
**Standard Specification for
Performance Engineered Concrete Pavement
Mixtures**

AASHTO Designation: MP XX-17

DRAFT



**American Association of State Highway and Transportation Officials
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Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures

AASHTO Designation: R XX-17



1. SCOPE

- 1.1. Specifications for concrete pavement mixtures have traditionally been prescriptive, with State Highway Agencies (SHA) specifying means and methods for both constituent materials and specific requirements for proportioning. The result of this places the majority of the performance risk on the SHA, and limits innovation. Recent trends of blending cementitious materials, reducing paste content, using innovative additives and admixtures, and other innovations in the industry open the opportunity to move towards specifying the performance characteristics of concrete mixtures and allowing industry to design mixtures that address specific performance required. New methods to evaluate concrete performance have been developed, and others are being formulated, that can result in improved performance and economics. Shifting the responsibility for performance to the contractor provides an opportunity for innovation.
- 1.2. This specification covers the tests methods and values for a concrete pavement mixture design that considers, and includes, performance characteristics for acceptance.
- 1.3. This specification respects some SHA traditions of using prescriptive methods while offering the choice to include performance measures in Section 6.
- 1.4. This specification is intended to provide SHAs flexibility in their approach to the use of performance characteristics and includes a range of choices that can be selected to best fit the needs of the agency.
- 1.5. Performance values included are for an average concrete pavement life in the range of 30 years. Due to normal materials and testing variability some risk in predicting actual service life exists. As service life prediction models and test methods mature, that risk is expected to reduce.
- 1.6. The values stated in SI units are to be regarded as the standard. The values given in parentheses are provided for information only.
- 1.7. The inclusion of performance measures increases the importance of Quality Control (QC), as the acceptance criteria are predicated on a well designed and executed QC program that includes process, production, and construction control.
- 1.8. *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. REFERENCED DOCUMENTS

- 2.1. *AASHTO Standards*

- T 22, Compressive Strength of Cylindrical Concrete Specimens
- T 23, Making and Curing Concrete Test Specimens in the Field
- TP 95 Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration
- T 97, Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
- TP 118, Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method
- TP 119, Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test
- T 121, Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
- T 152, Air Content of Freshly Mixed Concrete by the Pressure Method
- T 161, Resistance of Concrete to Rapid Freezing and Thawing
- T 196, Air Content of Freshly Mixed Concrete by the Volumetric Method
- T 318, Water Content of Freshly Mixed Concrete using Microwave
- T 334, Estimating the Cracking Tendency of Concrete
- T 336, Coefficient of Thermal Expansion of Hydraulic Cement Concrete
- R 39, Making and Curing Concrete Test Specimens in the Laboratory
- PP 65, Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction

2.2. *ASTM Standards*

- C125, Standard Terminology Relating to Concrete and Concrete Aggregates
- C157, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
- C1646, Standard Practice for Making and Curing Test Specimens for Evaluating Resistance of Coarse Aggregate to Freezing and Thawing in Air-Entrained Concrete
- C1585, Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes

2.3. *Other Publications*

- Quality Assurance Procedures for Construction (23 CFR 637.207)
<http://www.fhwa.dot.gov/legregs/directives/fapg/cfr0637b.htm>
- Field Reference Manual for Quality Concrete Pavements (FHWA-HIF-13-059)
<http://www.fhwa.dot.gov/pavement/concrete/pubs/hif13059.pdf>
- Testing Guide for Implementing Concrete Paving Quality Control Procedures
http://publications.iowa.gov/13618/1/testing_guide.pdf

3. **TERMINOLOGY**

The definitions for concrete and concrete aggregate terms used in this specification are provided in ASTM C125.

4. **MATERIALS**

- 4.1. Provide Materials in accordance with the following
 - 4.1.1. Provide aggregates meeting the requirements of:
 - 4.1.1.1. Fine Aggregate - AASHTO M 6/ASTM C33
 - 4.1.1.2. Coarse Aggregate - AASHTO M 80/ASTM C33
 - 4.1.1.3. Recycled concrete aggregate (RCA) - AASHTO M 80/ASTM C33

4.1.1.4. Lightweight Aggregate (for internal curing) - AASHTO M 195/ASTM C1761

Note 1— Intermediate aggregates are typically those that are passing the 0.5 inch sieve and are retained on the No. 4 sieve. As such, they fall under a coarse aggregate classification in accordance with AASHTO M 80.

4.1.2. Provide cement meeting the requirements of:

4.1.2.1. Portland Cement - AASHTO M 85/ASTM C150

4.1.2.2. Blended Hydraulic Cement - AASHTO M 240/ASTM C595

4.1.2.3. Performance Hydraulic Cement - ASTM C1157

4.1.3. Provide Supplementary Cementitious Materials meeting the requirements of:

4.1.3.1. Fly Ash and Raw or Calcined Natural Pozzolans - AASHTO M 295/ASTM C618

4.1.3.2. Slag Cement - AASHTO M 302/ASTM C979

4.1.3.3. Silica Fume - AASHTO M 307/ASTM C1240

4.1.3.4. High Reactivity Pozzolans - AASHTO M 321

4.1.3.5. Alternative Supplementary Cementitious Materials (ASCM) - ASTM C1709

4.1.4. Provide water meeting the requirements of:

4.1.4.1. Potable water – no testing required

4.1.4.2. Recycled Water - ASTM C1602

4.1.5. Provide Admixtures meeting the requirements of:

4.1.5.1. Air-Entraining Admixtures - AASHTO M 154/ASTM C260

4.1.5.2. Chemical Admixtures - AASHTO M 194/M 194M/ASTM C949

4.1.5.3. Corrosion Inhibiting Admixtures – ASTM C1582

4.1.6. Provide Fibers meeting the requirements of:

4.1.6.1. Steel Fibers - ASTM A820/A820M

4.1.6.2. Cellulose Fibers - ASTM D7357

4.1.6.3. Polyolefin Chopped Strands - ASTM D7508/D7508M

4.1.6.4. Macro Synthetic Fibers - ASTM C1116

4.1.6.5. Micro Synthetic Fibers - ASTM C1116.

5. SAMPLING

- 5.1. Sample aggregates in accordance with AASHTO T 2 (ASTM D75).
- 5.1.1. Reduce aggregate samples in accordance with AASHTO T 248 (ASTM C702).
- 5.2. Sample freshly mixed concrete in accordance with AASHTO R60 (ASTM C172).
- 5.3. Make and cure concrete specimens in the field in accordance with AASHTO T 23 (ASTM C31).

6. PROPORTIONING

- 6.1. Proportion hydraulic cement concrete to comply with minimum requirements identified below.
- 6.2. Submit concrete mixture design, based on trial batch testing, a minimum of 30 days before concrete production. Include laboratory test data and samples of all materials to be used in the mixture, identifying the proposed source or manufacturer of the materials.
 - 6.2.1. Submit revised concrete mixture designs when a change in the source or brand of any materials or product is proposed as directed by the SHA.
- 6.3. Concrete Strength
 - 6.3.1. Minimum concrete flexural strength of 4.1 MPa (600psi) at 28 days using AASHTO T 97.

Note 2—Concrete strength that meets the specific project design requirements may be substituted here as it is not uncommon for agencies to select other flexural strengths. Agency may elect to only require either flexural strength or compressive strength.
 - 6.3.2. Minimum concrete compressive strength of 24 MPa (3500 psi) at 28 days using AASHTO T 22.

Note 3—Concrete pavement designs are based on flexural strength, consideration may be given to conducting acceptance testing based on compression cylinders calibrated with flexural beams for the mixture during the qualification stage.

Note 4—The specification provides the selection of one or more choices in the following sections to address local conditions and needs.
- 6.4. Cracking Tendency of Concrete
 - 6.4.1. Prescriptive specification for shrinkage cracking caused by hygral volume change (Choose one):
 - 6.4.1.1. The volume of the paste should be limited to 25% as determined in Appendix X1.1.

- 6.4.1.2 The unrestrained volume change should be less than 420 $\mu\epsilon$ at 28 days as determined from ASTM C157.
- 6.4.2. Performance specification for shrinkage cracking caused by hygral volume change (Choose one):
- 6.4.2.1. The unrestrained volume change as determined from ASTM C157 at an age of 91 days should result in a probability of cracking of less than 5, 20, or 50% depending on the application. Suggested limits are 360 $\mu\epsilon$, 420 $\mu\epsilon$, or 480 $\mu\epsilon$ respectively as described in Appendix X1.2.
- 6.4.2.2. Crack free at 180 days as determined using AASHTO T 334
- 6.4.2.3. The mixture should have a stress less than 60% of the splitting tensile strength when tested in the dual ring (AASHTO XXX) with a temperature of 23 ± 1 C (73.4 ± 1.8 °F), and RH of $50 \pm 2\%$, RH for 7 days.
- 6.4.2.4. The shrinkage of the mixture can be determined using evaluations performed on a computational program and determined to have a probability of cracking of less than 5, 20, or 50% depending on the application and curing conditions (Appendix X1).
- 6.5. Durability of Hydrated Cement Paste (HPC) in Freeze-Thaw Environments
- 6.5.1. Prescriptive specification for freeze-thaw durability:
- 6.5.1.1. Water to cement ratio (w/cm) should be less than 0.45, and (chosed one):
- 6.5.1.2. Air content between 5 and 8% using AASHTO T 152, AASHTO T 196, or AASHTO TP 118.
- 6.5.1.3. Air content greater than 4% and SAM number less than 0.20 using AASHTO TP 118.
- 6.5.2. Performance specification for freeze-thaw durability (Choose one):
- 6.5.2.1. A calculated time to saturation of greater than X years using the procedure outlined in Appendix X.4.4. X is typically assumed to be 30 years for plain concrete pavements, however this can be varied depending upon the agency preferences.
- 6.5.3. Prescriptive specification for reducing joint damage due to deicing salt when CaCl_2 or MgCl_2 is used (Choose one)
- 6.5.3.1. SCM should be used to replace the cement with a volume of at least 35%.
- 6.5.3.2. A topical treatment (sealer) should be used consistent with AASHTO M 224.
- 6.5.4. Performance specification for reducing joint damage due deicing salt durability when CaCl_2 or MgCl_2 is used.)
- 6.5.4.1. The calcium oxychloride should be determined to be less than 15 g CAOXY/100 g cementitious paste as determined following [Performance of Concrete Pavement in the Presence of Deicing Salts and Deicing Salt Cocktails (IN SPR-3864)]. **The proposed test method has been transmitted to AASHTO and is enclosed as a separate attachment with this draft.**
- 6.6. Transport Properties
- 6.6.1. Prescriptive specification for a transport related property (Choose one):

- 6.6.1.1. The w/cm shall be less than 0.45.
- 6.6.1.2. The RCPT value should be identified as meeting the requirement described in Table 1.
- 6.6.1.3. The saturated F factor value (as determined using electrical resistivity as described in Appendix X.5) should be identified as meeting the requirement described in Table 1.

Table 1- RCPT and Saturated F Factor Limits

Chloride Ion Penetrability	Minimum Charge Passed @ 6 hours	Maximum Charge Passed @ 6 hours	Greatest Saturated F Factor	Lowest Saturated F Factor
	Coulombs	Coulombs	~	~
High	4000	~	500	~
Moderate	2000	4000	1000	500
Low	1000	2000	2000	1000
Very Low	100	1000	20000	2000
Negligible	0	100	~	20000

Note: A conversion between RCPT and saturated formation factor is provided in reference assuming a pore solution resistivity of 0.10 Ω m [Barrett et al. 2016]

- 6.6.2. Performance specification for a transport related property:
 - 6.6.2.1. A formation factor (as determined from electrical resistivity) should be specified that is related to the desired depth of ionic penetration for a given ion exposure during a 30 year life. Details on how this is determined are available in Appendix X2.

6.7. Durability (Aggregate stability)

- 6.7.1. Evaluate aggregates for the potential susceptibility to damage due to freezing and thawing (D-Cracking) using ASTM C1646 and AASHTO T 161, or accepted local SHA practice.
- 6.7.2. Evaluate aggregates for the potential susceptibility to alkali-aggregate reactivity (AAR) using AASHTO PP 65.
 - 6.7.2.1. Comply with mitigation strategies described in AASHTO PP 65 if aggregates susceptible to alkali silica reaction (ASR) are used.

Note 5—Accepted SHA practice should be used to address local durability issues not addressed in this specification.

- 6.8. Workability: Evaluate using either the Box Test or V-Kelly Test
 - 6.8.1. Box Test: Edge slump less than 6 mm (0.25 in) and less than 30% surface voids (Ranking of 2 or less). The Box Test is described in Appendix X3
 - 6.8.2. V-Kelly Test: Results between 15 and 30 mm (0.6 and 1.2 inches) per root second. The V-Kelly is described in Appendix X4

6.9. Mixture Qualification

6.9.1. Report the following additional data in Table 2 for mixture qualification purposes:

Table 2- Properties to Report for Mixture Qualification

Property	Test Method	Purpose
Rate of flexural strength development to 90 days	AASHTO T 97	Calibration with compression
Rate of strength development to 90 days	AASHTO T 22	Calibration with flexural
Coefficient of thermal expansion	AASHTO T 336	Design check
Unit weight	AASHTO T 121	Basis for QC monitoring

6.10 Table 3 summarizes the properties, tests, values and identifies the reason for the tests, along with clarifying the available choices when customizing a project specific specification

6.10.1 Use Table 3 to select the property or properties desired from each section that corresponds with the narrative above to develop project specific requirements.

Table 3- Specification worksheet

Section	Property	Specified Test	Specified Value	Mixture Qualification	Acceptance	Selection Details	Special Notes
6.3 Concrete Strength							
6.3.1	Flexural Strength	AASHTO T 97	4.1 MPa	600 psi	Yes	Choose either or both	
6.3.2	Compressive Strength	AASHTO T 22	24 MPa	3500 psi	Yes		
6.4 Reducing Unwanted Cracking Due to Shrinkage							
6.4.1.1	Volume of Paste		25%		Yes		
6.4.1.2	Unrestrained Volume Change	ASTM C157	420 µm	at 28 day	Yes		Curing Conditions
6.4.2.1	Unrestrained Volume Change	ASTM C157	360, 420, 480 µm	at 91 days	Yes	Choose only one	
6.4.2.2	Restrained Shrinkage	AASHTO T 334	crack free	at 180 days	Yes		
6.4.2.3	Restrained Shrinkage	AASHTO T ???	σ < 60% f _r	at 7 days	Yes		
6.4.2.4	Probability of Cracking	~	5, 20, 50%	as specified	Yes		
	Commentary	Quality control check	~	~	No		Variation controlled with mixture proportion observation or F Factor and Porosity Measures
6.5 Durability of Hydrated Cement Paste for Freeze-Thaw Durability							
6.5.1.1	Water to Cement Ratio	~	0.45	~	Yes	Choose Either 6.5.1.1 or 6.5.2.1	
6.5.1.2	Fresh Air Content	AASHTO T 152, T196, TP 118	5 to 8	%	Yes	Choose only one	
6.5.1.3	Fresh Air Content/SAM	AASHTO T 152, T196, TP 118	> 4% Air, SAM ≤ 0.2	%, psi	Yes		
6.5.2.1	Time of Critical Saturation	"Bucket Test" Specification	30	Years	Yes	Note 1	Variation controlled with mixture proportion observation or F Factor and Porosity Measures
6.5.3.1	Deicing Salt Damage	~	35%	SCM	Yes		Are calcium or magnesium chloride used
6.5.3.2	Deicing Salt Damage	~	~	~	Yes	Choose one	Are calcium or magnesium chloride used, needs a use of specified sealers
6.5.4.1	Calcium Oxide Limit	Test sent to AASHTO	< 0.15g CaO/W/g paste		Yes		Are calcium or magnesium chloride used
6.6 Transport Properties							
6.6.1.1	Water to Cement Ratio	~	0.45	~	Yes		
6.6.1.2	RCP Value	AASHTO T ???	2000	~	Yes	Choose Only One	Other criteria could be selected
6.6.1.3	Formation Factor/Resistivity	AASHTO xx or AASHTO Yy	500	~	Yes		* Note this is currently based on saturated curing and an adjustment is needed to match with AASHTO Spec
6.6.2.1	Ionic Penetration, F Factor	AASHTO xx or AASHTO Yy	25 mm at 30 year	Yes, F through p			
6.7 Aggregate Stability							
6.7.1	D Cracking	AASHTO T 161, ASTM C 1646	~	~	Yes		
6.7.2	Alkali Aggregate Reactivity	AASHTO PP 65	~	~	Yes		
6.8 Workability							
6.8.1	Box Test	~	< 6.25 mm, < 30% Surf. Void		No		
6.8.2	Modified V-Kelly Test	~	15-30 mm per root seconds		No		
	Note 1:	Choose Either 6.5.1.1 or 6.5.2.1					
	Note 2:	Choose either 6.5.1.2, 6.5.1.3, or 6.5.2.1					

7. CONCRETE ACCEPTANCE REQUIREMENTS

Note 6—The SHA is responsible for developing a Quality Assurance Program (QAP) as described in 23 CFR 637.207. The agency QAP includes the acceptance program, quality assurance, and other facets such as independent assurance, dispute resolution, qualified laboratories, and the use of qualified personnel. Agencies should use their existing best practices developed based on their experience to fully describe acceptance requirements that best meet their needs that address the properties selected from Table 3. Values included in this section may be varied and additional properties added or substituted based on agency best practices.

- 7.1. Accept Fresh concrete based on the following (chose one):
 - 7.1.1. Air content of 5% minimum after placement using AASHTO T 152, T 196 or AASHTO TP 118. With no more than 3% loss through the paver
 - 7.1.2. Air content of 4% minimum after placement and a SAM number of 0.20 or lower using AASHTO TP 118
 - 7.1.2.1. Reject concrete if SAM number is above 0.25, modify concrete mixture if between 0.20 and 0.25
- 7.2. Accept hardened concrete based on the following:
 - 7.2.1. Compressive strength of 24 MPa (3500 psi) at 28 days using AASHTO T 22
- 7.3. A job specific resistivity (as determined the saturated F Function obtained from Section 6.6 and the pore solution resistivity as predetermined at the trial batch as described in Appendix X2.2)

Note 7— Resistivity can also be determined based on the procedure described in X2.3

Note 8—Additional acceptance requirements can apply based on SHA practices and requirements. This specification does not include other possible acceptance requirements such as smoothness and thickness. FHWA publication number FHWA-HIF-13-059, Field Reference Manual for Quality Concrete Pavements, provides guidance about overall quality assurance program for concrete pavements

8. QUALITY CONTROL

- 8.1. Develop and submit a quality control plan for approval prior to beginning work.
 - 8.1.1. The Quality Control Plan shall include, but not be limited to, the following:
 - 8.1.1.1. Detailed descriptions of actions to monitor the quality of constituent materials, construction processes, and the final product including test methods and frequencies of those tests
 - 8.1.1.2. Examples of how QC data will be managed and reported, including the use of control charts exhibiting acceptable ranges and control limits

8.1.1.3. Detailed descriptions of actions to be taken when control limits are exceeded.

Note 9—Target values and action limits should be set following the guidance in Chapter 5 of the Testing Guide for Implementing Quality Control Procedures.

8.1.2. The following tests shall be included as a minimum.

Table 4- Minimum QC Testing

Test	Test Method	Frequency	Target	Control Limit
Unit Weight	AASHTO T 121	Weekly	*	*
Air Content/SAM number	AASHTO T 152, T 196, or TP 118	1000 m ² (1200 yd ²) or daily	*	*
Water Content	AASHTO T 318	Daily	*	*
Formation Factor	Appendix X2	1000 m ² (1200 yd ²) or daily	*	*
Strength	AASHTO T 97 and/or T 22	1000 m ² (1200 yd ²) or daily	*	*

8.1.3. Use values provided (where listed) or proposed alternative values as developed and approved in the QC plan.

8.2. Submit testing results and summary of any corrective actions taken on a daily basis

9. TEST REPORTS

9.1. Submit test reports for all materials to be used in the concrete mixture as noted in accordance with Section 6.2 and the following.

9.1.1. Rate of flexural strength

9.1.2. Rate of strength development

9.1.3. Coefficient of Thermal Expansion

9.1.4. Unit weight

9.2. Submit test reports for prescriptive and performance concrete properties selected in Sections 6.3, thru 6.8 as shown in Table 3.

- 9.3. Submit test reports for quality control and acceptance in accordance with Table 5 and the approved Quality Control Plan

Table 5- Properties to Report for Quality Control and Acceptance

Property	Test Method	Purpose
Strength	AASHTO T 22 or T97	QC and Acceptance
Air Content	AASHTO T 152 or TP 118	QC and Acceptance
SAM Number	AASHTO TP 118	QC and Acceptance
Unit weight	AASHTO T 121	QC
F Factor	AppendixX2	Mixture Approval

APPENDIXES

(Nonmandatory Information)

X1. CRACKING AND VOLUME CHANGE APPENDIX

X1.1. Volume of Paste (V_{Paste})

The volume of paste is determined by computing the volume of liquid and binder phases in a cubic yard of concrete. This means that the volume of the aggregate and air is not considered in the calculation. The volume of the paste can be determined by using Equation X1.1.1:

$$V_{Paste} \% = \frac{\sum_i^n \frac{Mass_i}{SG_i 62.4}}{27 \text{ ft}^3} \times 100 \quad (\text{Eqn. X1.1.1})$$

where:

$Mass_i$ = the mass of constituent i (e.g., cement, supplementary cementitious material, water, admixtures)

SG_i = the specific gravity of constituent i (e.g., cement, supplementary cementitious material, water, admixtures)

An example of the calculation for the mixture design provided in Table X.3.1a is described in equation X.3.1.2.

$$V_{Paste} \% = \frac{\frac{464}{3.15 \cdot 62.4} + \frac{100}{2.62 \cdot 62.4} + \frac{237}{62.4}}{27 \text{ ft}^3} \times 100 = 25.1\% \quad (\text{Eqn. X1.1.1})$$

Table X1.1a: Volumetric proportions for computing the volume of paste (%).

Materials	Mass (lb/yd ³)	SG (SSD)	Volume, ft ³
Cement	464	3.15	2.36
Fly Ash	100	2.62	0.61
Sand	1510	2.75	8.80
Coarse Aggregate 1	1800	2.68	10.76
Coarse Aggregate 2	0	2.763	0.00

Water	237	1	3.80
Air	0	~	0.67
Σ	4111	~	27.00
Volume of Paste (%)	~	~	25.1

X1.2. Probability of Cracking

A performance based approach was developed using Monte Carlo analysis to specify the probability of cracking due to drying shrinkage. Figure X1.2 is based on calculations assuming a degree of restraint of 60% which is typical of elements like bridge decks (this can be modified for pavements). The shrinkage provided in this graph is the total shrinkage that would result in cracking. As a result if drying shrinkage is expected to result in less than 60% of the stress in the concrete, the unrestrained volume change as determined from ASTM C157 at an age of 91 days should result in a probability of cracking of less than 5, 20, or 50% would have values of 360 $\mu\epsilon$, 420 $\mu\epsilon$, or 480 $\mu\epsilon$ respectively. The approach used in determining Figure X1.2a can be used for a wide variety of conditions [Radlińska, A. and Weiss, J. (2012). "Toward the Development of a Performance-Related Specification for Concrete Shrinkage." J. Mater. Civ. Eng., 10.1061/(ASCE)MT.1943-5533.0000364, 64-71].

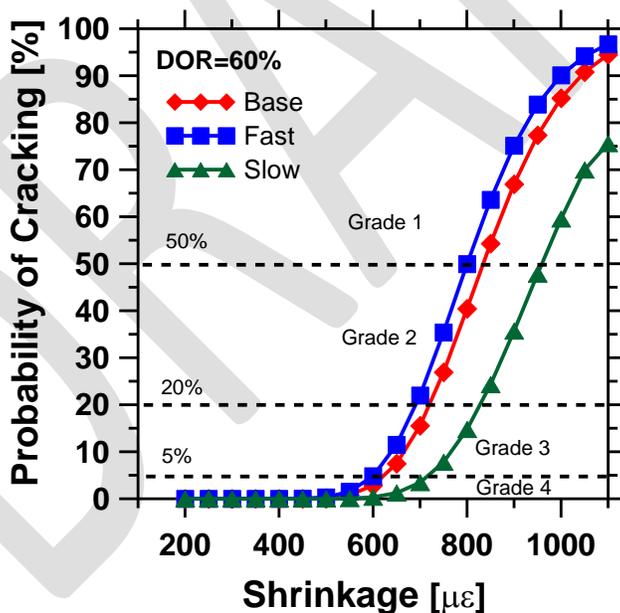


Fig. X1.2a. Performance grade characteristics for three concrete mixtures with a degree of restraint of 60%. Fast, Base and slow refer to the speed of the hydration reaction used.

Note: It should be noted that ASTM C157 provides an insufficient measure of total shrinkage for concrete with w/cm less than ~ 0.40 . For these concretes both autogenous and drying shrinkage should be combined. [Measurement of volume change in cementitious materials at early ages: review of testing protocols and interpretation of results," G Sant, P Lura, J Weiss - Transportation Research Record: Journal of the Transportation Research Board, 2006]

X1.3. Probability of Cracking (using Monte Carlo or LRFD Approaches)

Several predictive models have been developed to estimate the combination of conditions that can cause cracking. The majority of these predictive models rely on the comparison of time-dependent residual stress development and the time-dependent strength. Research has shown that Monte Carlo simulation approach could be used to assign variability to the material property inputs based on assumed statistical distributions. This would then enable a probability to be assigned to the cracking prediction. This is a similar approach to Load and Resistance Factor Design (LRFD) approach used in structural design. This would allow the probability of cracking to be determined for a given level of material variability [Aleksandra Radlinska and J. Weiss, 2006, "Determining Early-Age Cracking Potential in Restrained Concrete Elements Using a Load and Resistance Factor Design (LRFD) Approach", Quebec City, Canada, 11-13 September, 2011]

X2. FORMATION FACTOR AND PORE SOLUTION RESISTIVITY

X2.1. Formation Factor

The formation factor (F) can be used to characterize the pore structure of concrete since it is a constant value that is only dependent on the pore geometry and connectivity. The formation factor is defined as the ratio of the resistivity of a bulk body (ρ) and the resistivity of the pore solution in the body (ρ_o), as shown in Eq. 1.

$$F = \frac{\rho \text{ } [\Omega \cdot m]}{\rho_o \text{ } [\Omega \cdot m]} \quad (X2.1)$$

Table 2.1 A Table that relates the charge passed using the rapid chloride permeability test, resistivity and formation factor (While a pore solution resistivity of 0.1 Ω m was assumed for this table, section X.5.2 describes a series of methods to determine pore solution resistivity) [Spragg, R., J. Castro, T. Nantung, M. Paredes, and J. Weiss. Variability Analysis of the Bulk Resistivity Measured Using Concrete Cylinders. Advances in Civil Engineering Materials, Vol. 1, No. 1, 2012]

While the formation factor discussed in this section is assumed to be the ‘fully saturated formation factor’ recent work has indicated that determining the formation factor for a sealed concrete element has merit and should be considered for future specifications due to benefits of improved testing in field conditions.

The pore solution conductivity can be determined as described in section X2.2. The specifier should state which of these options are permissible/preferred for their specification.

ASTM C1202 Classification ⁽¹⁾	Charge Passed (Coulombs) ⁽¹⁾	Resistivity (kOhm·cm) ⁽²⁾	Formation Factor
High	>4,000	< 5.2	520
Moderate	2,000 - 4,000	5.2 - 10.4	520-1040
Low	1,000 - 2,000	10.4 - 20.8	1040-2080
Very Low	100 - 1,000	20.8 - 207	2080-20700
Negligible	< 100	> 207	20700

⁽¹⁾ from ASTM C1202-12

⁽²⁾ calculated using first principles

X2.2. Pore Solution Resistivity

The pore solution resistivity (ρ_o) of a concrete is influenced by the alkali contents of the cementitious materials, the mixture proportions, and the degree of hydration of the cementitious materials. This appendix outlines three approaches to determine the pore solution.

X2.2.1. Level A — Assuming a Constant Pore Solution

The pore solution resistivity can be assumed to be a constant value. The pore solution resistivity can be estimated using equation X.5.2.1.

$$\rho_o = 0.10 [\Omega \cdot m] \quad [X2.2.1]$$

X2.2.2. Level B — Estimate Pore Solution from the constituents of the Chemistry

The pore solution can be estimated to provide an estimate of the electrical conductivity (S/m) of the pore solution in a concrete based on the mixture proportions and achieved degree of hydration.

The pore solution resistivity can be estimated using a combination of mixture proportions, chemistry of the cementitious materials, and a degree of hydration. The calculations are performed by estimating the conductive species and the volume of pore solution (<http://ciks.cbt.nist.gov/poresolncalc.html>). [Bentz, D. P. A virtual rapid chloride permeability test. Cement and Concrete Composites, Vol. 29, No. 10, 2007, pp. 723–731.]

The pore solution conductivity from this website (σ_o) is provided in units of S/m, which is the inverse of resistivity as shown in Equation X2.2.2:

$$\rho_o [\Omega \cdot m] = \frac{1}{\sigma_o [S/m]} \quad [X2.2.2]$$

X2.2.3. Level C — Experimentally Measure Pore Solution

The pore solution resistivity can be experimentally determined. Currently, two primary methods exist including: pore solution expression or measurement of pore solution resistivity using embedded sensors.

Pore solution expression involves the extraction of the pore solution from a hardened cementitious samples [Barneyback, R. S., and Diamond, S., "Expression and analysis of pore fluids from hardened cement pastes and mortars," *Cement and Concrete Research*, Volume 11, Issue 2, March 1981, Pages 279-28]. Specimens are placed into a high pressure die, repeatedly cycled at high pressure, and pore solution is expelled through a channel at the bottom of the die. The pore solution resistivity can be measured in a small resistivity cell [Spragg, R., and Weiss, W. J., (2016) "Chapter 11: Assessing a concrete's resistance to chloride ion ingress using the formation factor," *Corrosion of Steel in Concrete Structures*, 1st Edition].

Pore solution resistivity can be measured using embedded sensors which measure changes in the pore solution resistivity due to the hydration of cementitious materials [F. Rajabipour, J. Weiss, 'Material Health Monitoring of Concrete by Means of Insitu Electrical Conductivity Measurements', *Cement Wapno Beton*, 2 (March 2007) 76-92].

X2.3 Converting a Saturated Resistivity to a Sealed Resistivity

In some cases resistivity is being measured in a sealed condition. Sealed resistivity removes the need for sample conditioning. To relate the sealed resistivity to the saturated resistivity equation X.2.3 is used

$$\rho_{sealed} [\Omega \cdot m] = \rho_{saturated} [\Omega \cdot m] S^{-m} \quad (X2.3)$$

where ρ_{sealed} is the resistivity of a sealed sample, $\rho_{saturated}$ is the resistivity of a saturated sample and m is the saturation coefficient (generally a unitless number that generally ranges from 3 to 5). [Weiss, J., Snyder, K., Bullard, J., and Bentz, D. (2013). "Using a Saturation Function to Interpret the Electrical Properties of Partially Saturated Concrete." *J. Mater. Civ. Eng.*, 10.1061/(ASCE)MT.1943-5533.0000549, 1097-1106.] During a recent sample exchange of Midwest paving mixtures this value was determined to be 3.8. [Coyle, et al.]

Note X.2 1: The saturated test is performed after vacuum saturating the material. Vacuum saturation is heavily dependent on the level of vacuum drawn, however a vacuum of at least 50 Torr is needed to determine $\rho_{saturated}$. [Bu, Y., Spragg, R., and Weiss, W. J. "Comparison of the Pore Volume in Concrete as Determined Using ASTM C642 and Vacuum Saturation," *Advances in Civil Engineering Materials*, Vol. 3, No. 1, 2014, pp. 308-315, <http://dx.doi.org/10.1520/ACEM20130090>. ISSN 2165-3984]

X2.4 Relating Formation Factor to Depth of Chloride Penetration

The fully saturated formation factor can be related to the depth of ion penetration (chloride ions used here) over a period of time (30 years in this example). Figure X.2.4 illustrates the relationship between the sealed formation factor, the depth of chloride penetration, and the concentration of the ions in the pore solution (assuming no binding). C_s is the concentration of the ion of interest in the pore solution at the surface of the pavement, C_x is the concentration of the ion of interest in the pore solution at the depth of penetration and C_0 is the concentration of the ion of interest in the base concrete.

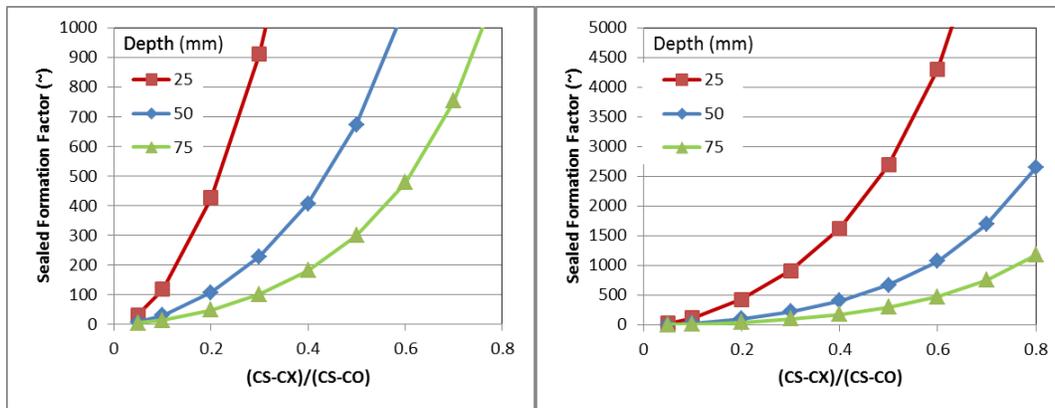


Figure X.2.4 illustrates the relationship between the sealed formation factor, the depth of chloride penetration, and the concentration of the ions in the pore solution (assuming no binding).

For example, if one wanted was interested in the formation factor for the case where: $(C_S - C_X)/(C_S - C_O) = 0.4$, depth of interest was 50 mm, and time was 30 years the formation factor would be 407. Similarly, if one wanted was interested in the formation factor for the case where: $(C_S - C_X)/(C_S - C_O) = 0.4$, depth of interest was 25 mm, and time was 30 years the formation factor would be 1630.

X3. BOX TEST

X3.1. Perform the Box Test to evaluate the workability of concrete paving mixtures as follows:

X3.2. Equipment

X3.2.1. Use a 0.028 m^3 (1 ft^3) wooden formed box that consists of a 12.5 mm (0.5 in.) plywood with a length, width, and height of 300 mm (12 in.) with 50 mm (2 in.) L-brackets in two corners. Two pipe clamps with a span of 460 mm (18 in.) were used to hold the other two corners together as shown in Figures X1.1 and X1.2

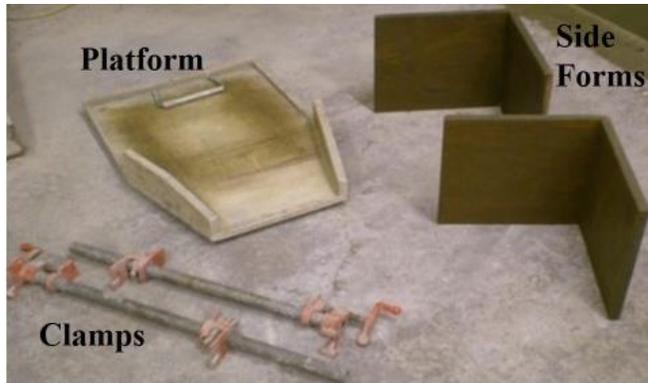


Figure X3.1- Equipment

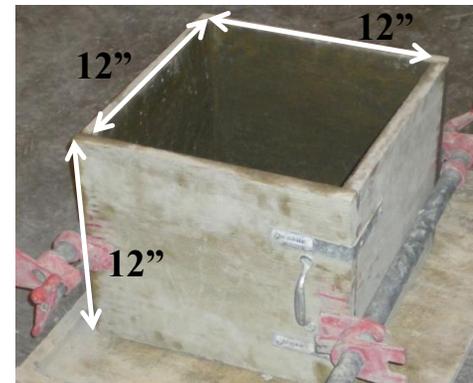
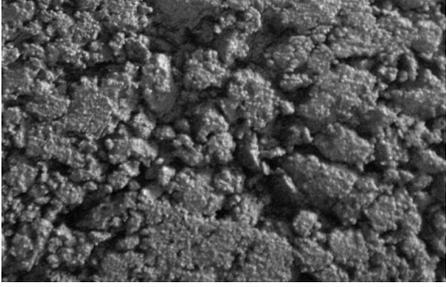
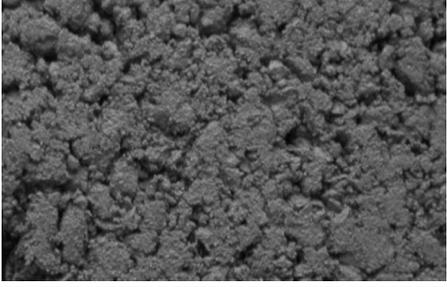
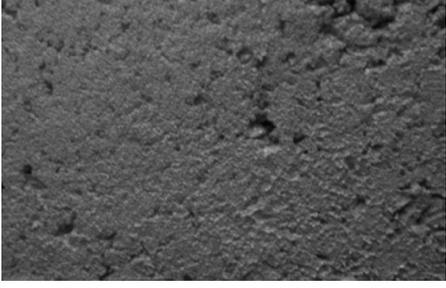
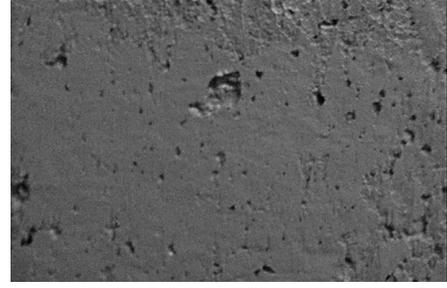


Figure X3.2- Assembled Equipment

- X3.2.2. Assemble the components and uniformly hand scoop the mixture into the box up to a height of 240 mm (9.5 in.).
- X3.2.3. Consolidate the concrete with a 25 mm (1 in.) square head vibrator at 12,500 vibrations per minute by inserting it into the top surface of the concrete at the center of the box. Lower the vibrator straight down for three seconds to the bottom of the box and then raise straight upward for three seconds.
- X3.2.4. Immediately remove the clamps from the side wall forms and remove the forms.
- X3.2.5. The four steps of the Box Test are shown in Figure X1.3
- X3.2.6. Inspect the sides for surface voids and report using the rubric shown in Figure X1.4
- X3.2.7. Measure top and bottom and record edge slump to the nearest 5 mm (0.25 in.) by placing a straightedge at a corner and horizontally using a tape measure to find the length of the highest extruding point.

	
<p style="text-align: center;">Step 1</p> <p>Assemble the components. Hand scoop mixture into box until the concrete level is 240 mm (9.5 inches).</p>	<p style="text-align: center;">Step 2</p> <p>From the top surface of the concrete, vibrate straight downward for 3 seconds.</p>
	
<p style="text-align: center;">Step 3</p> <p>Now, vibrate straight upward for 3 seconds. Then remove vibrator.</p>	<p style="text-align: center;">Step 4</p> <p>After removing the clamps and forms, inspect the sides for surface voids and edge slumping.</p>

Figure X3. 3- Four Steps of the Box Test

	
4	3
Over 50% overall surface voids.	30-50% overall surface voids.
	
2	1
10-30% overall surface voids.	Less than 10% overall surface voids.

X3.2.8.

Figure X3.4- Surface Voids Rubric

X3.2.9.

X3.2.10.

X3.3.

X4. V-KELLY TEST

X4.1. Perform the V-Kelly to evaluate the workability of concrete paving mixtures as follows:

X4.2. Equipment

X4.2.1. V-Kelly test apparatus is shown in Figure 1. The test apparatus is available in a kit from the National Concrete Pavement Technology Center as shown in Figure X4.1.



Figure X4.1 - V-Kelly test apparatus

X4.2.2. The test apparatus requires the following assembly as shown in Figure X2.2:

X4.2.3. A rubber tub: 17 in. diameter top by 15 in. diameter bottom by 8 in. depth with a 6.5 gallons capacity

X4.2.4. Four pieces of the frame for stabilizing the Kelly Ball: one base, two side bars, and one top bar

X4.2.5. A WYCO square vibrator head: 13/16" square by 13 in. length (Part #W877-520), 5 ft cable, with "quick disconnect" adaptor (Part #423500)

X4.2.6. A steel Kelly Ball mounted on a graduated shaft with a total weight of 30 lbs

X4.2.7. Two pins and two bolts: stabilize the frame and the graduated shaft



Figure X4.2 - Assembly unit from each kit

X4.2.8. Assemble the test apparatus with all the units in the kit as shown in Figure X2.3:

X4.2.9. Insert the two side bars into the base, bolt holes down

X4.2.10. Assemble and tighten the two bolts to secure the base

- X4.2.11. Insert the graduated shaft in the yoke of the top bar with 1” protrusion upward and tighten the top bar to the side bars
- X4.2.12. Insert the two pins into the top and bottom holes in the graduated shaft
- X4.2.13. Center the square vibrator head in the yoke of the graduated shaft and tighten securely
- X4.2.14. The other end of the vibrator head should be assembled with a vibration motor that can provide 72 foot-pound force (lbf) energy at 8,000 vibration per minute (vpm) (i.e., Wyco Sure Speed, Model WVG1). It is noted that the vibration motor is not included in the kit but is the same as that provided for the Box test last year. It will require a 15 Amp and 120 Volt (~approximately 2000 W) power source.

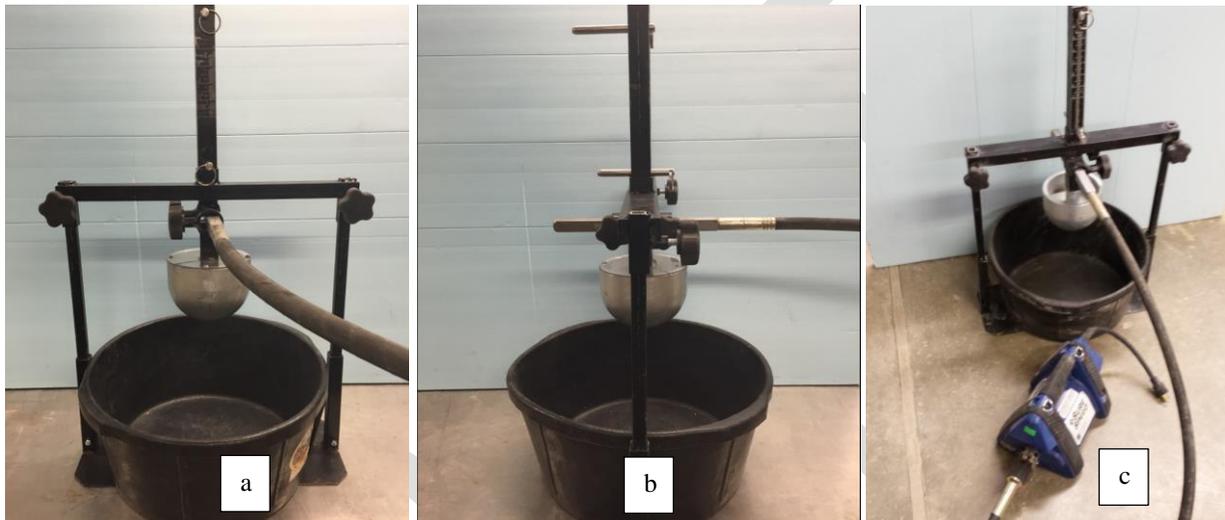


Figure X4.3. Assembled apparatus (a) front view; (b) side view; (c) final setup

Note X4—The following test procedures are recommended for the VKelly test on both static (refer to California Test 533) and dynamic measurements (Taylor et al. 2015). It is noted that the static part of the test should agree with Kelly ball test apparatus and procedures.

- X4.3. Test samples
 - X4.3.1. Fresh concrete should be placed in the tub to a depth of at least 6 in. for 1-in. aggregate or smaller and 8 in. for larger aggregate.
 - X4.3.2. Create leveled area on the concrete surface of about 1.5 ft² without tamping, vibrating, or consolidating the concrete manually. Do not overwork the surface or cause mortar to rise as this will resulting in erroneously high penetration readings.
- X4.4. **Procedure**
 - X4.4.1. Pull out the bottom pin, store it into the top of one side bar and gently lower the ball until it touches the surface of the concrete. Make sure the shaft is in a vertical position and free to slide through the yoke. Take an initial reading to the nearest 0.1 in. and then gently lower the ball into the concrete. Record to the nearest 0.1 in. a second reading when the ball comes to the rest as shown in Figure X4.4.



Figure X4.4. On-going V-Kelly Test

- X4.4.2. Turn on the vibrator motor and set it to 8,000 vpm, and simultaneously start the timer. Record the readings on the graduated shaft every six seconds up to 36 seconds. A digital laser measurer (Bosch Professional GLM 40 or similar) can be installed on the top bar to help record the ball penetration depth during vibration. Alternatively use a video recorder to monitor the graduated scale for the duration of the test.
- X4.4.3. In the laboratory: remove the tub and remix the testing concrete for about 30 seconds then repeat procedures on a new leveled concrete surface.
- X4.4.4. In field condition repeat the procedure using fresh concrete from the same batch.
- X4.4.5. Repeat again to obtain three sets of readings and report the average. Readings should agree within ½ in. of penetration at any given time.

X4.5. Calculation and Reporting

- X4.5.1. Plot the averaged penetration readings in inches (vertical axis) against the square root of time in seconds (horizontal axis) (Figure 5), and determine the slope of the best fit line through the data (Equation 1).

$$D_{pene} = V_{index} \times \sqrt{t} + c$$

where,

D_{pene} = penetration depth at time t

t = elapsed time of vibration

c = initial penetration

V = VKelly Index

- X4.5.2. Report the initial penetration (c) in inches and the slope (V) in in./√s.

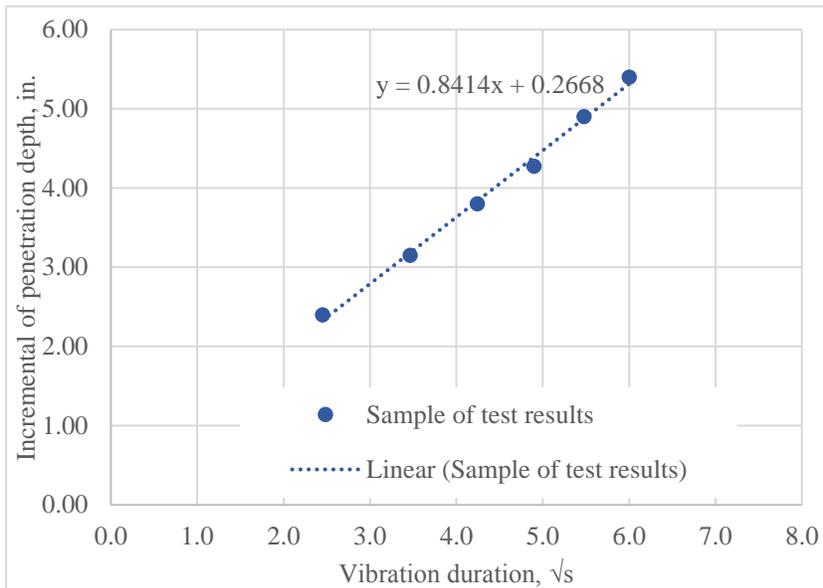


Figure X4.5- Sample Plot of V-Kelly Test

X4.6. References

- X4.6.1. California Test 553. 2014. Method of test for ball penetration in fresh Portland cement concrete. Department of Transportation, Sacramento, California.
- X4.6.2. Taylor, P., Wang, X., and Wang X. 2015. Concrete Pavement Mixture Design and Analysis (MDA): Development and Evaluation of Vibrating Kelly Ball Test (VKelly Test) for the Workability of Concrete. Technical Report TPF-5(205). National Concrete Pavement Technology Center, Iowa State University, Ames, Iowa.

X4.7.

X5. TRANSPORT AND PORE STRUCTURE

X5.1. Volume of Pores (V_{Pores})

The volume of pores in concrete is a useful measure that can be used to assess the performance of concrete. These concrete samples should be at least 25 cubic inches. A typical sample is 2 inches tall and 4 inches in diameter. The samples are dried in an oven at 110 +/-5C for 24 hours after which time their mass is recorded (m_{OD}). After drying, the samples are placed in vacuum chamber with at least 50 Torr. The samples are maintained in this environment for atleast three hours before adding in deaired water while the sample is under vacuum. The vacuum was maintained for one extra hour after which time the vacuum was turned off and the samples remained under water for an additional 18 ± 2 hours. The samples are then removed and toweled to saturated surface dry at which time their mass was recorded (m_{SS}). The sample was then weighed in water and the mass was recorded (m_{SSB}).The volume pore for each sample was determined using Equation 1:

$$V_{Pores} \% = \frac{m_{SS} - m_{OD}}{m_{SS} - m_{SSB}} * 100 \quad (\text{Eqn. 1})$$

where:

m_{SS} = the mass of the completely saturated sample.

m_{OD} = the mass of the oven dry sample, and

m_{SSB} = the mass of the sample in water.

X5.2. Degree of Saturation (S)

The degree of saturation (S) of concrete is the proportion of the pore volume that is occupied by a liquid phase. While there is great benefit in using the volumetric relationship, the calculation of the degree of saturation (S) is more commonly performed on a mass base following equation 2, assuming the liquid phase has the density of water:

$$S = \frac{m - m_{OD}}{m_{SS} - m_{OD}} \times 100\% \quad (\text{Eqn. 2})$$

where:

S= degree of saturation,

m = the mass of the sample at any condition,

m_{OD} = the mass of the oven dry sample, and

m_{SS} = the mass of the completely saturated sample.

Note: ASTM C642-13 and the 'boil test' are used to provide measures of the porosity of concrete. These methods do not appear to include the majority of the entrapped or entrained air void system. Rather, they instead measure the porosity of the matrix. Tests for porosity measured using vacuum saturation is heavily dependent on the level of vacuum drawn, however a vacuum of at least 50 Torr makes it possible to obtain a complete measure of porosity. [Bu, Y., Spragg, R., and Weiss, W. J. "Comparison of the Pore Volume in Concrete as

X5.3. DETERMINATION OF SORPTION PARAMETERS

Absorption properties can be determined using an approach similar to ASTM C1585 (Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes), however two modifications to ASTM C1585 are needed. First, the conditioning procedure described in ASTM C1585-04 is notable to eliminate the "moisture history" of the samples, and thus can lead to a misunderstanding of the water absorption test results, especially in field samples which have obtained a lower relative humidity. It is recommended that field samples be pre-saturated prior to being exposed to the conditioning regimen of ASTM C1585. (Castro, J, Bentz, D. P., and Weiss, W. J., (2011) "Effect of Sample Conditioning on the Water Absorption of Concrete," *Cement and Concrete Composites*," Vol 33. P 805-813. Further, it has been identified that unlike ASTM C1585-04 which is based on mass gain only, values should be based on the degree of saturation as described using sections x.4.1 and x.4.2 (Li, W., Pour-Ghaz, M., Castro, J., and Weiss, W. J., (2012) "Water Absorption and Critical Degree of Saturation Relating to Freeze-Thaw Damage in Concrete Pavement Joints," *Journal of Materials in Civil Engineering* 24(3):299-307 DOI: 10.1061/(ASCE)MT.1943-5533.0000383). The properties that should be measured and reported include: 1) the degree of saturation at the time of matrix filling which can be measured or calculated, 2) the rate of change in degree of saturation during the secondary slope (secondary sorption), and 3) the critical degree of saturation as a function of air quality (i.e., volume or SAM number). This approach is outlined in Todak et al. 2016.

X5.4. PERFORMANCE RELATED SATURATION

A sorption based freeze-thaw model to predict the time it takes a concrete specimen to reach critical saturation with continuous exposure to water. The model has three parts: 1) the initial saturation of gel and capillary pores, 2) the filling of entrained and entrapped air voids, and 3) the concept of a critical degree of saturation which corresponds to the onset of freeze thaw damage. Figure X.4.3 illustrates the time required to reach a critical degree of saturation assuming a typical concrete paving mixture with 564 lb/yd³ of cement, 20% saturation to require repair, a 5% COV in w/c and 15% COV in Air Content. This figure shows that the w/c plays a significant role in determining the time to saturation, with higher w/c mixtures resulting in shorter times to reach critical saturation. This is expected due to fact that higher w/c mixtures have a greater capillary porosity, which increases both S_{matrix} and S_2 when compared to similar mixtures with lower w/c.

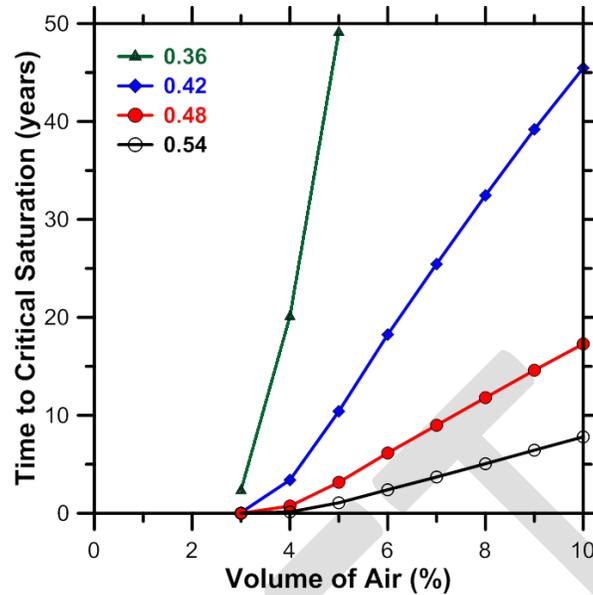


Figure X5.3 The time required to reach a critical degree of saturation assuming a typical concrete paving mixture with 564 lb/yd³ of cement, 20% saturation to require repair, a 5% COV in w/c and 15% COV in Air Content.

Equation X5.5.1 can be used to compute the time to reach critical saturation for a given concrete mixture.

$$S(t) = S_{Nick} + \phi S_2 \sqrt{t} \leq DOS_{Critical} \quad (X5.5.1)$$

Where :

S_{nick} - is the degree of saturation for a concrete where the gel and capillary pores are filled. This is commonly referred to in ASTM C1585 as the nick point. While this can be determined by ASTM C1585 this can also be computed directly from mixture proportions using an approach similar to that described in X.4.1

ϕ - for concrete pavement this should be taken as 1.0 to represent continuous contact with water. This value may be increased when deicing salt is used to 1.3.

S_2 - is the slope of the line of DOS vs $t^{0.5}$ after the nick point saturation determined in accordance with ASTM C1581 and the use of saturation as described in X.4 in this document.

DOS_{crit} - is the critical degree of saturation for a concrete where damage will begin to occur. This can be initially assumed to be 0.85 for a concrete with sufficient air void spacing. Current work is extending this value to the SAM number; however it is known that a SAM value of 0.2 corresponds to a value of 0.85.

Work is currently underway to enable these properties to be predicted using a combination of mixture proportioning and the formation factor [Ley, T., and Weiss, W. J., (2016) "Pooled Fund Study"].

DRAFT