Performance Engineered Mixtures – The Key to Predictable Long-Live Pavement Performance

Concrete
Pavement Association of Minnesota

March 9, 2017

PEM - The Path to Implementation

Acknowledgments

- Dr. Peter Taylor, Iowa State University
- Dr. Jason Weiss, Oregon State University
- Dr. Tyler Ley, Oklahoma State University
- Dr. Tom Van Dam, NCE
- Cecil Jones, Diversified Engineering Services
- Mike Praul, FHWA-Office of Asset Mgt., Pavements & Construction

PEM - The Path to Implementation

What is PEM?

- A program to:
  - Understand what makes concrete last
  - Specify critical properties and test for them
  - Prepare the mixtures to meet those specifications

Tech Center

PEM - The Path to Implementation

Why are PEM specifications needed?

- Pavements have not always performed at designed
- Premature pavement distress has become more severe
  - Changes in cements, SCMs, admixtures, and winter maintenance practices
- Allow innovation
- Increase sustainability of our mixture designs

PEM - The Path to Implementation

Current specifications typically:

- Do not directly measure engineering parameters related to performance
  - Commonly specify air, slump, and strength,
  - Local aggregate requirements
- Changes in source materials can be difficult to handle
- Mixtures are often over cemented
- Mixtures are often built around previous failures – thereby introducing unintended consequences.

CP Tech Center

Minnesota Acceptance Requirements for Grade A Portland Cement Paving Concrete

Acceptance will be based on the following criteria (incentives and disincentives are detailed):

- Aggregates tested for freeze-thaw and ASR susceptibility
- Maximum w/cm of 0.40 (0.42 if ternary/slag)
- Range in cementitious content 530 to 615 lb/cy
- Maximum allowable SCM contents specified
- Specified aggregate grading
- Air content 6% to 9% before consolidation (at least 5% after consolidation
- Strength requirements for opening to traffic

Tech Center

A Better Specification

- Require the things that matter
  - Transport properties (everywhere)
  - Aggregate stability (everywhere)
  - Strength (everywhere)
  - Cold weather resistance (cold locations)
  - Shrinkage (dry locations)
  - Workability (everywhere)

CP Tech Center

PEM - The Path to Implementation

<u>The Vision:</u>

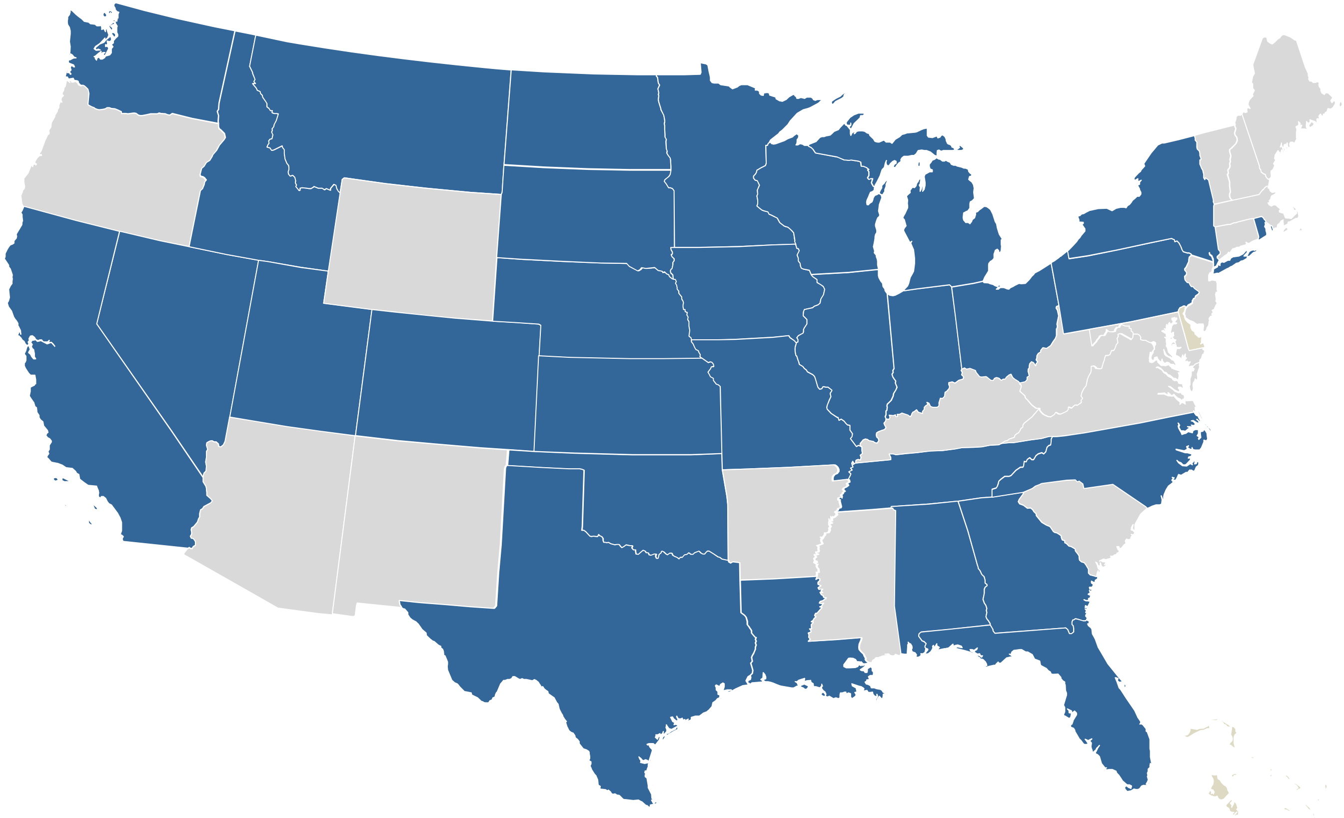
- Concrete Mixtures that are **<u>engineered</u>** to meet or exceed the design requirement, are predictably durable, with increased sustainability
- Keys:
  - ✓Design and field control of mixtures around engineering properties related to performance
  - ✓Development of practical specifications
  - ✓Incorporating this knowledge into a implementation system (Design, Mat'ls, Construction, Maintenance)
  - ✓Validated and refined by performance monitoring

CP Tech Center

30 DOTs, FHWA, Illinois Tollway, Manitoba

NATIONAL CONCRETE CONSORTIUM

TTCC Pooled Fund States



Tech Center

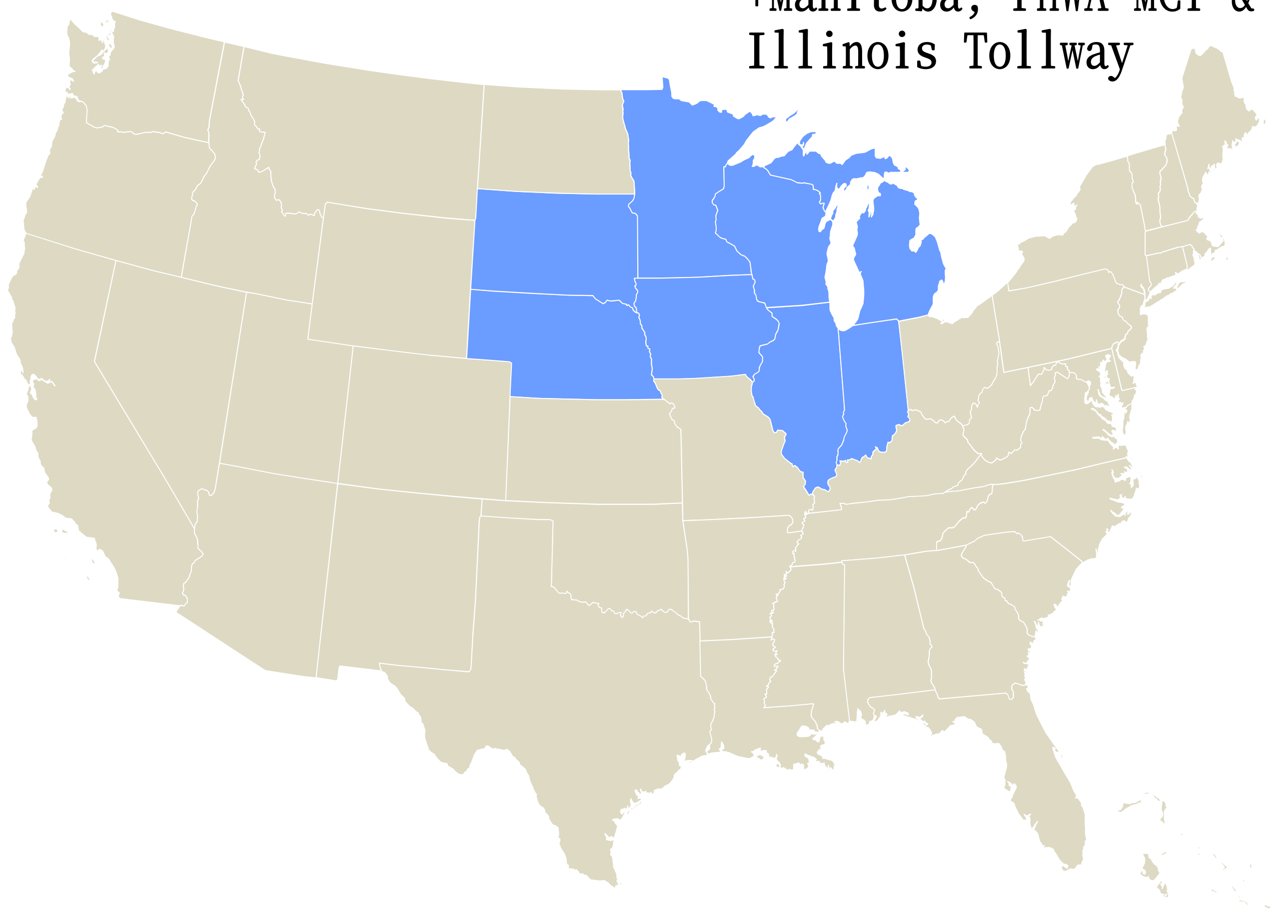
PEM - The Path to Implementation

<u>NCC Reno meeting April 2015</u>

- The NCC decided to organize champion states to work with FHWA & leading national researchers to evaluate new testing technologies & develop a PEM framework

PEM Champion States

+Manitoba, FHWA MCT &
Illinois Tollway



Tech Center

PEM - The Path to Implementation

- Development Team
  - Dr. Peter Taylor, Director CP Tech Center
  - Cecil Jones, Diversified Engineering Services
  - Dr. Jason Weiss, Oregon State University
  - Dr. Tyler Ley, Oklahoma State University
  - Dr. Tom Van Dam, NCE
  - Mike Praul, FHWA
  - Tom Cackler, CP Tech Center
- Industry Participants/Reviewers
  - Champion States & ACPA Chapter Execs
  - ACPA National
  - PCA
  - NRMCA

Tech Center

PEM - The Path to Implementation

What has been accomplished:

- New testing technologies that measure properties related to critical engineering properties have been integrated into a specification framework
- Ongoing evaluation of new test methods
- AASHTO (PP 84)Provisional Specification Approved
- Pooled fund established to assist DOTs with implementation - Solicitation # 1439

Tech Center

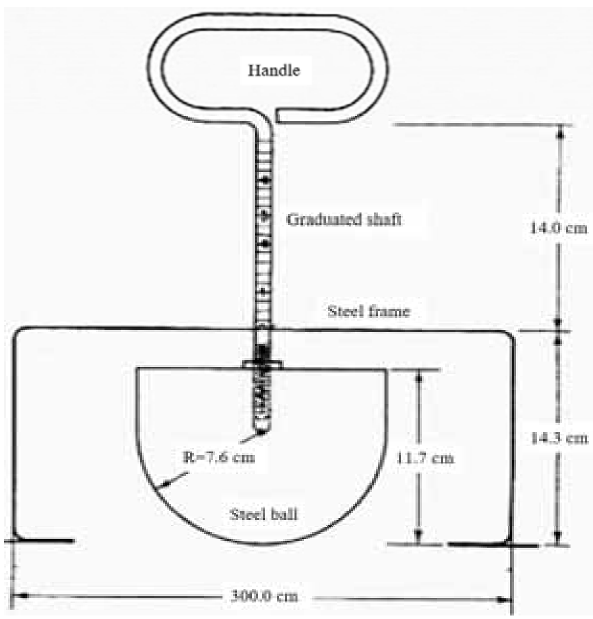
Test Methods

- Workability
  - VKelly
  - Box
- SAM
- Resistivity/Formation Factor
- Sorptivity
- Oxychloride Formation
- Shrinkage

Tech Center

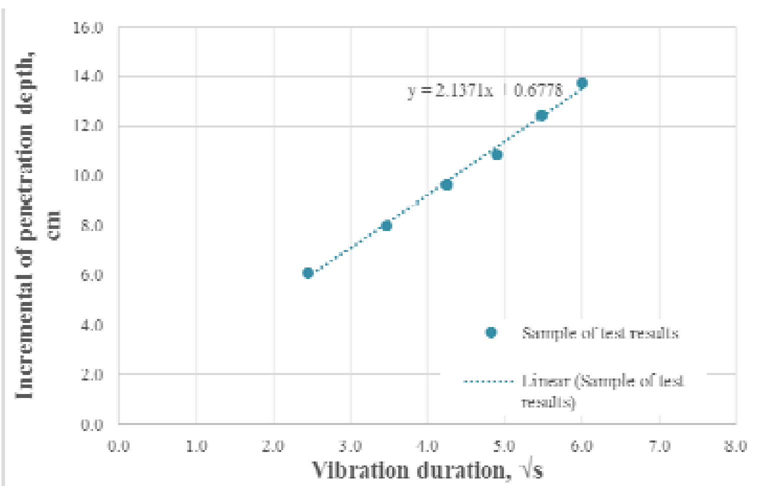
VKelly

- Kelly ball test
  - Developed in the 1950s in US
  - Standardized as Caltrans test method
  - Comparable to slump test
    - ➢1.1 to 2.0 times the Kelly ball reading



VKelly

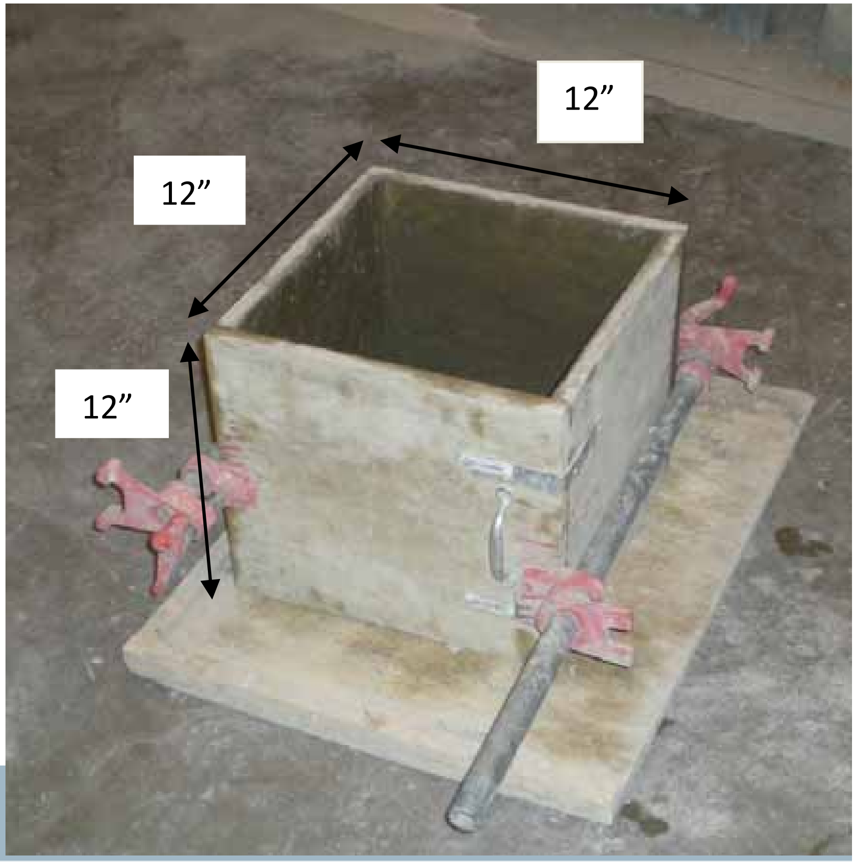
- Measure initial slump (initial penetration)
- Start vibrator for 36 seconds at 8000 vpm
- Record depth every 6 seconds
- Repeat
- Plot on square root of time
- Calculate slope = VKelly Index



Tech Center

Box Test

- A simple test that examines concrete:
  - Response to vibration
  - Filling ability of the grout (avoid internal voids)
  - Ability of the concrete to hold an edge

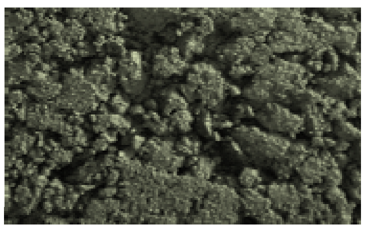


Box Test

- Add 9.5” of unconsolidated concrete to the box
- Insert 1” diameter stinger vibrator (8000 vpm) into the center of the box over a three count and then remove over a three count

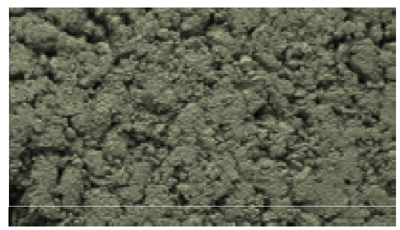
Box Test

- The sides of the box are then removed and inspected for honeycombing and edge slump



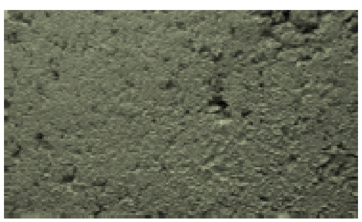
4

Over 50% overall surface voids.



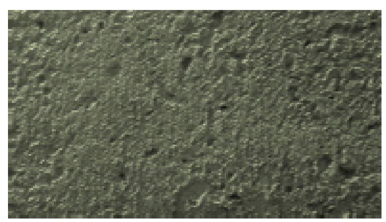
3

30-50% overall surface voids.



2

10-30% overall surface voids.



1

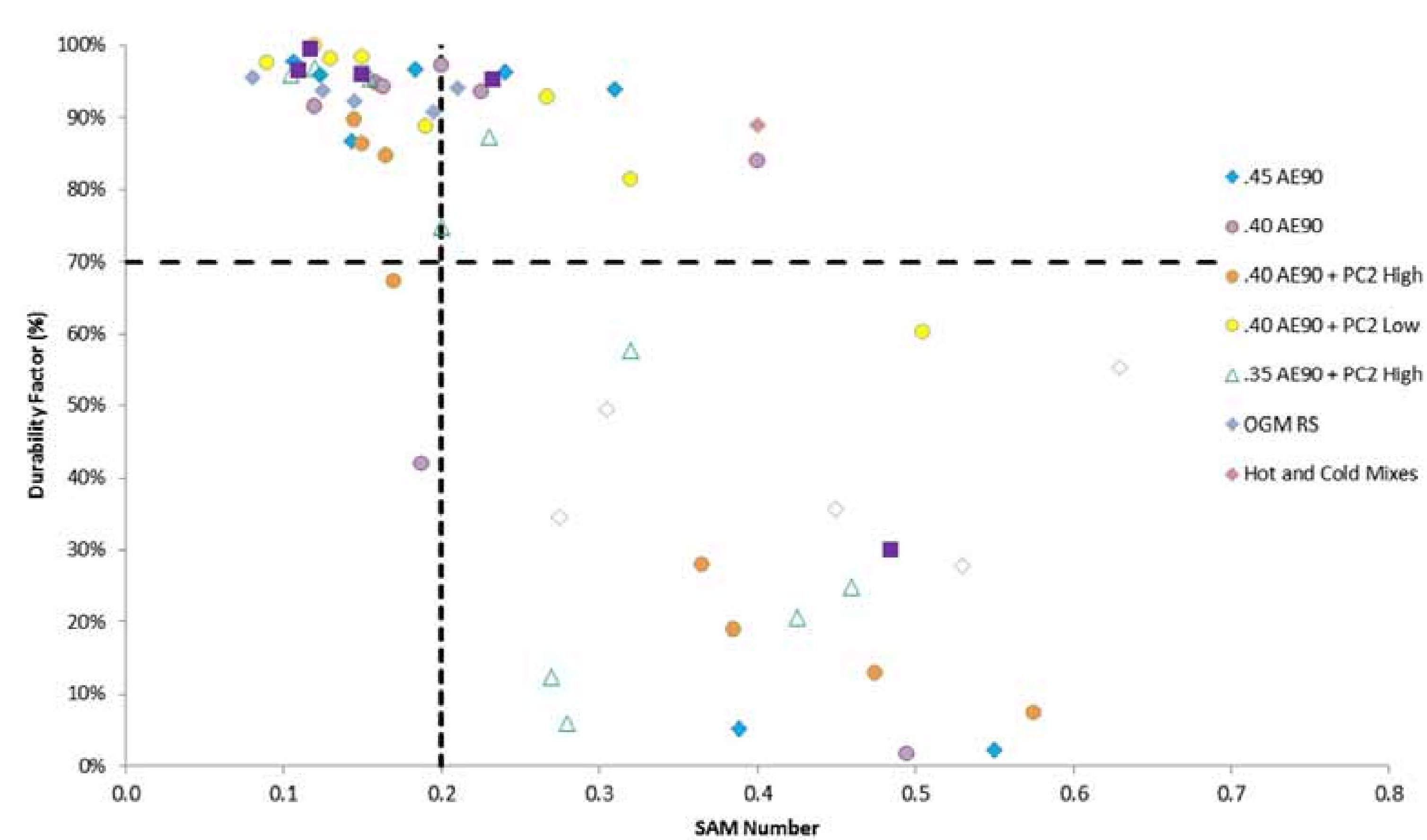
Less than 10% overall surface voids.

Super Air Meter (SAM)

- AASHTO TP 118
- Pump to 3 increasing pressures in 2 cycles
- Dial reports a “SAM number”

SAM

- 8-10 minutes with the air pump
- 4-6 minutes with the CAPE



Resistivity Testing

- 4 – pin AASHTO TP 95-14
- Uniaxial
- Proper sample conditioning

Formation Factor

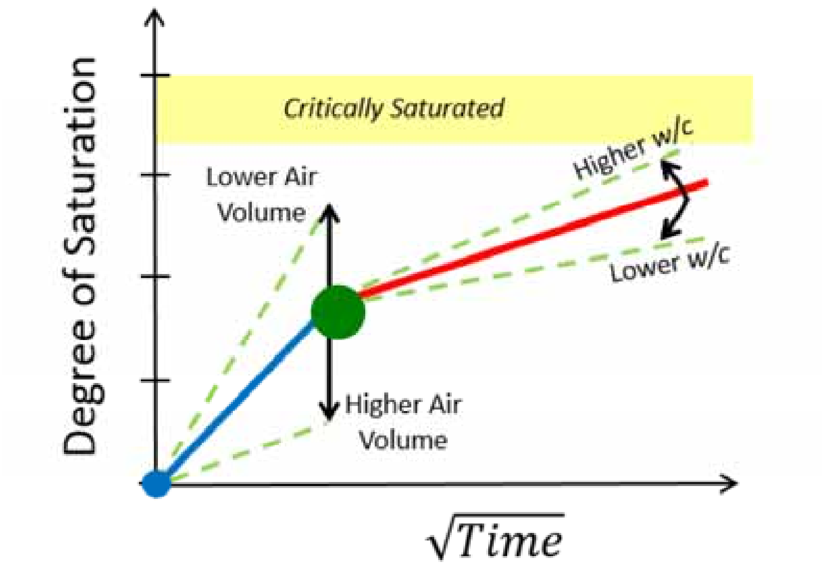
- Normalizes the results of the resistivity test (or rapid chloride penetrability test)
- A true measurement of the volume and connectivity of the concrete pore system
  - Relates to how ions move through concrete
- This information makes it much easier to predict moisture and ion penetration into concrete
  - Better understanding of subsequent long term performance

How do we get it?

- The resistivity test gives you a single number that is an indication of a lot of different things -
  - Moisture
  - Temperature
  - Geometry
  - Curing conditions
  - **Ionic concentration of the pore solution**
  - **Formation Factor**
- We can fix all of the other variables but the last two. *If we can establish the chemistry of the pore solution then we can back out the formation factor*

Sorptivity

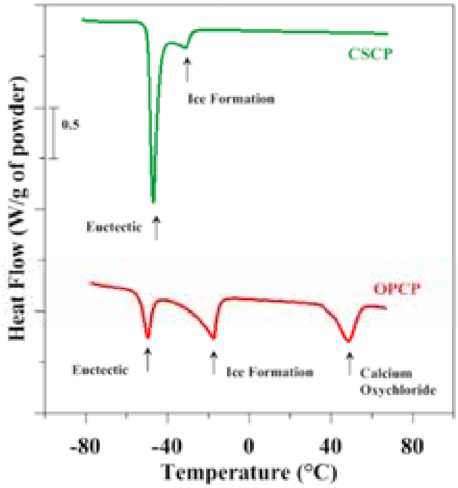
- Volume of pores
  - Measure mass change in concrete from oven dry to saturated condition under sorption
- Degree of saturation
  - Compare mass of sample with oven dry and saturated masses
- Sorptivity Test
  - ASTM C1585 (modified)

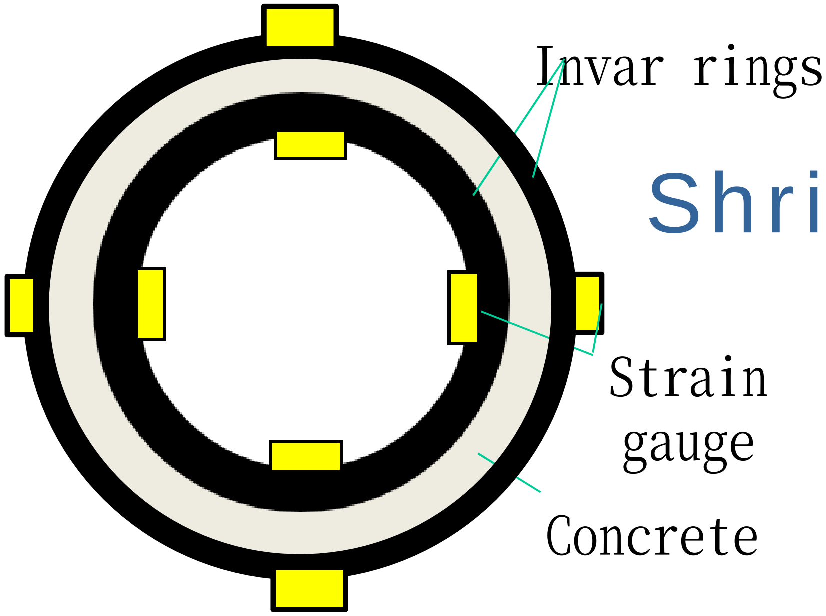


Tech Center

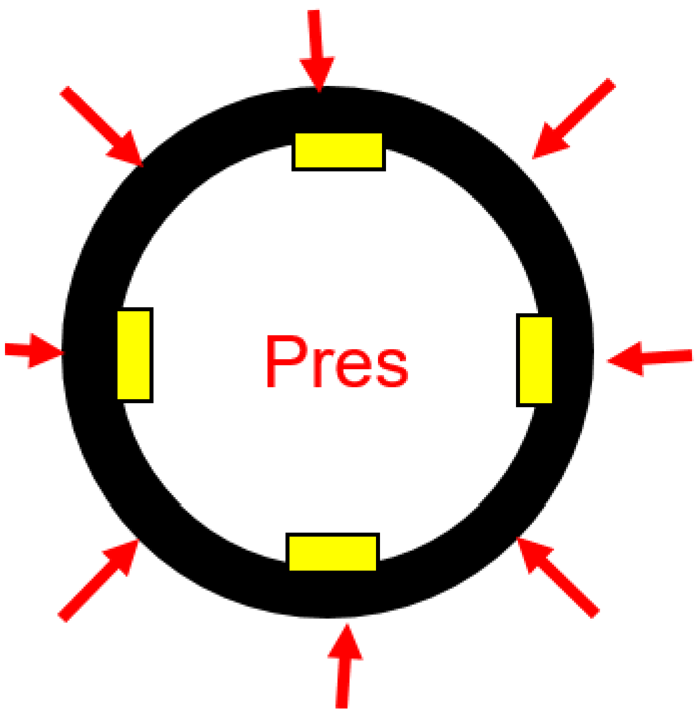
Oxychloride Formation

- $CaCl_2$ and $MgCl_2$ may react with CH to form expansive oxychloride compounds
- Need enough silica in binder system to bind up the calcium – CH to CSH
- Assessed using low-temperature differential scanning calorimetry





Plan View



Shrinkage: Dual Ring Test

The dual ring can measure both expansion and contraction.

As the concrete shrinks the ring can measure the strains that occur.

A temperature gradient is induced into the concrete, making it crack. The stress generated is compared that to 60% of the split tension capacity after 7 days.

Weiss

PEM - The Path to Implementation

AASHTO PP 84 - Provisional Standard Specification for Performance Engineered Concrete Pavement Mixtures & Commentary

Will be published in March 2017

Tech Center

PEM - The Path to Implementation

PEM Mixture Design Parameters (Test the things that matter)

- Strength (follow State requirements)
- Cracking tendency (dimensional stability)
- Freeze-thaw durability
- Resistance to fluid transport
- Aggregate stability
- Workability

Performance and prescriptive options for each, except strength

CP Tech Center

PEM - The Path to Implementation

- <u>Specification Framework</u>
  - Measure properties at the right time
    - Prequalification
    - Process control
    - Acceptance

Consider This to Be A Specification Menu

- One needs to stop and think about this specification
- It is not an ‘off the shelf’ implementation
- Rather it’s a menu of items to choose from
- It is intended to work within the framework already established by agencies

Section	Property	Specified Test	Specifed 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	Yes	Choose either or both		
6.3.2	Compressive Strength	AASHTO T 22	24 MPa	3500 psi	Yes	Yes			
6.4 Reducing Unwanted Cracking Due to Shrinkage									
6.4.1.1	Volume of Paste		28%		Yes	No	Choose only one		
6.4.1.2	Unrestrained Volume Change	ASTM C157	420 με	at 28 day	Yes	No			Curing Conditions
6.4.2.1	Unrestrained Volume Change	ASTM C157	360, 420, 480 με	at 91 days	Yes	No			
6.4.2.2	Restrained Shrinkage	AASHTO T 334	crack free	at 180 days	Yes	No			
6.4.2.3	Restrained Shrinkage	AASHTO T ???	σ < 60% f'r	at 7 days	Yes	No			
6.4.2.4	Probability of Cracking	~	5, 20, 50%	as specified	Yes	No			
Commentary	Quality control check	~	~	~	No	Yes			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	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	Yes		Choose only one	
6.5.1.3	Fresh Air Content/SAM	AASHTO T 152, T196, TP 118	5 to 8, SAM 0.2	%, psi	Yes	Yes			
6.5.2.1	Time of Critical Saturation	"Bucket Test" Specification	30	Years	Yes	No	Note 1	Note 2	Variation controlled with mixture proportion observation or F Factor and Porosity Measures
6.5.3.1	Deicing Salt Damage	~	35%	SCM	Yes	Yes	Choose one		Are calcium or magnesium chloride used
6.5.3.2	Deicing Salt Damage	~	~	~	Yes	Yes			Are calcium or magnesium chloride used, needs a use of specified sealers
6.5.4.1	Calcium Oxychloride Limit	Test sent to AASHTO	< 0.15g CaOXY/g paste		Yes	No			Are calcium or magnesium chloride used
6.6 Transport Properties									
6.6.1.1	Water to Cement Ratio	~	0.45	~	Yes	Yes	Choose Only One		
6.6.1.2	RCPT Value	AASHTO T ???	2000	~	Yes	Yes			Other criteria could be selected
6.6.1.3	Formation Factor/Resistivity	AASHTO xx or AASHTO Yy	500	~	Yes	through ρ			* 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 ρ			
6.7 Aggregate Stability									
6.7.1	D Cracking	AASHTO T 161, ASTM C 1646	~	~	Yes	No			
6.7.2	Alkali Aggregate Reactivity	AASHTO PP 65	~	~	Yes	No			
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									

Tech Center

Each Sections Has Selections

Section	Property		Mixture Qualification	Acceptance
6.5 Durability of Hydrated Cement Paste for				
6.5.1.1	Water to Cement Ratio		Yes	Yes
6.5.1.2	Fresh Air Content		Yes	Yes
6.5.1.3	Fresh Air Content/SAM		Yes	Yes
6.5.2.1	Time of Critical Saturation		Yes	No
6.5.3.1	Deicing Salt Damage		Yes	Yes
6.5.3.2	Deicing Salt Damage		Yes	Yes
6.5.4.1	Calcium Oxychloride Limit		Yes	No
6.6 Transport Properties				
6.6.1.1	Water to Cement Ratio		Yes	Yes
6.6.1.2	RCPT Value		Yes	Yes
6.6.1.3	Formation Factor/Resistivity		Yes	through ρ
6.6.2.1	Ionic Penetration, F Factor		Yes, F	through ρ
6.7 Aggregate Stability				
6.7.1	D Cracking		Yes	No
6.7.2	Alkali Aggregate Reactivity		Yes	No
6.8 Workability				
6.8.1	Box Test	d		No
6.8.2	Modified V-Kelly Test	ds		No

Concrete Strength (6.3)

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	Yes	Choose either or both	
6.3.2	Compressive Strength	AASHTO T 22	24 MPa	3500 psi	Yes	Yes		

Tech Center

Reducing Unwanted Cracking Due to Shrinkage (6.4)

Section	Property	Specified Test	Specified Value		Mixture Qualification	Acceptance	Selection Details	Special Notes
6.4 Reducing Unwanted Cracking Due to Shrinkage								
6.4.1.1	Volume of Paste		25%		Yes	No		
6.4.1.2	Unrestrained Volume Change	ASTM C157	420 microstrain	at 28 day	Yes	No		
6.4.2.1	Unrestrained Volume Change	ASTM C157	360, 420, 480 microstrain	at 91 days	Yes	No		
6.4.2.2	Restrained Shrinkage	AASHTO T 334	crack free	at 180 days	Yes	No	Choose only one	
6.4.2.3	Restrained Shrinkage	AASHTO T ???	σ < 60% f'r	at 7 days	Yes	No		
6.4.2.4	Probability of Cracking	~	5, 20, 50%	as specified	Yes	No		

Hardened Cement Paste Freeze-Thaw Durability (6.5)

Section		Property	Specified Test	Specified Value		Mixture Qualification	Acceptance	Selection Details		Special Notes
6.5 Durability of Hydrated Cement Paste for Freeze-Thaw Durability										
	6.5.1.1	Water to Cement Ratio	AASHTO T 318	0.45	~	Yes	Yes	Choose Either 6.5.1.1 or 6.5.2.1		0.40
	6.5.1.2	Fresh Air Content	AASHTO T 152, T196, TP 118	5 to 8	%	Yes	Yes	Choose only one		6.0 to 9.0%
	6.5.1.3	Fresh Air Content/SAM	AASHTO T 152, T196, TP 118	≥ 4% Air; SAM ≤ 0.2	%, psi	Yes	Yes			
	6.5.2.1	Time of Critical Saturation	ASTM C1585	30	Years	Yes	No	Note 1	Note 2	Variation controlled with mixture proportion observation or F Factor and Porosity Measures
	6.5.3.1	Deicing Salt Damage	~	35%	SCM	Yes	Yes	Choose one		Are calcium or magnesium chloride used
	6.5.3.2	Deicing Salt Damage	~	~	~	Yes	Yes			Are calcium or magnesium chloride used, needs a use of specified sealers
	6.5.4.1	Calcium Oxychloride Limit	Test sent to AASHTO	< 0.15g CaOXY/g paste		Yes	No			Are calcium or magnesium chloride used

Transport Properties/Permeability (6.6)

Section	Property	Specified Test	Specified Value	Mixture Qualification	Acceptance	Selection Details	Special Notes
6.6 Transport Properties							
6.6.1.1	Water to Cement Ratio	AASHTO T 318	0.45	Yes	Yes		0.40
6.6.1.2	RCPT Value	AASHTO T 277	2000	Yes	Yes		Other criteria could be selected
6.6.1.3	Formation Factor/Resistivity	AASHTO xx or AASHTO yy	500	Yes	through ρ	Choose Only One	* 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 ρ		

Aggregate Stability (6.7)

Section	Property	Specified Test	Specified Value	Mixture Qualification	Acceptance	Selection Details	Special Notes
6.7 Aggregate Stability							
6.7.1	D Cracking	AASHTO T 161, ASTM C 1646/666	~ ~	Yes	No		
6.7.2	Alkali Aggregate Reactivity	AASHTO PP 65	~ ~	Yes	No	ASTM C 1260/1561 <0.015%	

Workability (6.8)

Section	Property	Specified Test	Specified Value	Mixture Qualification	Acceptance	Selection Details	Special Notes
6.8 Workability							
6.8.1	Box Test	~	<6.25 mm, < 30% Surf. Void	Yes	No		
6.8.2	Modified V-Kelly Test	~	15-30 mm per root seconds	Yes	No		

The Agency Makes Their Choice

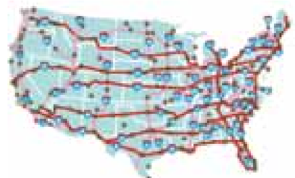
Section	Property	Specified Test	Specifed Value at Qualification	Specifed Value at Acceptance
6.3 Concrete Strength				
6.3.1	Flexural Strength	AASHTO T 97	4.1 MPa (600 psi)	4.1 MPa (600 psi)
6.4 Reducing Unwanted Cracking Due to Shrinkage				
6.4.1.1	Volume of Paste		28%	No
6.5 Durability of Hydrated Cement Paste for Freeze-Thaw Durability				
6.5.1.3	Fresh Air Content/SAM	AASHTO T 152, T196, TP 118	5 to 8%, SAM 0.2	5 to 8%, SAM 0.2
6.5.4.1	Calcium Oxychloride Limit	Test sent to AASHTO	< 0.15g CaOXY/g paste	No
6.6 Transport Properties				
6.6.1.3	Formation Factor/Resistivity	AASHTO xx or AASHTO Yy	500*, ρ > 5 KΩcm*	p > 5 KΩcm
6.7 Aggregate Stability				
6.7.1	D Cracking	AASHTO T 161, ASTM C 1646	~	No
6.7.2	Alkali Aggregate Reactivity	AASHTO PP 65	~	No
6.8 Workability				
6.8.2	Modified V-Kelly Test	~	-30 mm per root secon	No
* Assumed Level A pore solution resisivity				

Quality Control

- PEM acknowledges the key role of QC in a performance specification
- Requires an approved QC Plan
- Requires QC testing and control charts
  - Unit weight
  - Air content/SAM
  - Water content
  - Formation Factor
  - Strength
- Provides guidance for QC
  - Testing targets, frequency, and action
  - Guidance will expand on this

Road Map to the Future of Performance

- Pooled fund to provide technical support for performance approach to concrete
  - FHWA
  - States
  - Industry
- Follow-up FHWA initiatives
  - Introduce PEM and a performance approach to concrete acceptance programs
  - Support PEM with Concrete Pavement Trailer
  - Provide additional guidance on tests/implementation
  - Develop quality control guidance
  - Calibrate durability models



PEM - The Path to Implementation

Pooled Fund Work Tasks

1. Implementing what we know: Education, Training & Technical Support
2. Performance Monitoring and Specification Refinement
3. Measuring and Relating Early Age Concrete Properties to Performance

Tech Center

PEM - The Path to Implementation

Pooled Fund Elements

- Phase 1 with the Scope described
  - 5 years (2017-2021)
  - $3 million
  - Ready to support work by January 1, 2017
- Phase 2 (to support performance monitoring)
  - 5 years (2022-2026)
  - $ TBD

CP Tech Center

PEM - The Path to Implementation

Proposed Funding

- Total of $3 million over 5 years
  - FHWA - $200,000/ year = $1m
  - DOTs – 14 @ $15,000/ year = $1.05m
    - Currently (5): Iowa, Ohio, Pennsylvania, South Dakota, Wisconsin
  - Industry - $200,000/ year = $1m

FHWA Follow-Up Initiatives

- Introduce PEM and a performance approach to concrete acceptance programs (including QC)
- Support PEM with Concrete Pavement Trailer and workshop
- Provide additional guidance on tests/implementation

Questions?

Thomas Van Dam, Ph.D., P.E.
NCE
tvandam@ncenet.com

www.cptechcenter.org