process, as well as during the construction of the pavement.

TESTING CONSTITUENT MATERIALS

Concrete constituents are routinely tested as part of the mixture design approval process. For example, common requirements present in standard specifications, such as AASHTO M 85 (ASTM C150) for portland cement and AASHTO M 6/M 80 (ASTM C33) for aggregates, need to be met. In addition, further testing of constituent materials may be required, depending on the environment in which the concrete will be placed or to address specific durability concerns.

Cementitious Materials: Resistance to Sulfate Attack

External sulfates (usually from sulfate bearing soils) can attack HCP, potentially resulting in severe damage to concrete structures. Approaches to addressing external sulfate attack are to reduce the water-to-cementitious materials ratio (*w/cm*), use sulfate resistant cement, and use increasing amounts of certain supplementary cementitious materials (SCMs) (ACI 2008).

Table 1. Summary of common test methods used to assess the durability of concrete (APTech 2017).

Distress Mechanism	Construction Phase	Test Method	Brief Description of Test
Paste Freeze-Thaw Deterioration	Mix Design	ASTM C457	Microscopic analysis of hardened air-void system
	Mix Design	AASHTO T 161	Cyclic freeze-thaw test of hardened concrete beams
	Mix Design and Construction QA	AASHTO T 152, T 196, T 121	Common tests of air content in fresh concrete
	Mix Design and Construction QA	AASHTO TP 118	Super Air Meter (SAM) of air in fresh concrete
Aggregate Freeze-Thaw Deterioration	Constituent Materials and Mixture Design	ASTM C1646 AASHTO T 161	Cyclic freeze-thaw test of hardened concrete beams
Alkali-Aggregate Reactivity (AAR)	Constituent Materials	ASTM C295	Petrographic evaluation of aggregate
	Constituent Materials	CSA A23.2-26A	Chemical composition of carbonate aggregates for alkali-carbonate reactivity (ACR)
	Constituent Materials	ASTM C1105	ACR concrete prism test
	Constituent Materials	ASTM C1293	Concrete prism test in which ASTM C856 used to determine cause of expansion
	Constituent Materials and Mixture Design	AASHTO T 303	Accelerated mortar bar test for alkali-silica reactivity (ASR)
External Sulfate Attack	Constituent Materials	ASTM C1012	Length change of mortar bars exposed to sulfate solution
Transport Properties	Mix Design and Construction QA	ASTM C1585	Absorptivity
	Mix Design and Construction QA	AASHTO T 277	Rapid chloride penetration test
	Mix Design and Construction QA	AASHTO T 358	Surface resistivity

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The test method used to assess the sulfate resistance of cementitious systems is ASTM C1012, *Length Change of Hydraulic-Cement Mortars Exposed to Sulfate Solution*. In this test method, mortar bars are made and tested using the cementitious system being evaluated. ASTM C1105 can be used to test portland cement (AASHTO M 85/ASTM C150), blended cement (AASHTO M 295/ASTM C595), performance cement (ASTM C1157), and SCMs blended with cements. After curing, the mortar bars are immersed in a sulfate solution (the standard solution contains 352 moles of Na_2SO_4 per m^3 or 50 g/L) and length change is assessed over time. The limit on length change set by ACI (2008) is 0.10 percent and the level of mitigation is based on the age at which this level of expansion is exceeded. Moderate, severe, and very severe exposure conditions require 6 months, 12 months, and 18 months of immersion in the sulfate solution without exceeding the expansion limit, respectively.

Aggregates

Two common MRDs are directly related to aggregates: aggregate freeze-thaw deterioration and alkali-aggregate reactivity.

Resistance to Freeze-Thaw Deterioration

Certain coarse aggregates fracture or dilate when subjected to repeated cycles of freezing and thawing in a critically saturated state. This results in cracking of the surrounding mortar and deterioration of concrete. Often the deterioration first appears as staining and fine cracking parallel to joints and cracks on a pavement surface. Eventually the “stained” areas break down, further cracking occurs, and the concrete deteriorates.

Highway agencies experiencing aggregate freeze-thaw damage have developed screening protocols that are almost exclusively based on variations of AASHTO T 161 (ASTM C666), *Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing.* The concrete specimens tested in AASHTO T 161 must be rigorously prepared and cured using a procedure such as ASTM C1646, *Standard Practice for Making and Curing Test Specimens for Evaluating Resistance of Coarse Aggregate to Freezing and Thawing in Air-Entrained Concrete*; otherwise considerable variability may be introduced in the test results.

ASTM C1646 provides the standard requirements for evaluating aggregates in air-entrained concrete to determine their susceptibility to damage resulting from cyclic freezing and thawing. Specimens prepared in accordance with ASTM C1646 are then tested according to AASHTO T 161, and deterioration assessed based on changes in dynamic modulus, linear expansion, or weight loss (Kosmatka and Wilson 2011). In this test method, concrete beams are prepared with the aggregate under evaluation and subjected to rapid freezing and thawing cycles. In Procedure A, the specimens are frozen and thawed in water whereas in Procedure B freezing occurs in air while thawing is done in water. Procedure A is the preferred method for aggregate screening (TRB 2013).

This combination of two testing standards, one for specimen preparation and one for the testing sequence, is the most widely used test method for evaluating freeze-thaw resistance of aggregate (Nmai 2006). It has been widely adopted, often with slight modification, by a number of Midwestern state highway agencies to address their specific needs and observations as an aggregate screening tool.

The main criticism of the test method is that it is not representative of actual field conditions. The concrete is subjected to rapid freezing and thawing in a saturated state, which is unlikely to occur in the field. Thus, although the test is able to rank aggregate from excellent to poor, some say it cannot be used reliably to predict the field performance of marginal aggregate (Nmai 2006). Because the test is more severe than actual field conditions, aggregates that pass this test are generally going to perform well in the field at the expense of potentially rejecting aggregate sources that have demonstrated good field performance.

The test method is well documented in AASHTO T 161 and in ASTM C1646. The potential for deterioration is most often assessed through the linear expansion of the specimen or through the reduction in the dynamic modulus of elasticity of the concrete as indicated below:

- A maximum expansion failure criterion of 0.035 percent dilation at 350 freeze-thaw cycles is used as an indicator of aggregate susceptibility to freeze-thaw deterioration (Kosmatka and Wilson 2011).
- A durability factor (DF) criterion (often 60 or 80 percent) based on changes in the dynamic modulus of the specimen determined through the resonant frequency method (ASTM C215). Typically the test is run between 300 and 350 cycles.

The acceptance criteria are set by each agency.

Resistance to Alkali-Aggregate Reactivity (AAR)

The pore solution present in HCP is highly alkaline, typically having pH values in excess 12. As alkalinity increases certain aggregate minerals can become unstable, resulting in instability within the aggregates themselves and the formation of reaction products that may swell and damage the concrete. There are two widely recognized deleterious alkali-aggregate reactions: alkali-carbonate reactivity (ACR) and alkali-silica reactivity (ASR). Both are discussed in detail by Thomas, Fournier, and Folliard (2013).

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 is a result of a chemical reaction between the hydroxyl ions of alkalis in the pore solution and certain carbonate rocks (notably calcitic dolostone and dolomitic limestones) (Thomas, Fournier, and Folliard 2013). There is no known strategy that can be employed to prevent ACR other than identifying ACR susceptible aggregates and avoiding their use in concrete. Tests that can be used to screen aggregate sources for ACR susceptibility include:

- ASTM C295, *Standard Guide for Petrographic Examination of Aggregates for Concrete*. Aggregates are microscopically evaluated by a trained petrographer who evaluates them for the presence of reactive constituents. The reliability is highly dependent upon the experience and skill of the petrographer, who looks for specific diagnostic features within the calcareous dolomites and dolomitic limestones that are indicative of ACR susceptibility.
- CSA A23.2-26A, *Determination of Potential Alkali-Carbonate Reactivity of Quarried Carbonate Rocks by Chemical Composition*. The CaO, MgO, and Al_2O_3 contents of the carbonate rock are measured and the Al2O3 content in percent is plotted on the horizontal axis against the log of the ratio of CaO/MgO on the vertical axis. Aggregates that are considered potential expansive have a composition that will plot:
    - above a line drawn from an Al2O3 content of 0 (zero) and a CaO/MgO of approximately 3.3 to an Al2O3 content of approximately 6.5 and a CaO/MgO of approximately 1.75, and
    - below a line drawn from an Al2O3 content of 0 (zero) and a CaO/MgO of approximately 12.5 to an Al2O3 content of approximately 5.5 and a CaO/MgO of approximately 63.

  See CSA A23.2-26A for more information.
- ASTM C1105, *Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock Reaction.* This is a concrete prism test that is conducted with lower cement alkali content than ASTM C1293 (discussed next). At the lower alkali loading, ASR will not occur and thus expansion is associated with ACR. The expansion limit is set at 0.025 percent at 6 months or 0.030 percent at 1 year. Aggregates exceeding these limits are considered to be ACR susceptible.
- ASTM C1293, *Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction*. As the name indicates, this test is designed to evaluate aggregates

for ASR, but it will also trigger expansion in aggregates due to ACR. Therefore, concrete that suffers unacceptable expansion in this test should be evaluated petrographically using ASTM C856, *Standard Practice for Petrographic Examination of Hardened Concrete* to determine the cause of expansion. This test will be discussed in more detail with regards to ASR.

The reader is directed to Thomas, Fournier, and Folliard (2013) and AASHTO PP 65 for a more in-depth discussion of these test methods.

Alkali-Silica Reactivity

In contrast to ACR, most highway agencies in the U.S. have reported instances of 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 (including opal, chert, microcrystalline quartz, and acidic volcanic glass) that are present in some aggregates (Thomas, Fournier, and Folliard 2013). The reaction results in the formation of an alkali-silica gel that, under certain circumstances, can imbibe water, expand, and fracture the affected aggregate particles and surrounding paste. Extensive information is available regarding the mechanisms responsible for ASR and the strategies to mitigate it (Thomas, Fournier, and Folliard 2013). For highway applications, AASHTO PP 65 (*Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*) provides the most comprehensive recommendations on mitigating ASR. The protocols are detailed and should be consulted if ASR is a concern.

As with ACR, ASTM C295 can be used as part of an ASR testing regime to identify many, but not all, of the potentially reactive constituents within an aggregate source. But due to the uncertainties involved, it is recommended that the result be used in conjunction with other laboratory tests. To this end, the two test methods that are the centerpiece of AASHTO PP 65 for ASR mitigation are:

- AASHTO T 303 (ASTM C1260), *Standard Method of Test for Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction.*
- ASTM C1293, *Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reactivity.*

AASHTO T 303 is often referred to as the accelerated mortar bar test (AMBT) as it provides results in a relatively short time period of 16 days. This makes it useful as not only a screening test, but also a test that can be conducted during the mixture design process or even during construction if one of the relevant concrete constituents changes. The test consists of making mortar beams containing the aggregate of interest (either fine aggregate or crushed coarse aggregate) and after 2 days, soaking them in a 176 °F 1N NaOH solution for 14 days. Length change measurements are made periodically and the total expansion after the 14 days of soaking is typically used as the criteria to classify the aggregates as potentially reactive or not.

Different agencies have different criteria on the expansion limit. In AASHTO PP 65, the limit is 0.10 percent at 14 days of soaking in the NaOH solution (the total time elapsed since casting is 16 days). Aggregates with an expansion of less than 0.10 percent at 14 days are considered non-reactive. An important caveat in AASHTO PP 65 is that the results of the AASHTO T 303 are not as accurate as those from ASTM C1293 for evaluating the reactivity of aggregates, and thus there is some risk of accepting an aggregate source that may be reactive. A risk also exists in rejecting an aggregate source that is actually acceptable as the test is known to be very severe. It is therefore recommended that both AASHTO T 303 and ASTM C1293 be conducted for aggregate screening.

ASTM C1293 is commonly referred to as the concrete prism test (CPT), as concrete prisms made with the aggregates under evaluation are tested. The CPT is considered the best available test for assessing the potential field performance of aggregates (Thomas, Fournier, and Folliard 2013). In the CPT, a standard concrete mixture with an alkali loading of 1.25 percent by mass of cement (equivalent to an alkali loading of 8.85 lbs/yd^3) is made and cast into prisms. After an initial 24 hour curing, the concrete prisms are stored over water at 100 °F, typically for 1 year when screening aggregate for use in concrete containing only pure portland cement. The expansion limit, which is included in the ASTM C1293 appendix and cited in AASHTO PP 65, is 0.04 percent.

The major limitation of ASTM C1293 is the duration of testing (1 year), which is feasible for aggregate source screening but makes it highly impractical for project specific evaluation. Another problem is that alkalis are known to leach from the concrete during testing, an issue partially addressed by increasing the initial alkali loading beyond what would normally occur to compensate for the loss in alkalis over time. But this approach only partially addresses the issue as alkali leaching can have a profound effect in practice, and thus it is not recommended that ASTM C1293 be used to establish the alkali threshold for an aggregate source or aggregate-binder combination (Thomas, Fournier, and Folliard 2013). Regardless of the limitations inherent in ASTM C1293, it is currently recognized as the most accurate and effective test method for screening aggregates for ASR as described in AASHTO PP 65.

TESTING PROJECT-SPECIFIC CONCRETE MIXTURE

Due to constraints, some test methods discussed above are not feasible for testing project-specific concrete mixtures whereas other test methods are well-suited for this application. These are discussed below.

Resistance to Freeze-Thaw Damage

Once an aggregate source has been screened for freeze-thaw susceptibility, the susceptibility of a concrete mixture to cyclic freezing and thawing is largely dependent on the presence of an adequate air-void system (as described in the companion Tech Brief). It is recognized that the characteristic of importance is the size and spacing of the spherical air bubbles that have been purposely entrained in the concrete through the addition of an air-entraining admixture. Unfortunately this characteristic is difficult to measure directly. Thus, test methods are often employed that measure the total air content in the plastic concrete as a surrogate indicator of the hardened air-void system. The following are the current test methods that can be used during the mixture design process to assess the freeze-thaw durability of concrete.

Test of Air-Void System in Hardened Concrete

The most rigorous methodology to evaluate the air-void system in concrete is microscopically, viewing a polished concrete slab in accordance with ASTM C457, *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*. In addition to calculating the total volume of air in the concrete, ASTM C457 also provides the equations to calculate other air-void system parameters that are related to freeze-thaw durability including the spacing factor and specific surface. The spacing factor is a parameter that describes, for the majority of the paste, the distance to the nearest air void, whereas the specific surface is the surface area of the air voids divided by their volume. The ability of the concrete to resist freeze-thaw damage increases as the spacing factor decreases (i.e., the air voids become more closely spaced) and as specific surface increases. ASTM C457 discusses a desired maximum spacing factor of 0.008 inch for freeze-thaw resistance for concrete subjected to moderate exposure conditions, stipulating that this value can be higher for mild exposure and should be lower for severe exposure conditions, especially if the concrete is exposed to deicing chemicals.

Because this test method requires a trained technologist using a microscope and can take 3 hours or more to execute, alternative automated methods have been developed in which digitally captured images are analyzed (e.g., RapidAir 457, flatbed scanner method [Peterson et al. 2001]). These methods are currently undergoing standardization, but even the automated methods still require extensive sample preparation and can only be conducted on hardened concrete. As a result, ASTM C457 or related automated methods are suitable for air-void system evaluation during the concrete mixture design phase, but are not suitable for conducting QA testing during construction since the results take days to obtain.

Tests of Total Air Content in Fresh Concrete

A recommended approach to overcome this shortcoming is to correlate the observations made on hardened concrete with the results from more common tests conducted on plastic concrete for the specific mixture under consideration. To be most useful as a QA tool, the testing on fresh concrete must occur as it is delivered to the site prior to placement. Common test methods used to assess air in fresh concrete have focused almost exclusively on measurement of the total volume of air in the mixture, and not the size and distribution of the air voids. Standard tests (or variations thereof) used by state highway agencies include:

- AASHTO T 152*, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method (eq. ASTM C231).* The pressure method is the most commonly used test to assess the air content of paving grade concrete made with normal weight aggregates. It is based on Boyle's law that relates pressure to volume. Fresh concrete is placed in a pressure-type meter and a predetermined pressure applied, which compresses the air contained within the concrete sample including that within the aggregate (this is why the test is not suitable for use with lightweight or highly porous aggregates). The total air content present is read directly from the gauge of a calibrated Type B pressure meter.
- AASHTO T 196, *Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method (eq. ASTM C173)*. The volumetric method (also known as the Rollometer) can be used to measure the total air in fresh concrete containing any type of aggregate, including lightweight or porous aggregates. It is based on measuring the volume of air removed from a known volume of concrete through vigorous agitation in the presence of a known volume of water-isopropyl alcohol. Although this test method has broader application and does not require the use of a correction factor (as does the volumetric method), it is not as commonly used as it takes more time and is physically demanding on the technician responsible for agitating the concrete. Thus, its use is often restricted to concrete mixtures that cannot be assessed using the pressure method (such as those containing lightweight or porous aggregates).
- AASHTO T 121, *Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete (eq. ASTM C138).* The gravimetric method is based on the density (unit weight) of fresh concrete, in which the measured density is subtracted from the theoretical density determined from absolute volumes of the ingredients assuming no air is present. Because the test method accuracy is dependent on accurately knowing the volume and specific gravities of all the concrete constituents, the gravimetric method is not useful for a direct measurement of air content during construction, but instead is used as a "check" during laboratory mixture design and during construction as a comparison to the air content determined using one of the other methods.

The methods described above provide a measure of total air in the fresh concrete, but do not provide an indication of how the air is distributed or the size and spacing of the entrained air bubbles. This can be problematic as certain combinations of concrete-making materials can result in mixtures that have air contents that meet specification but have air-void system distributions that may not protect the concrete in a severe freeze-thaw environment (Freeman 2009; Felice, Freeman, and Ley 2012; Ram et al. 2012).

Air-Void Analyzer

In an attempt to address the shortcoming inherent in only measuring total air content, the air-void analyzer (AVA) was introduced into the U.S. market after being developed in Europe in the early 1990s. The test method is based on the principle of buoyancy, as larger air bubbles rise more rapidly through a viscous liquid than smaller bubbles. A small sample of concrete (the larger aggregates are sieved out) is agitated at the bottom of a cylinder containing the viscous liquid, releasing the air bubbles. These float to the top and accumulate under a pan, with the increase in buoyancy measured on a balance. The changes in buoyancy are plotted over time and related to the size distribution of the bubbles. The method for conducting this test is standardized in AASHTO T 348, *Standard Method of Test for Air-Void Characteristics of Freshly Mixed Concrete by Bouyancy Change*. Although this test method provides very useful information in many cases, it application as a QA tool is limited for the following reasons:

- The AVA will not provide an accurate measure of total air content, so additional testing is required if that is of interest (Kosmatka and Wilson 2011).
- The test requires expensive equipment that is very sensitive to vibration and other site conditions and must be housed in a trailer in the field.
- The test takes significantly more time to conduct than other common air tests such as the pressure method. This limits the number of tests that can be conducted.
- Concerns exist regarding variations in the test results and inconsistencies in the relationship between AVA results and other test results (Wang et al. 2008).
- Difficulties have been encountered in uniformly releasing the entrained air during agitation when using the AVA with stiff, low slump slipform paving grade concrete. This contributes to variability in the test results.

Because of the difficulties cited above, the initial enthusiasm regarding the adoption of the AVA has waned, even among early adopters of the technology.

Super Air Meter

An alternative method to characterize the air-void system in fresh concrete is the Super Air Meter (SAM), which is standardized under AASHTO TP 118, *Provisional Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method.* The SAM is a modified version of an AASHTO T 152 pressure meter (Ley and Tabb 2013; Welchel 2014), but instead of using a single testing pressure as is used in AASHTO T 152, the SAM uses sequential pressures to determine the volume of total air and to make an inference regarding the quality of the air-void system.

The SAM uses a traditional AASHTO T 152 pressure meter, with the traditional dial gage having been replaced by a digital gage and six clamps (instead of four) to provide additional restraint under the higher testing pressures. Figure 1 shows a modern production model of the SAM .

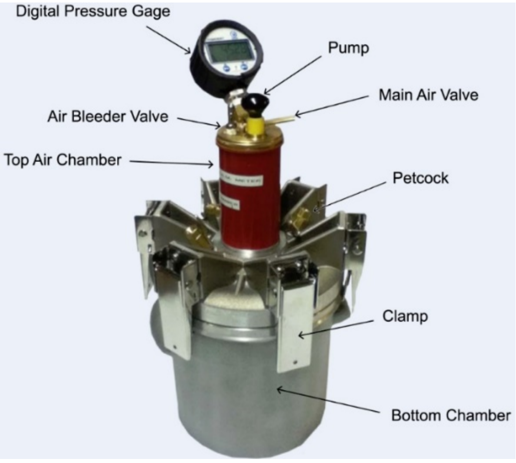

Figure 1. SAM device production model.

The SAM is used in two modes. The first mode uses the same analytical conditions that are used in an AASHTO T 152 Type B meter test (14.5 psi pressure); consequently, the same information is obtained with regards to air content. In the second mode, two additional sequential pressurizations are applied at 30 psi and 45 psi. After the first sequence, the pressure is released, and the sequence is repeated a second time. The difference in the equilibrium pressure at the highest pressure (45 psi in the top chamber) for the first and second sequence is reported as the SAM number, as illustrated in figure 2.

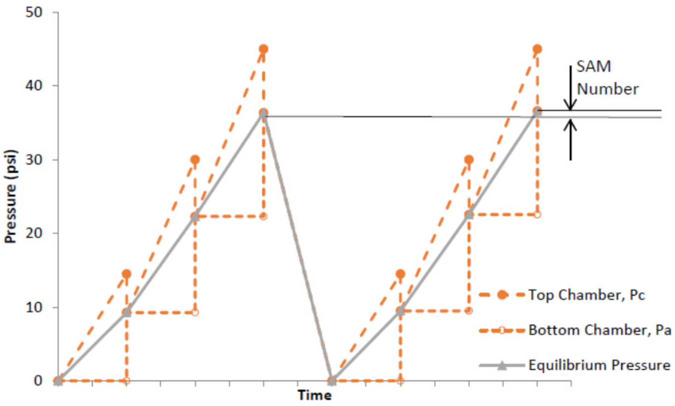

Figure 2. Sequential pressures applied in the SAM and calculation of the SAM Number (Welchel 2014).

The SAM Number has been correlated to the air-void spacing factor obtained through ASTM C457 and the Durability Factor (DF) of concrete as assessed in AASHTO T 161 (Ley and Tabb 2013; Welchel 2014). Figure 3 is a plot of the SAM Number versus the ASTM C457 spacing factor for multiple concrete mixtures. Dashed lines indicate the failure criteria for both test methods (0.2 psi for the SAM Number and 0.008 inch for the spacing factor). Similarly, figure 4 is a plot of SAM Number versus the AASHTO T 161 DF, again with dashed lines showing common failure criteria (70 percent for the DF). Results suggest that the SAM Number has a better correlation with results from AASHTO T 161 than it does to the ASTM C457 spacing factor (Ley 2015).

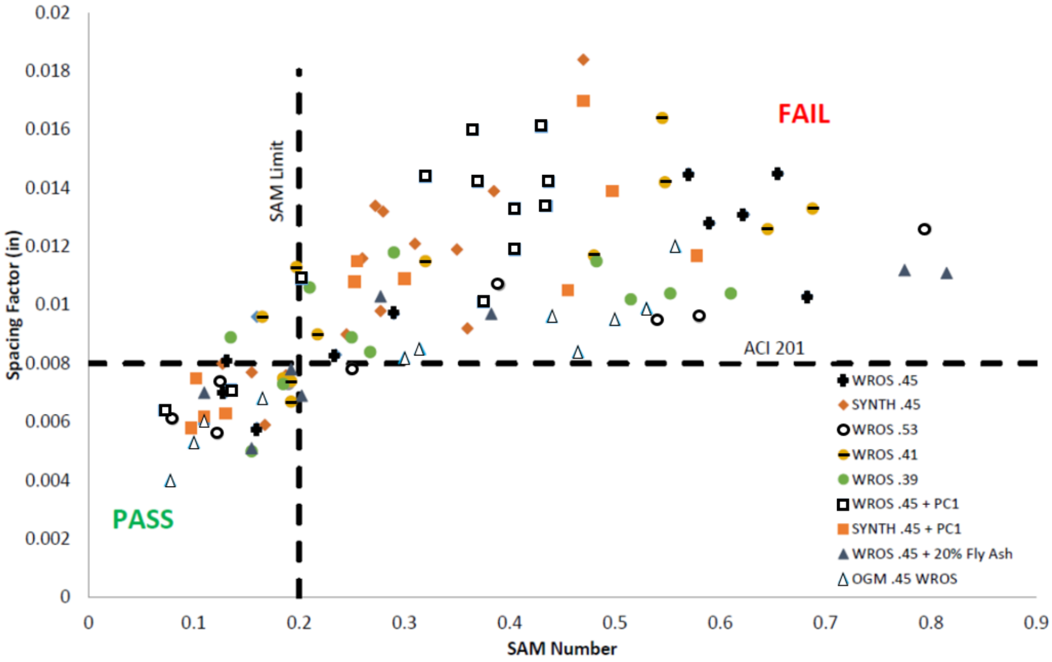

Figure 3. Plot SAM Number versus ASTM C457 spacing factor (Welchel 2014).

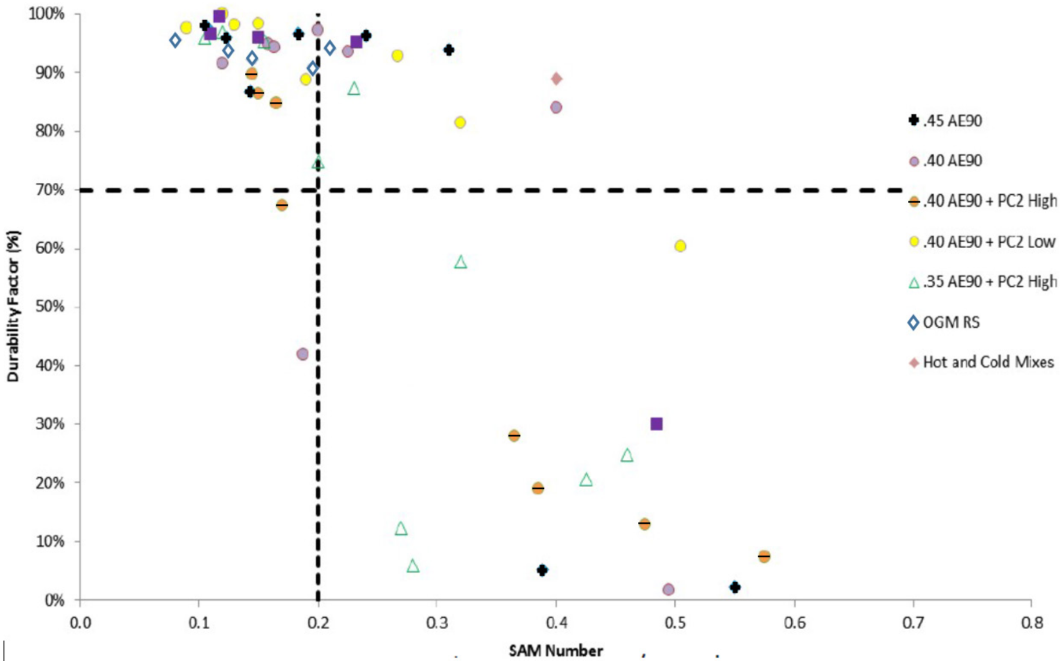

Figure 4. Plot of SAM Number versus AASHTO T 161 Durability Factor (Ley 2015).

The recommended acceptance criteria for the SAM test during the mixture design phase are (Ley 2015):

- Total air content should be greater than 5 percent.
- If the SAM Number is less than 0.20 psi, the concrete is acceptable.

Resistance to Alkali-Silica Reactivity (ASR)

As discussed under aggregate screening, an aggregate source found to be potentially susceptible to ACR must be rejected as there is no reliable method to mitigate this type of MRD. The situation is different for ASR in which various mitigation strategies are available depending on the reactivity of the aggregate, the importance of the structure, and the environmental conditions as described in the AASHTO PP 65 protocol. The effectiveness of mitigation during mixture design is assessed using two of the same test methods used for aggregate screening with minor modification. The first is the AMBT (AASHTO T 303/ASTM C1567), which is conducted with the same specimen geometry, aggregate gradation, storage conditions, and acceptance criteria as ASTM C1260, but some of the portland cement is replaced with SCMs. It is stipulated in the AASHTO PP 65 protocol that the test can only be used to test the effectiveness of a mitigation strategy if a reasonable correlation between AASHTO T 303 and ASTM C1293 was first developed during the aggregate screening process, as shown in figure 5 (Thomas, Fournier, and Folliard 2013). If the correlation in figure 5 is not established, the ASTM C1293 test should be used to assess effectiveness. The test method and acceptance criteria remain identical except that the test duration is extended to 2 years and SCMs may be used to replace portland cement, on a mass basis. If lithium nitrate is being considered as a mitigation strategy, the recommendations presented in AASHTO PP 65 must be followed.

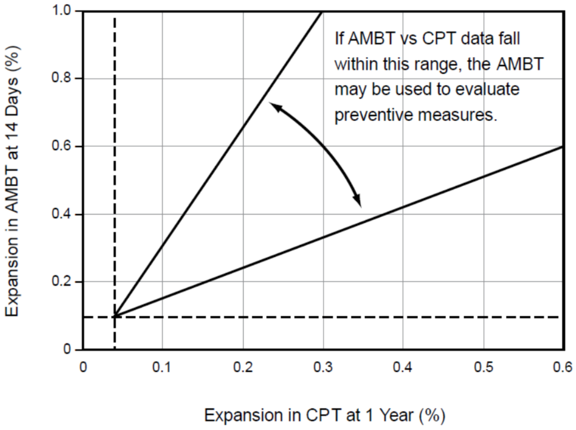

Figure 5. Determining suitability of AMBT for evaluating mitigation strategies.
(From AASHTO PP 65, *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*. Used by permission)

Transport Properties

The transport of fluids and gases into concrete is of great interest with regards to durability as all MRDs involve the transport of moisture into the concrete, and at times other substances such as chloride ions for corrosion or sulfate ions for external sulfate attack. The mechanisms and the test methods employed to directly or indirectly assess this transport are described in several documents, including Stannish, Hooton, and Thomas (2000); Hearn, Hooton, and Nokken (2006); and Weiss (2014). Three test methods in particular that have been employed to assess transport properties in paving concrete are:

- ASTM C1585, *Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concrete.*
- AASHTO T 277 (ASTM C1202), *Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.*
- AASHTO T 358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration.*

ASTM C1585

ASTM C1585 is a relatively simple absorption test in which the degree and rate of water absorption (I) is measured into a conditioned thin concrete sample (2 inch thick by 4 inch diameter) at specified intervals for a minimum of 8 days. A schematic of the test set up is shown in figure 6.

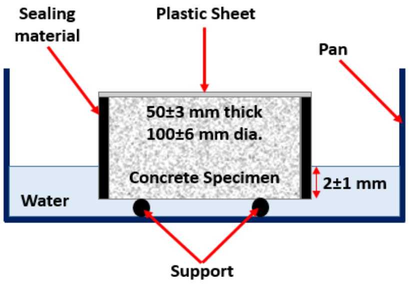

Figure 6. Schematic of specimen set up.

The rate of water absorption (mm/s$^{1/2}$) is defined as the slope of a best fit line of I plotted against the square root of time (s$^{1/2}$). It is typically observed that the slope makes a definitive change at some point, and thus two absorptions are defined: the initial absorption and the secondary absorption. This is illustrated in figure 7. The absorption can be converted to degree of saturation (S), defined as the ratio of the absolute volume of absorbed water to the total volume of water accessible pores. The degree of saturation at the intersection between the initial and secondary absorption is related to point where the capillary pore system becomes saturated; work is on-going in efforts to relate this to paste freeze-thaw deterioration (Weiss 2014).

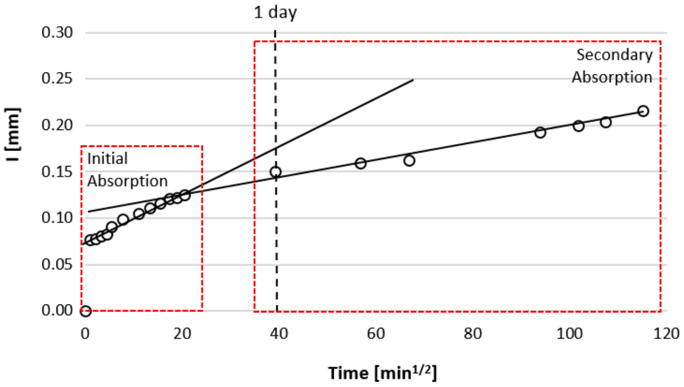

Figure 7. Illustration of initial and secondary absorption (Bentz et al. 2002).

AASHTO T 277 (ASTM C1202)

In the last decade, AASHTO T 277 has gained widespread acceptance by many highway agencies. It involves the measurement of the total charge passed by 60 VDC in 6 hours across a 2-inch thick, 4-inch diameter concrete specimen that has been placed between sodium hydroxide (NaOH) and sodium chloride (NaCl) solutions. The test measures the conductivity of the saturated concrete including the effects of all dissolved ions (Hearn, Hooton, and Nokken 2006). The results of the test in coulombs are used to make a general assessment of the chloride ion penetrability of the concrete based on table 2 (AASHTO T 277). It is noted that the assessment is not specific, but instead the chloride penetrability is assigned a qualitative rating.

Table 2. Chloride ion penetrability based on charge passed.

(From AASHTO T 277, *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. Used by permission)

Charge Passed (coulombs)	Chloride Ion Permeability
>4,000	High
2,000-4,000	Moderate
1,000-2,000	Low
100-1,000	Very Low
<100	Negligible

Although this test has been embraced by many SHAs due to its ease of use, it suffers a number of limitations including (Stannish, Hooton, and Thomas 2000):

- The current passed is related to all ions in the pore solution and not just chloride ions.
- The measurements are made before a steady-state migration is achieved.
- The temperature of the specimen increases due to the applied voltage.

AASHTO T 358

A number of highway agencies have recognized the limitations inherent in AASHTO T 277 and are investigating and adopting surface resistivity methods, as described in AASHTO T 358, as an alternative (Rupnow and Icenogle 2011; Tanesi and Ardani 2012; Jenkins 2015; Kevern, Halmen, and Hudson 2015). The surface resistivity test evaluates the electrical resistivity of water-saturated concrete, providing a rapid means to assess the concrete's permeability. In the studies cited above, an excellent correlation has been found between the surface resistivity and other electrical indicator tests, including AASHTO T 277. AASHTO T 358 takes approximately 5 minutes to conduct and the testing equipment is less expensive, does not involve the use of chemicals, and is generally easier to operate than that required for AASHTO T 277. The surface resistivity test is also nondestructive; thus test specimens can be used for other testing. For these reasons, AASHTO T 358 is gaining in popularity.

In AASHTO T 358, the resistivity of saturated concrete cylindrical specimens (4-inch diameter by 8 inches long, or a 6-inch diameter by 12 inches long) is measured using a 4-pin Wenner probe array, as illustrated in figure 8. An AC potential difference is applied in the outer pins of the Wenner array, generating current flow in the concrete. The two inner probes measure the potential difference generated by this current from which the resistivity of the concrete is calculated. The resistivity, in Ohms-cm, has been related to the resistance of the specimen to chloride ion penetration as shown in table 3.

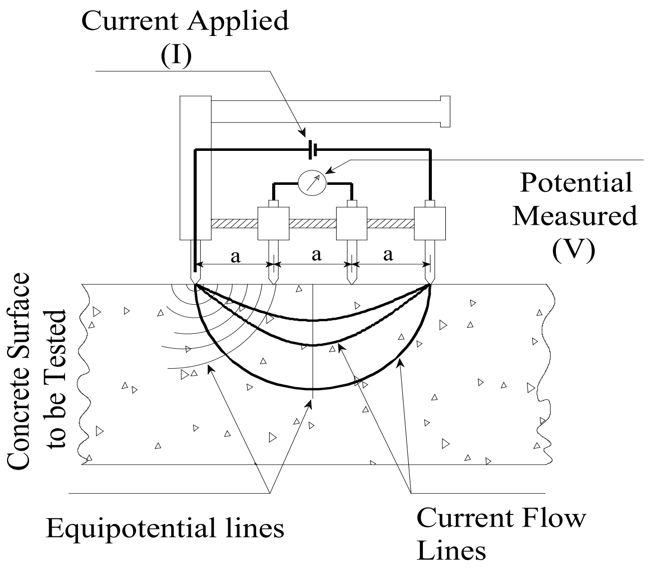

Figure 8. Four-point Wenner array probe set up (AASHTO T 358).

(From AASHTO T 358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*. Used by permission)

Table 3. Typical correlation between chloride ion penetrability from AASHTO T 277 and surface resistivity. (From AASHTO T 358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*. Used by permission)

Chloride Ion Penetrability	Surface Resistivity 100 x 200 mm (4 x 8 in.) Cylinder (KOhm-cm) a=1.5	Surface Resistivity 150 x 300 mm (6 x 12 in.) Cylinder (KOhm-cm) a=1.5
High	< 12	< 9.5
Moderate	12-21	9.5-16.5
Low	21-37	16.5-29
Very Low	37-254	29-199
Negligible	> 254	> 199

a = Wenner probe tip spacing.

Although AASHTO T 358 is conducted more easily and cheaply than AASHTO T 277, it suffers many of the same limitations in that the results are dependent on the sample geometry, test temperature, the degree of saturation, and how the sample was stored (Weiss 2014). To address these limitations, work is underway to normalize the results of all electrical tests through the development of standards based on the formation factor, which is directly related to the concrete pore volume and connectivity as well as the conductivity of the pore solution (Weiss 2014).

CONSTRUCTION QC/QA TESTING

Most of the durability tests discussed so far are suitable for laboratory development of concrete mixtures during the design phase, but not necessarily well-suited for use during construction due to the complexity of the test and the long testing duration. Thus they are often used to screen constituent materials and concrete mixtures, but not employed during construction. One durability test that is beginning to see more frequent use for construction QC is the SAM test (AASHTO TP 118, *Provisional Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method*) in which the following acceptance criteria are recommended for construction QA (Ley 2015):

- Total air content should be greater than 5 percent.
- If the SAM Number is less than 0.20 psi, the concrete is acceptable.
- If the SAM Number is between 0.20 psi and 0.25 psi, methods to increase air content in subsequent delivered concrete must be implemented.
- If the SAM Number is greater than 0.25 psi, freeze-thaw durability is a concern.

Another test that is becoming popular as a construction QA tool due to its ease of use is the surface resistivity test (AASHTO T 358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*). The use of this test will likely continue to grow as work on the development of the formation factor (described previously) comes to fruition.

CONCLUDING REMARKS

The durability of concrete is not an intrinsic material property, but instead reflects how the material maintains its integrity in the service environment. As such there is no test or suite of tests that directly measure the "durability" of concrete. Instead, multiple tests are employed to measure various attributes of the concrete-making materials and the concrete itself to make an assessment of whether it will be durable in a specific environment. This Tech Brief reviews common test methods used to assess constituent materials and project specific concrete mixtures with regards to sulfate attack, freeze-thaw damage, and resistance to alkali-aggregate reactivity. Test methods to assess the transport properties of concrete are also reviewed. Note that conducting this type of testing does not preclude the need for other commonly conducted testing during the mixture design and construction process.

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