Performance Engineered Concrete Mixtures: Where the Business, Engineering and Environment Meet

2023 T.E.A.M Conference

Branson, MO

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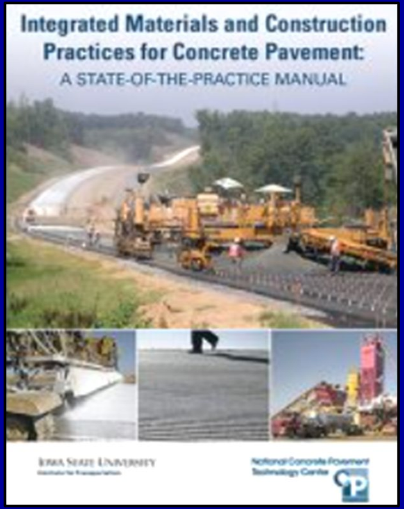
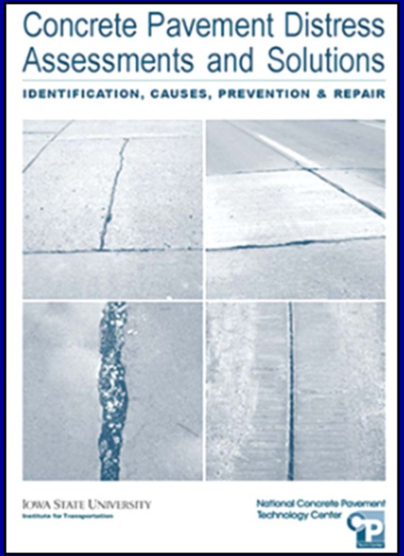
Acknowledgments

- A huge thanks to the National Concrete Pavement Technology Center (CP Tech Center) and the National Concrete Consortium (NCC)
- Utilized numerous slides from past presentations
- Recommend checking out their websites!!!



CP Tech Center

NATIONAL CONCRETE CONSORTIUM

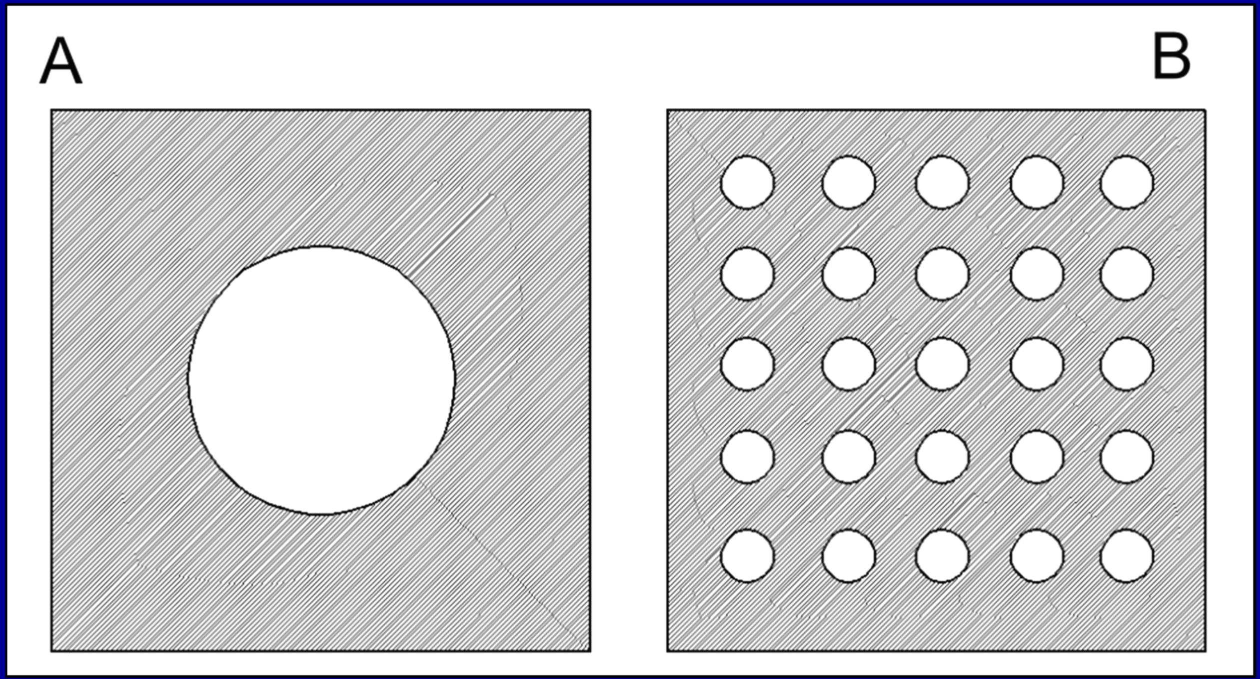


Currently

- Testing concrete has not changed much the last half century
- Performing the same tests for over 60 years
- Slump
- Air Content
- Strength
- Slab Thickness
- These test are not directly evaluating concrete durability

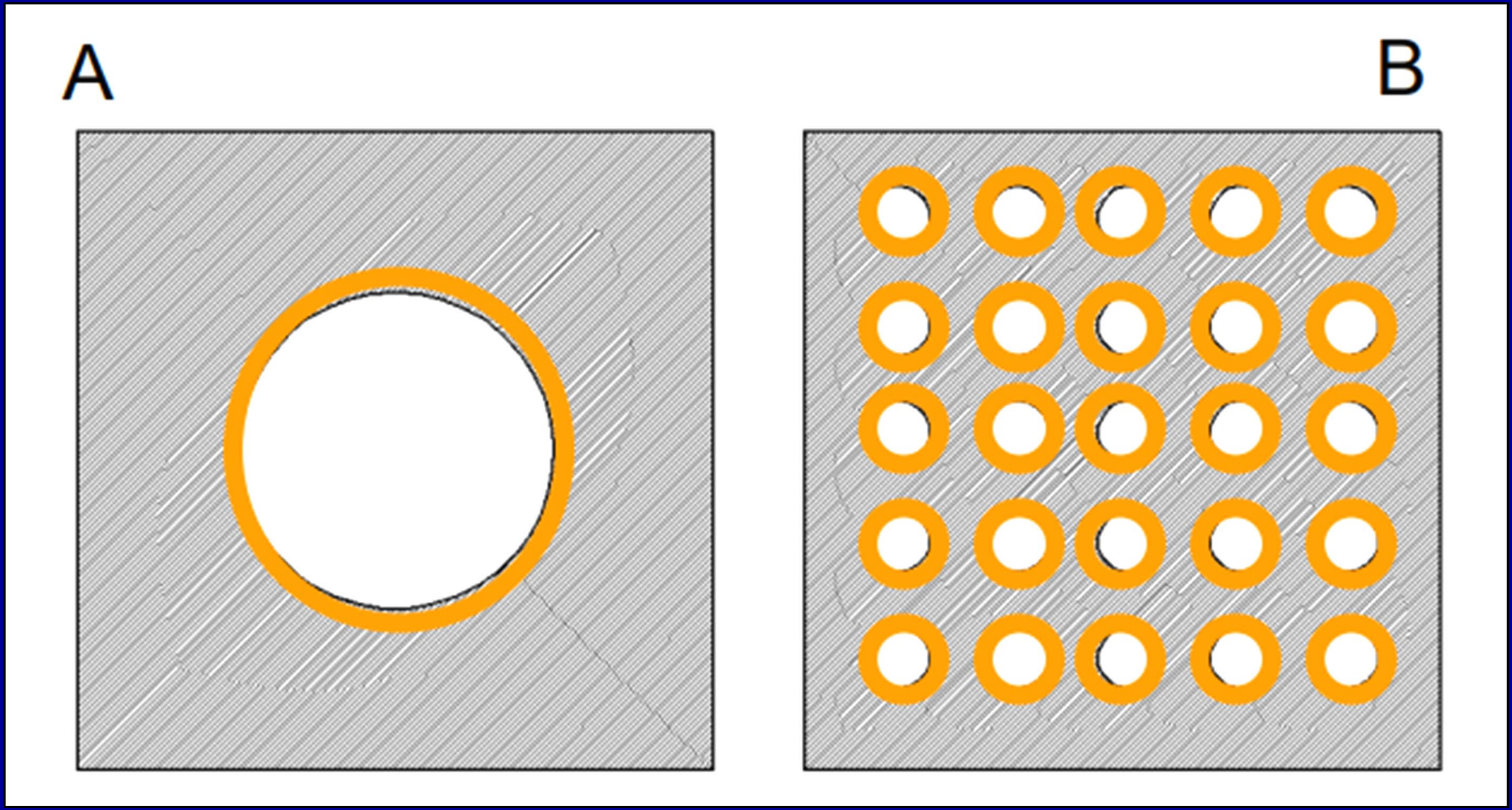
Currently

- What about strength and air content
- Need some strength to resist stress caused by freezing water
- Total air content is not the whole story



Currently

- Each air bubble protects a portion of the paste



Why PEM

- Around the country, concrete not performing as well as in the past
  - Utilizing very aggressive deicing salts
  - Cement fineness and chemistry have changed
  - Utilizing numerous admixtures to enhance concrete properties
- New test methods have recently come on-line
- Need to monitor the right properties impacting durability

What is PEM

- New specification that focuses on critical concrete properties needed to achieve satisfactory performance
- This involved the development and advancement of new test procedures
- In 2022, specifications adopted as an AASHTO Specification (R 101)
- Specification allows agencies to select prescriptive methods or performance measures

- Possibly a combination of both

What is PEM

- Six critical properties identified:

1) Strength
2) Shrinkage
3) Cold weather resistance
4) Transport properties (permeability)
5) Aggregate stability
6) Workability

Strength

- Strength has three important functions:

1) Support the load
2) Fatigue resistance
3) Durability

<u>Performance</u>

1) Flexural Strength (AASHTO T 97) - Min. 600 psi
2) Compressive Strength (AASHTO T 22) - Min. 4,000 psi

- MoDOT specifies 4,000 psi compressive strength

Shrinkage

- Controlling shrinkage reduces cracking potential

Prescriptive

- Volume of Paste - Max. 25%

Performance

1) Unrestrained Volume Change (AASHTO T 160) - 420 $\mu\varepsilon$ @ 28 day
2) Unrestrained Volume Change (AASHTO T 334) - No cracking @ 180 days
3) Restrained Volume Change (AASHTO T 363) - Max. 60% f’r @ 7 days

- MoDOT has no requirements

- Control volume of paste

Cold Weather Resistance

- Ensuring the concrete (i.e., paste) can survive in a freeze/thaw environment and exposure to deicing salts
- Three ways for achieving paste freeze/thaw durability:

Option No. 1 (Prescriptive)

- Water to Cementitious Ratio - Max. 0.45

- Fresh Air Content (AASHTO T 152) - 5 to 8%

- MoDOT has max. 0.50 water to cementitious ratio and requires the air content to be 4.5 to 7.5%

- Considering lowering the maximum water to cementitious ratio to 0.45

Freeze/Thaw Durability

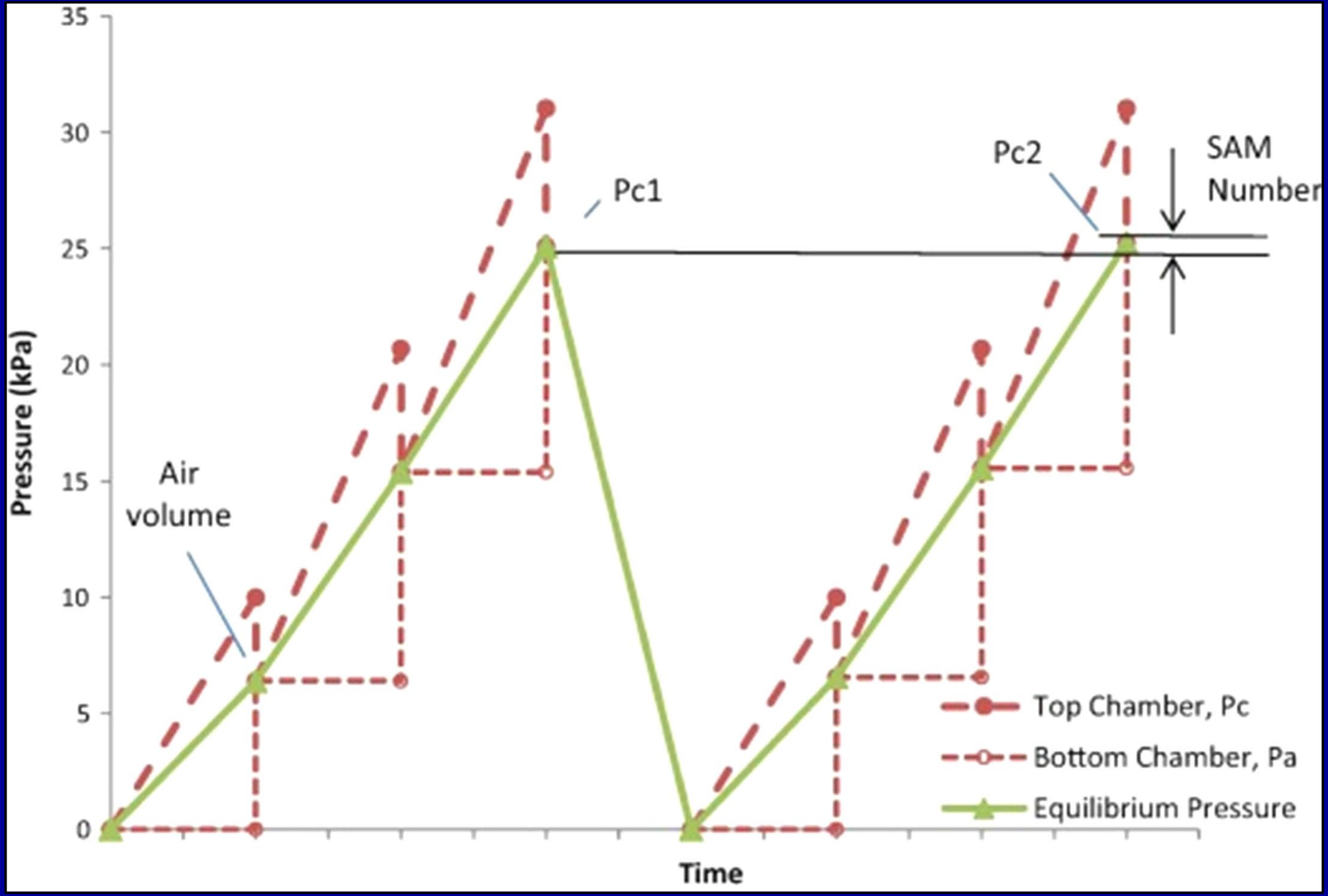
<u>Option No. 2 (Performance)</u>

- Water to Cement Ratio - Max. 0.45
- Fresh Air Content/SAM (AASHTO T 401) - Min. 4.0%
  SAM Index - Max. 0.20

- What does SAM stand for?
- Commonly referred to as the <u>S</u>uper <u>A</u>ir <u>M</u>eter
- MoDOT does own a SAM

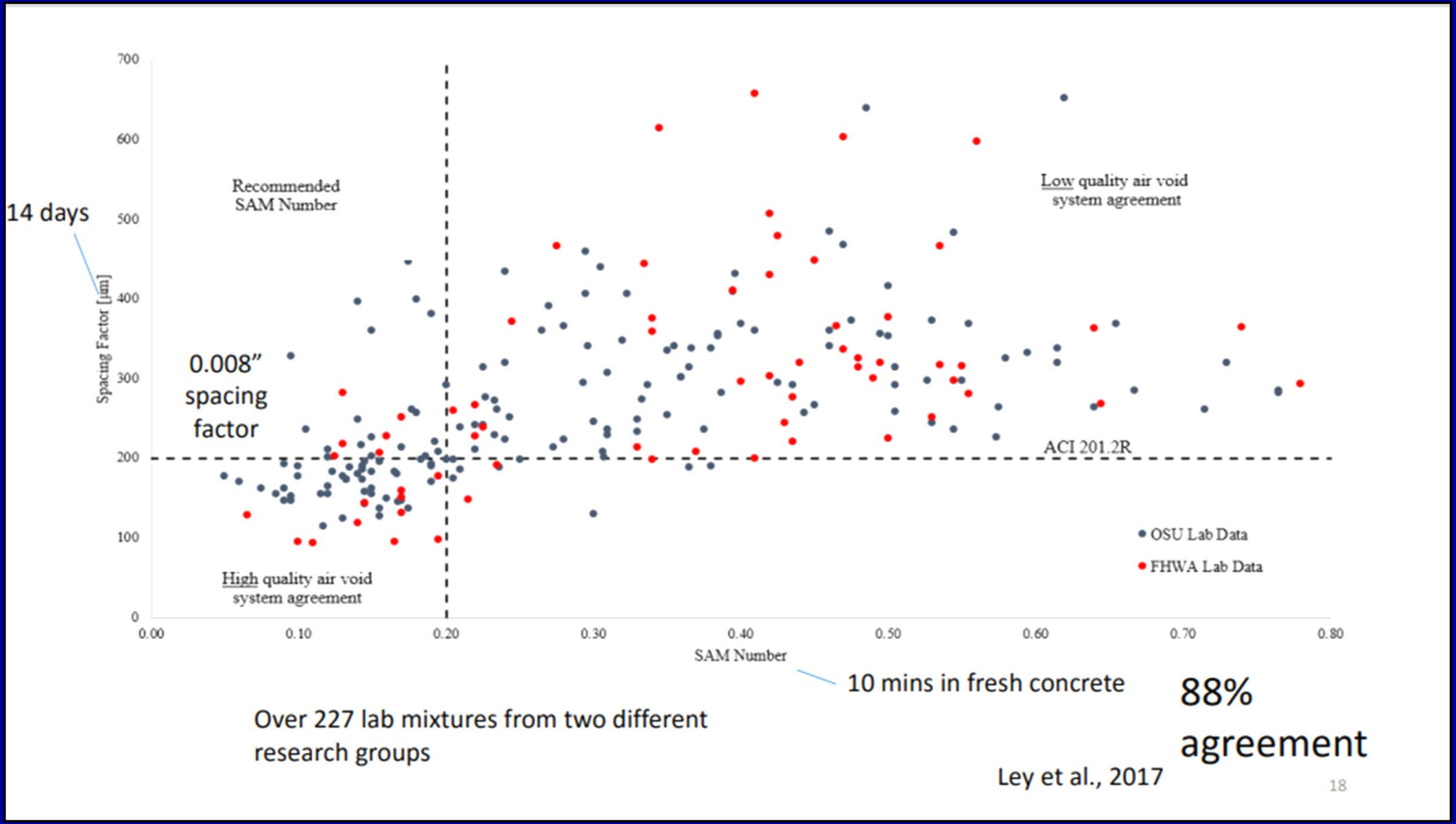
Freeze/Thaw Durability

- The SAM provides information about bubble spacing
- AASHTO TP 118
- How does it work:

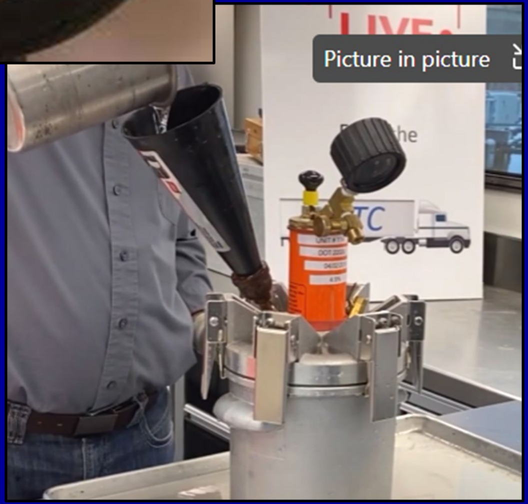


Freeze/Thaw Durability

- **How accurate is the SAM**



- **Test is very sensitive**

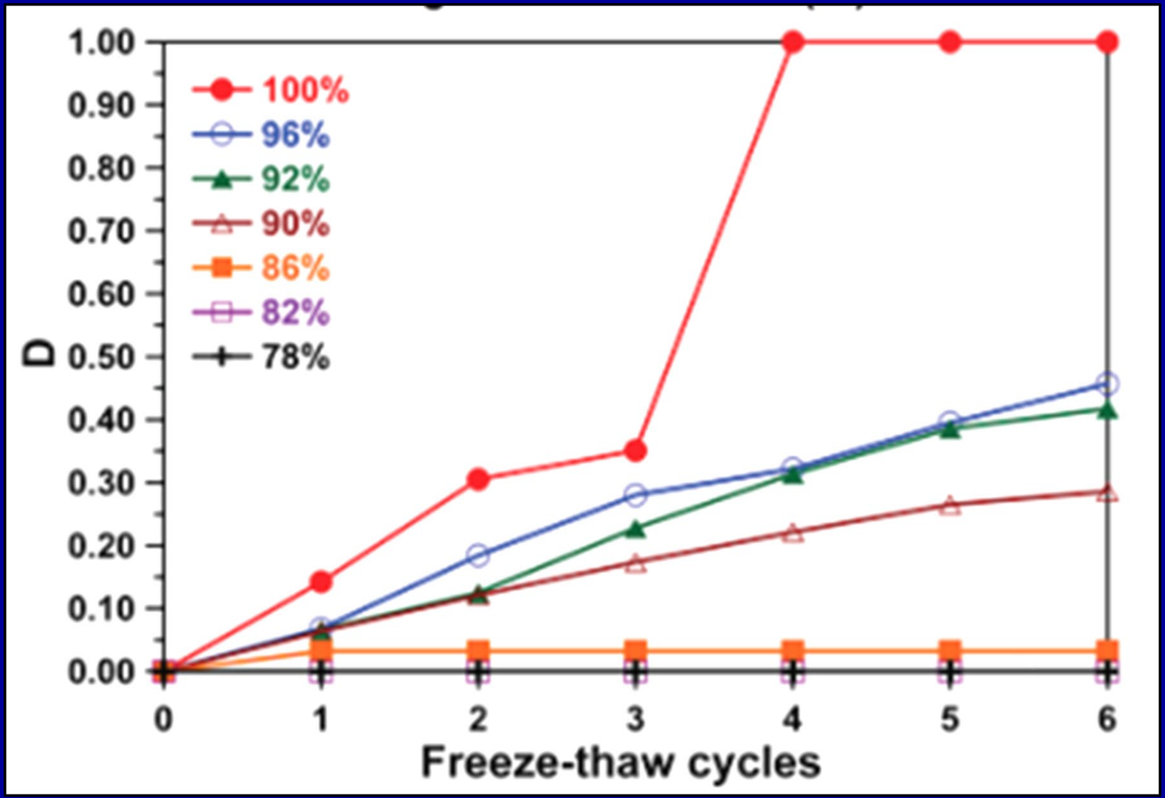


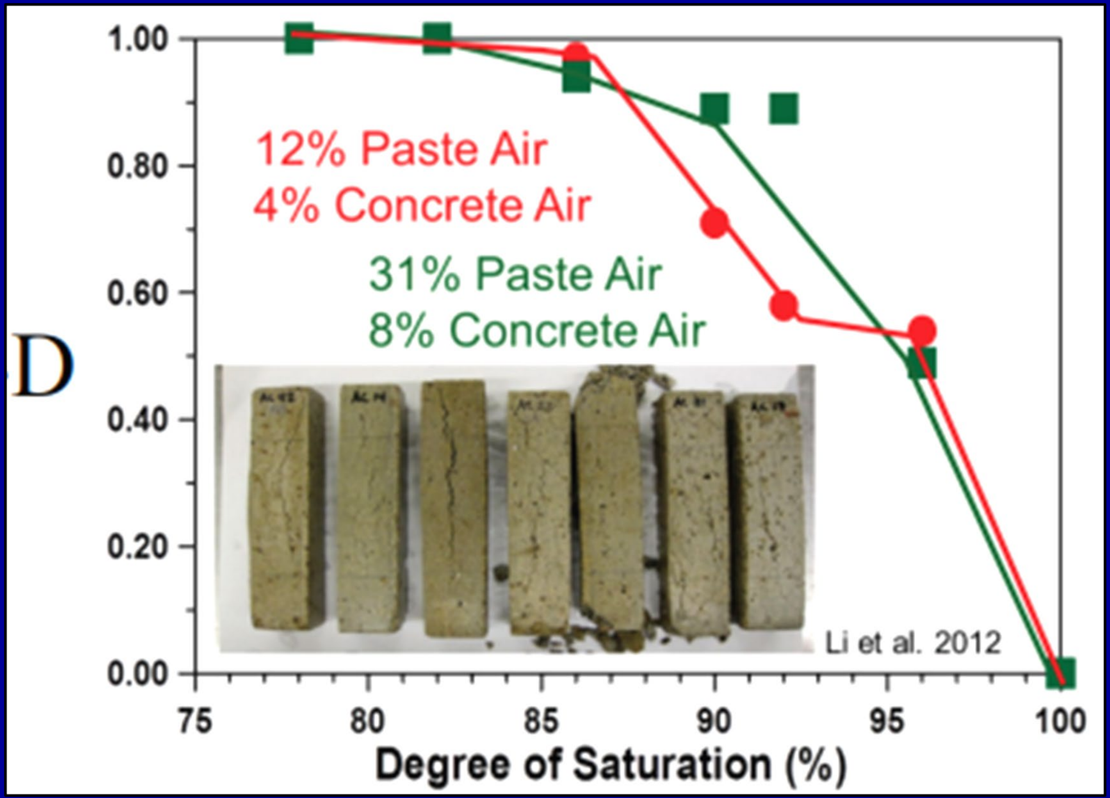
Freeze/Thaw Durability

Option No. 3 (Performance)

- Time of critical saturation (ASTM C1585) - 30 years

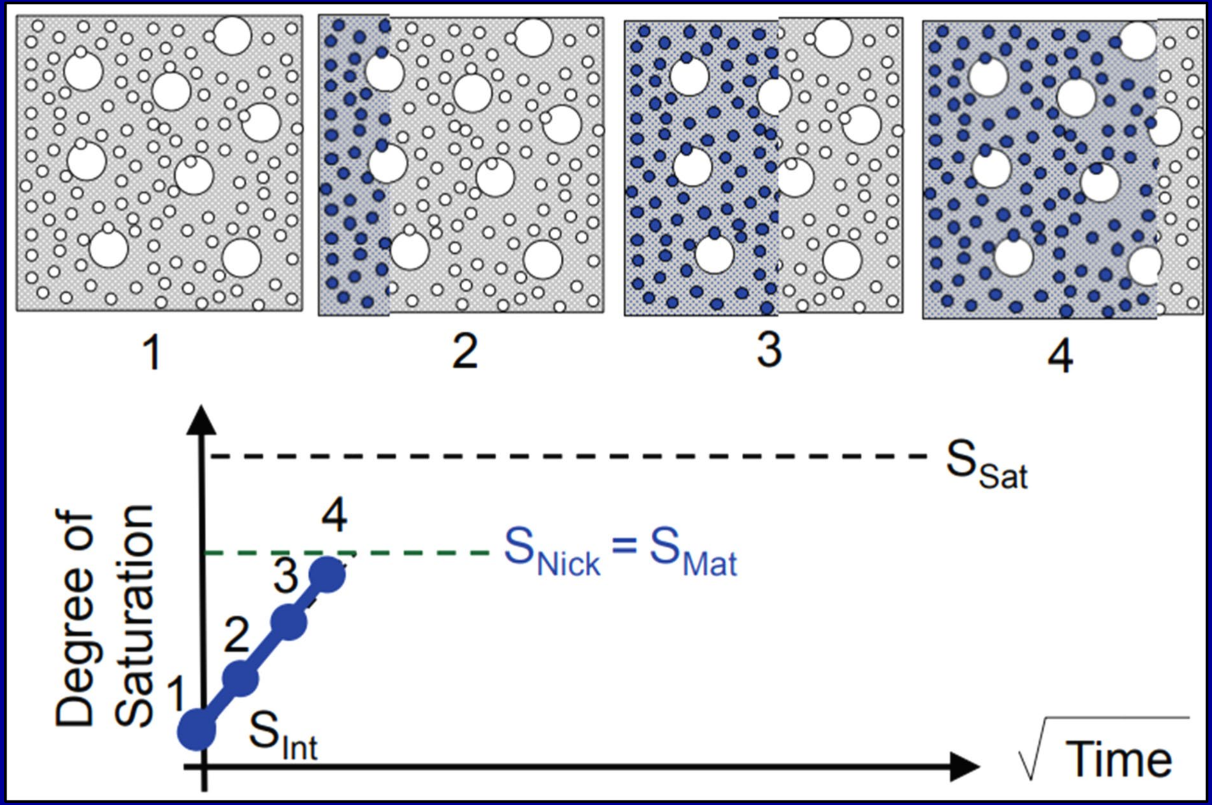
- Why look at critical saturation?

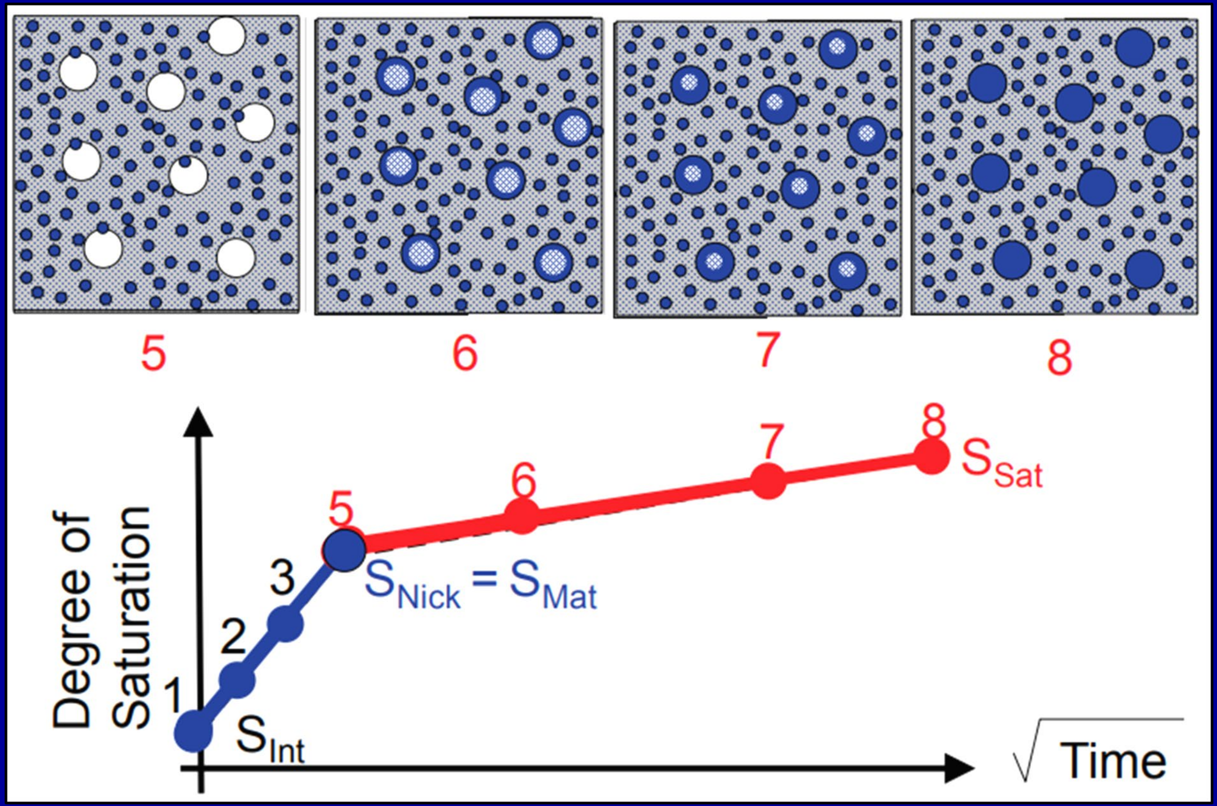




Freeze/Thaw Durability

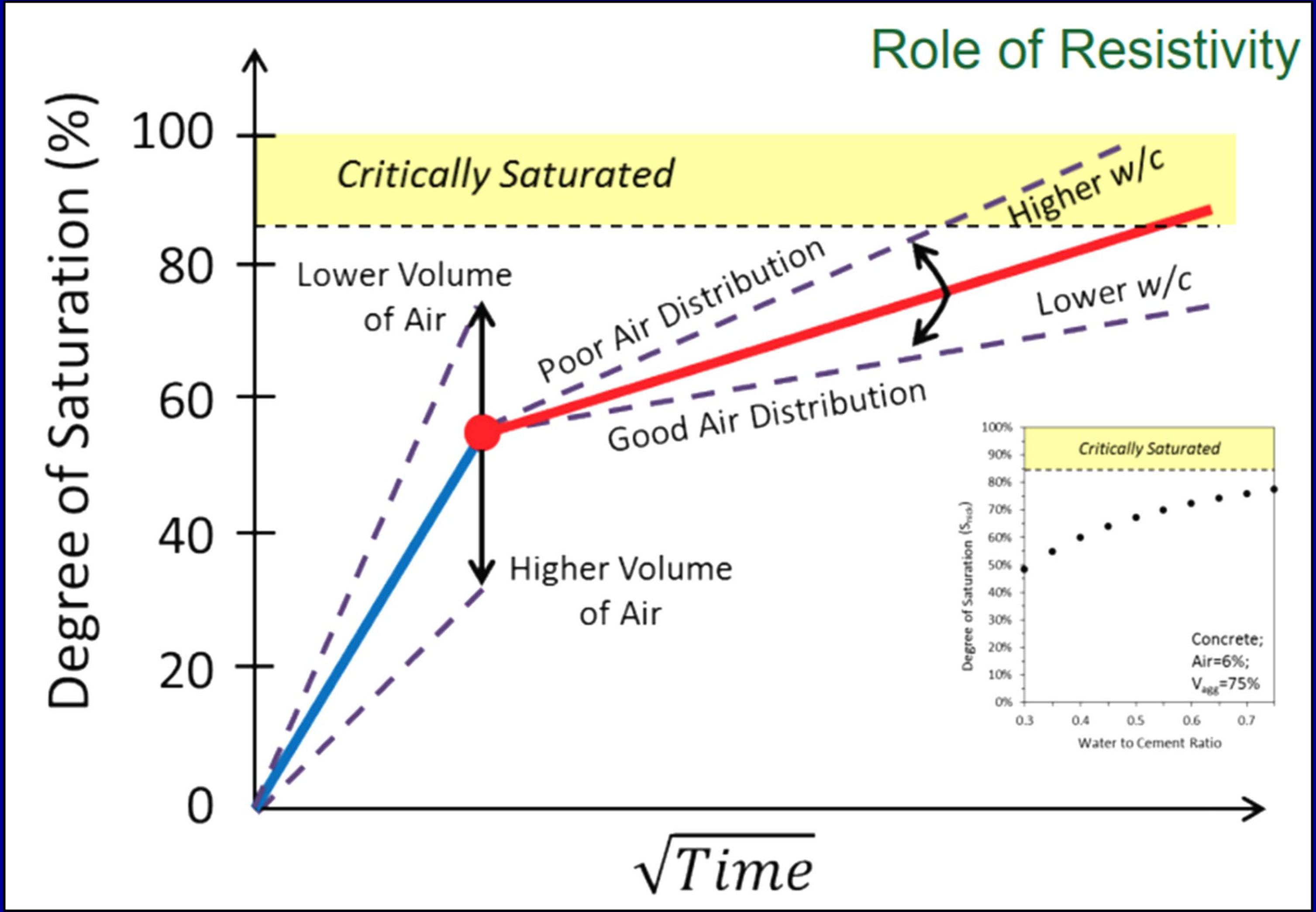
- Phases of concrete saturation





Freeze/Thaw Durability

- Critical factors



Cold Weather Resistance

- Three ways for preventing damage from deicing salts containing calcium chloride or magnesium chloride

Option No. 1 (Prescriptive)

- Utilize at least 30% SCM's (e.g., fly ash, slag, silica fume, metakaolin)

Option No. 2 (Prescriptive)

- Utilize a topical treatment to seal the pavement

Option No. 3 (Performance)

- Determine calcium oxychloride limit (AASHTO T 365)

- Less than 0.15 g CaOXY/100 g paste

Deicing Salts

- What in the world is calcium oxychloride?
- During the hydration process a by-product called calcium hydroxide is produced
- Calcium hydroxide reacts with deicing salts

- Calcium Chloride
- Magnesium Chloride

- Form compounds called calcium oxychloride or magnesium oxychloride

- These compounds expand approximately 30% in 40 to 50 deg. F

- Causes concrete to severely deterioration around the joints

Impact of Deicing Salts

- Research presented in 2008 by Dr. Larry Sutter, Michigan Tech

Control cylinders exposed to lime water solution after 84 days of exposure @ 40 ºF. From left to right: 0.40, 0.50, and 0.60 w/c mortar cylinders.

Cylinders exposed to NaCl solution after 84 days of exposure @ 40 ºF. From left to right: 0.40, 0.50, and 0.60 w/c mortar cylinders.

Impact of Deicing Salts

Cylinders exposed to $CaCl_2$ solution after 84 days of exposure @ 40 ºF. From left to right: 0.40, 0.50, and 0.60 w/c mortar cylinders.

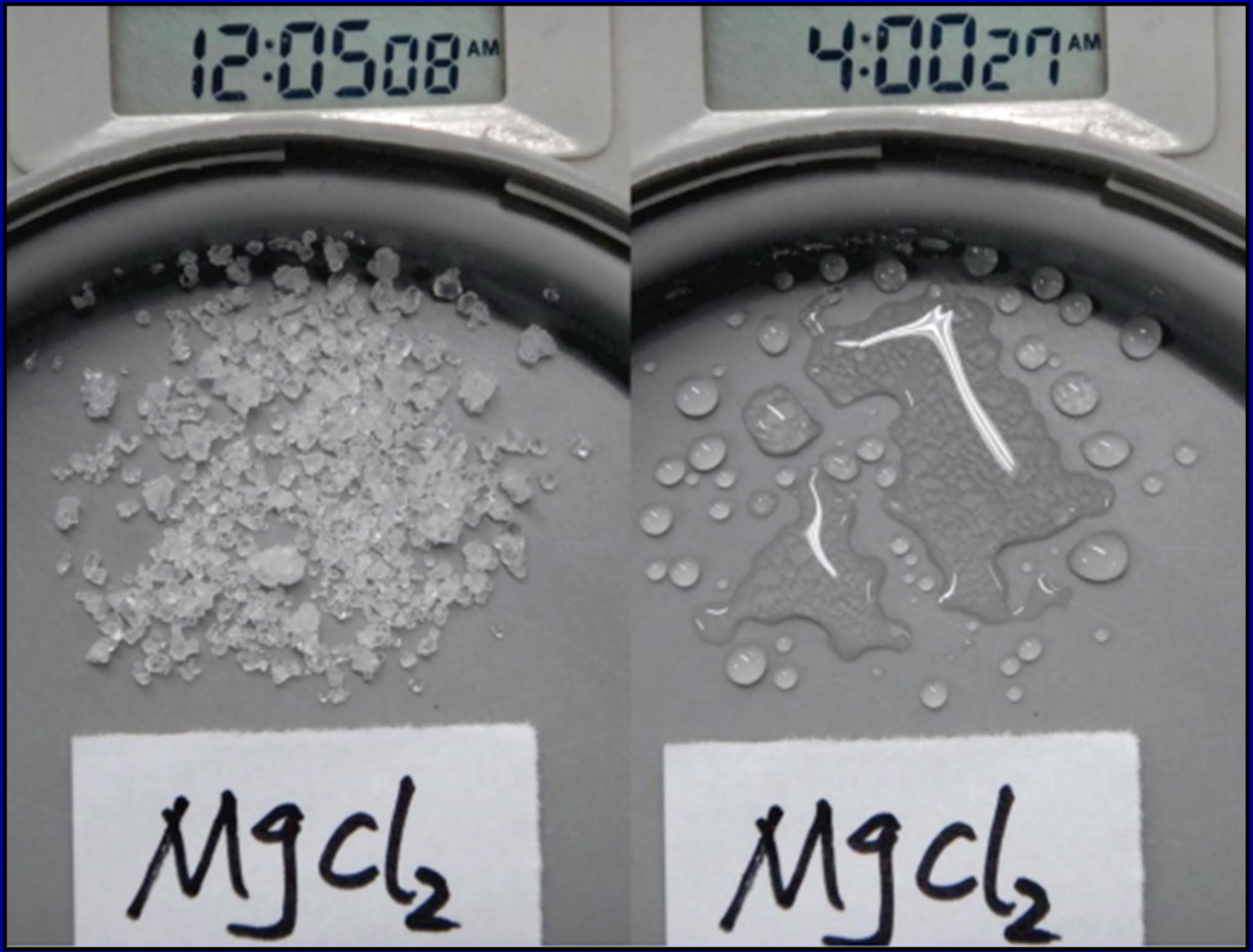
Cylinders exposed to $MgCl_2$ solution after 84 days of exposure @ 40 ºF. From left to right: 0.40, 0.50, and 0.60 w/c mortar cylinders.

Impact of Deicing Salts

- Joint Deterioration

Deicing Salts

- Deicing Salts are hydrophobic



Transport Properties

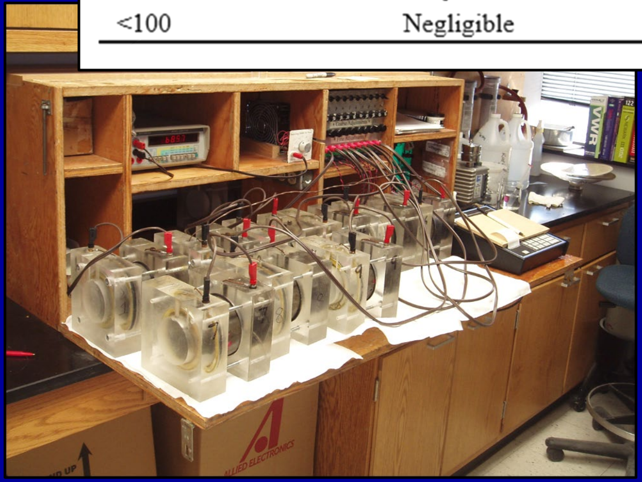
- Ensuring concrete has a low permeability
- Help keep water, deicing salts, and other harmful materials from entering the concrete
- Three ways of evaluating transport properties

<u>Option No. 1 (Prescriptive)</u>

- Specify a water to cementitious Ratio
- Freeze/Thaw Conditions: Max. 0.45
- Non Freeze/Thaw Conditions: Max. 0.50
- MoDOT currently specifies Max. 0.50
- MoDOT has used Rapid Chloride Permeability test

Table X1.1—Chloride Ion Penetrability Based on Charge Passed

Charge Passed, C	Chloride Ion Penetrability
>4000	High
>2000–4000	Moderate
>1000–2000	Low
100–1000	Very low
<100	Negligible



Transport Properties

<u>**Option No. 2 (Performance)**</u>

- Determine the Formation Factor
- Soak sample in calcium hydroxide for 6 days
- Determine resistivity using AASHTO T 358 or T 402
- Divide by 0.127 ohms-m (resistivity of pore solution)

$$\text{Formation Factor} = \frac{\text{Sample Resistivity}}{\text{Pore Solution Resistivity}}$$

- Freeze/Thaw Conditions: Min. 1000
- Non Freeze/Thaw Conditions: Min. 500
- MoDOT does use surface resistivity testing

Table X1.1—Chloride Ion Penetration

Chloride Ion Penetration	Apparent Surface Resistivity[a]: 100 by 200 mm (4 by 8 in.) Cylindrical Specimens (kΩ·cm) a = 3.8 cm	Apparent Surface Resistivity[a]: 150 by 300 mm (6 by 12 in.) Cylindrical Specimens (kΩ·cm) a = 3.8 cm
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] a = Wenner probe tip spacing

Transport Properties

Option No. 3 (Performance)

- Determine Ionic Penetration
- Criteria: 25 mm at 30 years
- Determine the Formation Factor and enter into a model
- AASHTO R 101 recommends the model discussed in the following report:

Weiss, W.J., Ley, T., Isgor, O.B., and Van Dam. "Towards Performance Specifications for Concrete Durability: Using the Formation Factor for Corrosion and Critical Saturation for Freeze/Thaw", Transportation Research Board, Paper 17-02543, Washington, DC, 2017.

- Other models can be used

Aggregate Stability

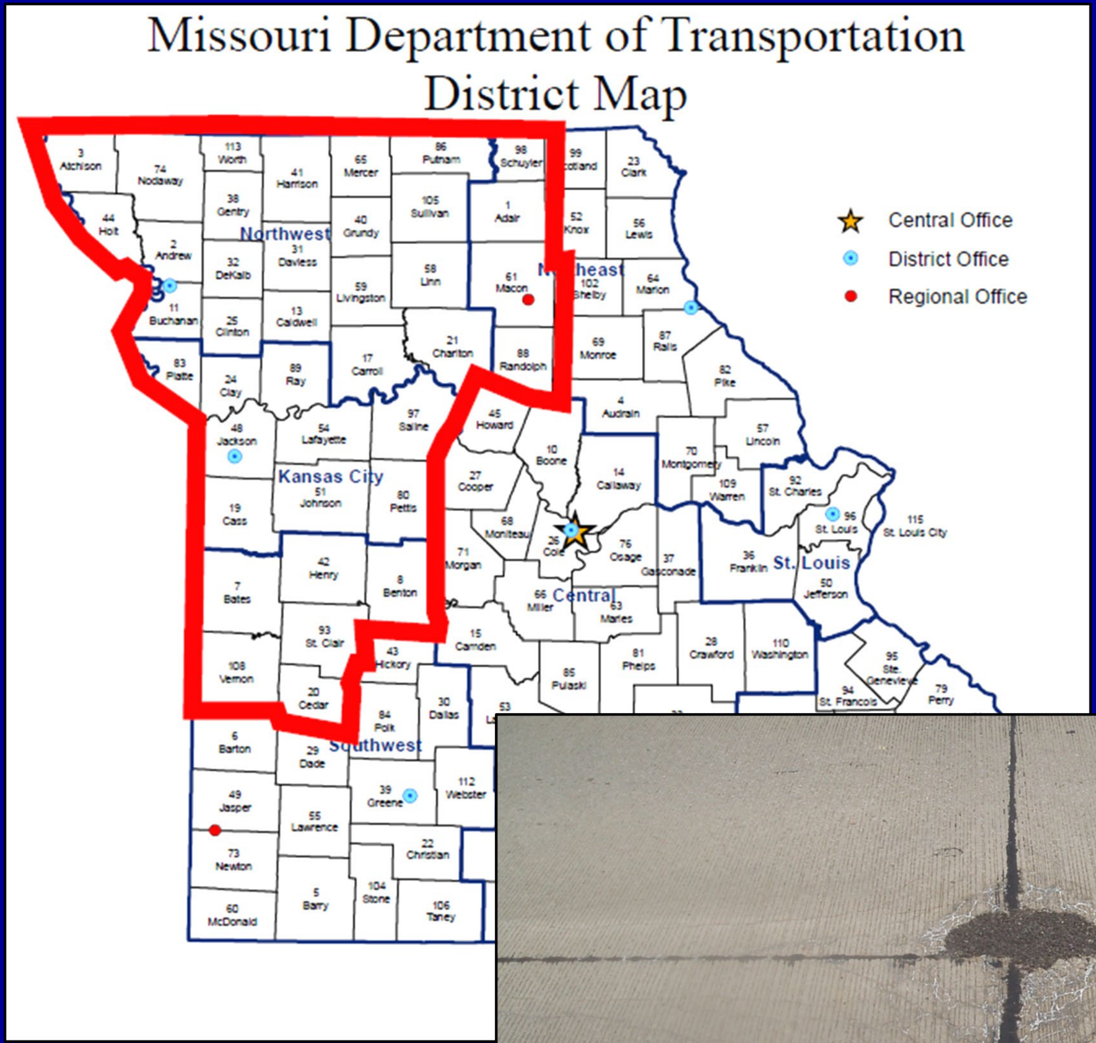
- Testing to ensure the coarse aggregates will perform satisfactory
- Evaluating for two aggregate issues

1) D-Cracking (AASHTO T 161, Procedure A)
2) Alkali Aggregate Reactivity (AASHTO R 80)

- MoDOT performs freeze/thaw durability testing to assess coarse for D-Cracking

- Utilize AASHTO T 161, Procedure B
- Perform for 300 cycles
- Min. durability factor of 75%

D-Cracking


Missouri Department of Transportation
District Map
Central Office
District Office
Regional Office
Northwest
Northeast
Kansas City
Central
St. Louis
Southwest
3 Atchison
74 Nodaway
113 Worth
41 Harrison
65 Mercer
86 Putnam
98 Schuyler
23 Clark
44 Holt
38 Gentry
40 Grundy
105 Sullivan
1 Adair
52 Knox
56 Lewis
2 Andrew
32 DeKalb
31 Daviess
59 Livingston
58 Linn
61 Macon
102 Shelby
64 Marion
11 Buchanan
25 Clinton
13 Caldwell
21 Chariton
88 Randolph
69 Monroe
87 Ralls
83 Platte
24 Clay
89 Ray
17 Carroll
82 Pike
4 Audrain
48 Jackson
54 Lafayette
97 Saline
45 Howard
10 Boone
14 Callaway
70 Montgomery
57 Lincoln
109 Warren
92 St. Charles
96 St. Louis
115 St. Louis City
51 Johnson
80 Pettis
27 Cooper
68 Moniteau
26 Cole
76 Osage
37 Gasconade
36 Franklin
50 Jefferson
19 Cass
7 Bates
42 Henry
8 Benton
71 Morgan
66 Miller
63 Maries
15 Camden
81 Phelps
28 Crawford
110 Washington
95 Ste. Genevieve
79 Perry
94 St. Francois
93 St. Clair
43 Hickory
85 Pulaski
108 Vernon
20 Cedar
84 Polk
30 Dallas
6 Barton
29 Dade
112 Webster
49 Jasper
39 Greene
55 Lawrence
22 Christian
73 Newton
5 Barry
104 Stone
106 Taney
60 McDonald

Aggregate Stability

- Limestone and dolomite formations utilized by MoDOT are not prone to alkali silica reactivity (ASR)
- MoDOT does have some limestone and dolomite formations prone to alkali carbonate reactivity (ACR)
- MoDOT follows protocol outlined in AASHTO R 80 for ACR

- Chemical testing
- Concrete prism testing (ASTM C1105)

Standard Practice for

Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction

AASHTO Designation: R 80-17 (2021)[1]

Technically Revised: 2017 Reviewed but Not Updated: 2021

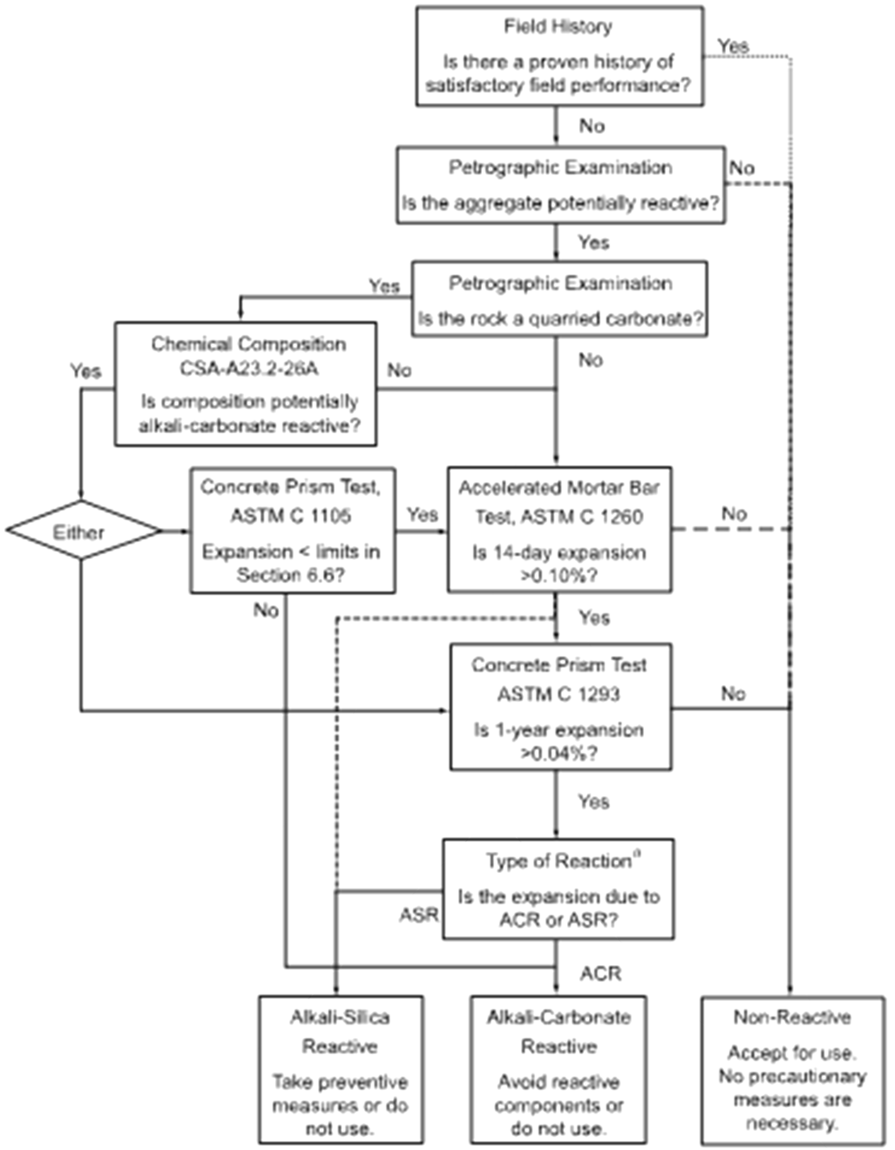
Technical Subcommittee: 3c, Hardened Concrete

AASHTO

American Association of State Highway and Transportation Officials
555 12th Street NW, Suite 1000
Washington, DC 20004

AASHTO R 80

- Follow chart being utilized to assess aggregate formations for ACR.



- The type of reaction needs to be determined only after the concrete prism test if the aggregate being tested is a quarried carbonate that has been identified as being potentially alkali–carbonate reactive by chemical composition in accordance with test method CSA A23.2-26A. The solid lines show the preferred approach. However, some agencies may want to reduce the amount of testing and accept a higher level of risk, and this can be achieved by following the direction of the dashed lines.

Figure 1—Sequence of Laboratory Tests for Evaluating Aggregate Reactivity

Chemical Testing

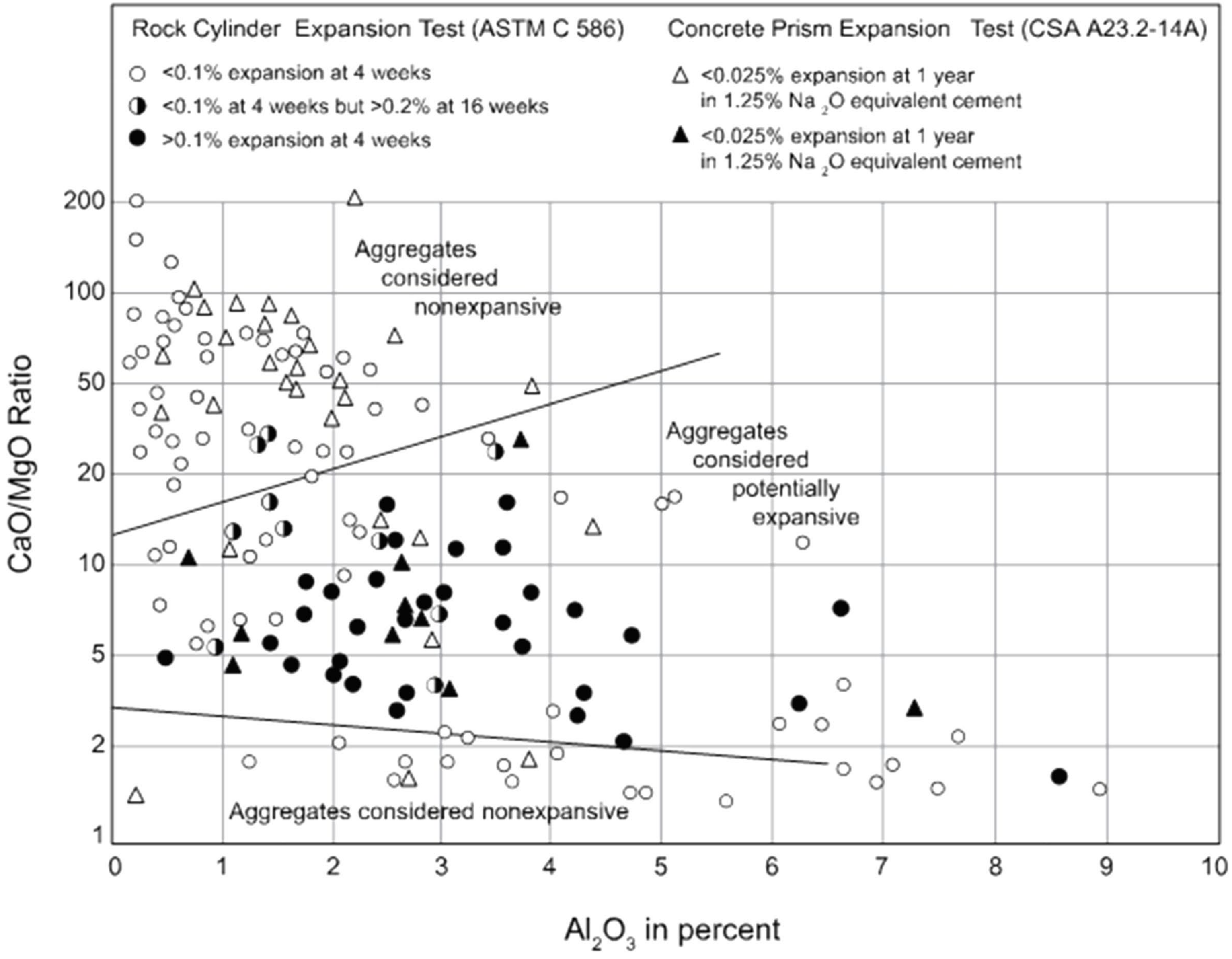
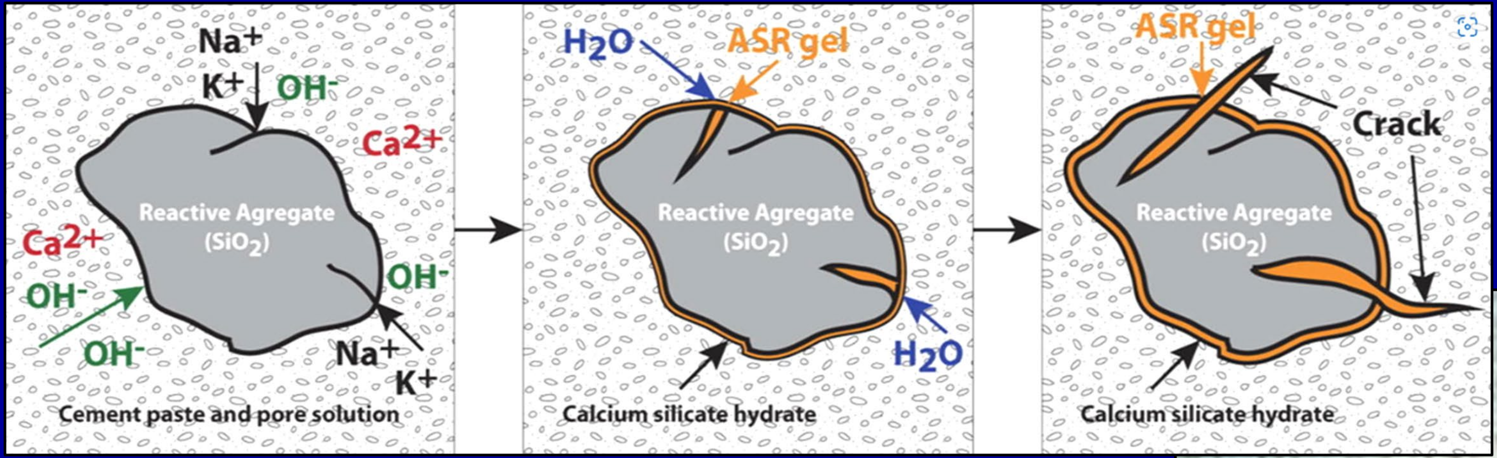
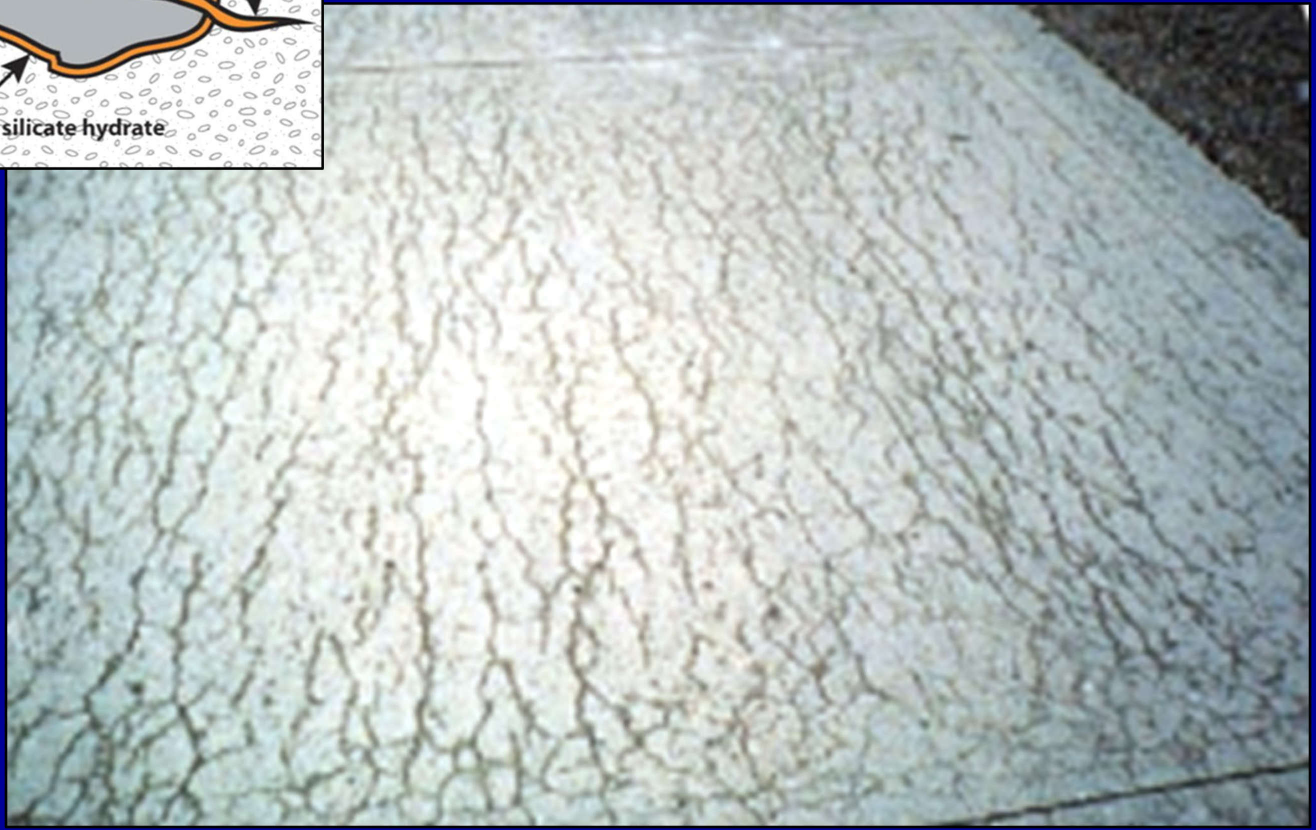


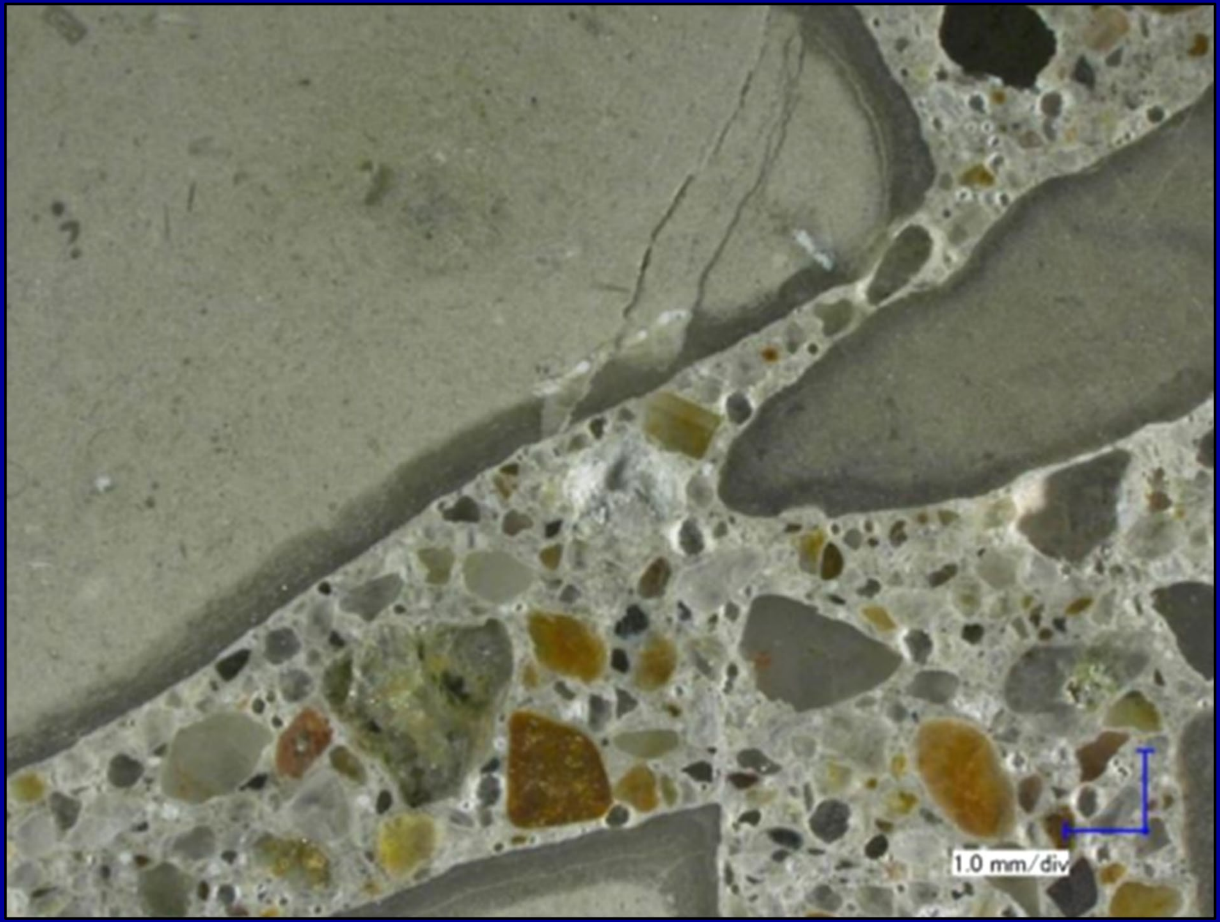
Figure 2—Using Chemical Composition as a Basis for Determining Potential Alkali–Carbonate Reactivity of Quarried Carbonates (from CSA A23.2-26A)

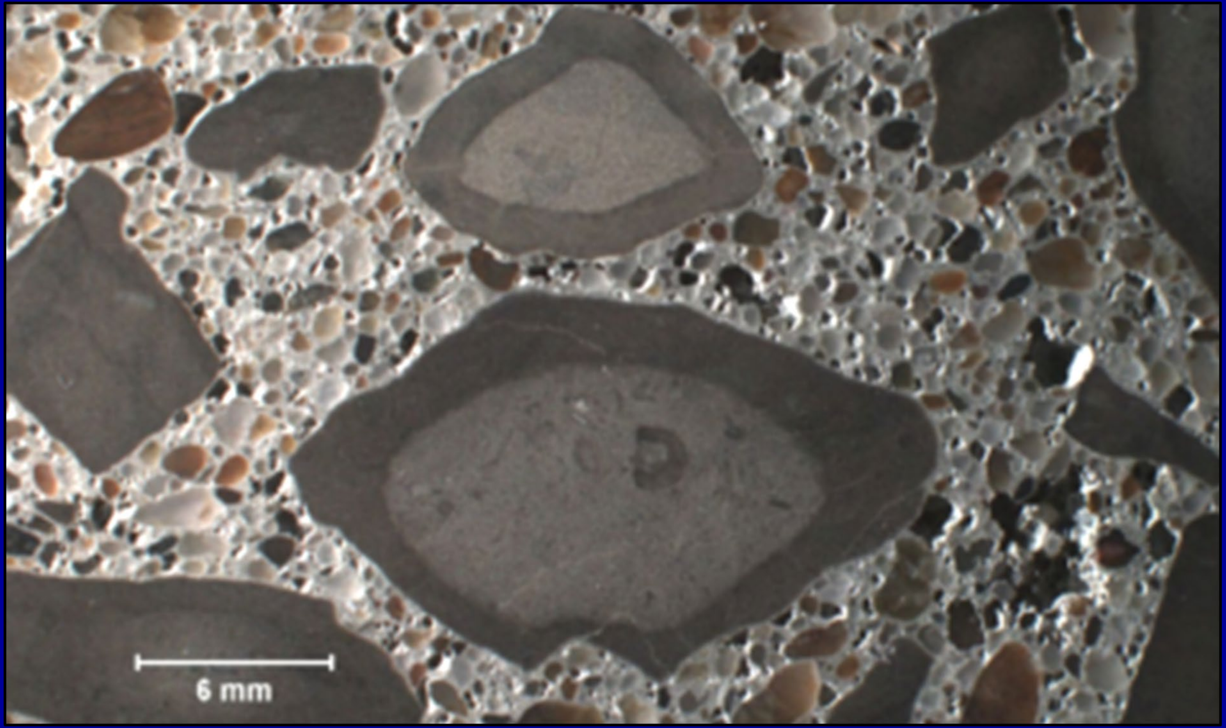
Alkali Silica Reactivity





Alkali Carbonate Reactivity





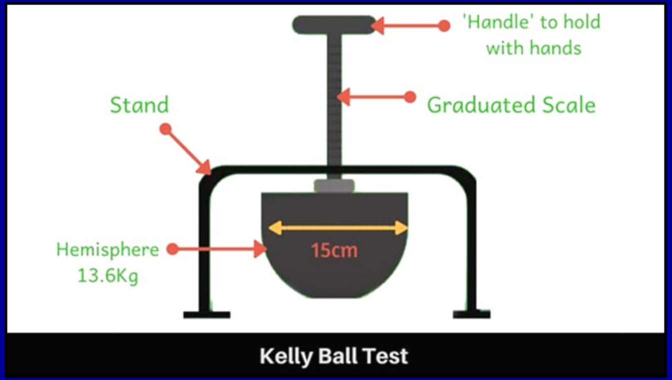
Alkali Carbonate Reactivity

Workability

- Testing to ensure concrete will consolidate as desired
- Two test methods available

1) Box Test (AASHTO T 396)
2) Modified V-Kelly Test (AASHTO T 403

- Assessing concrete to see how it will respond to vibration



Workability

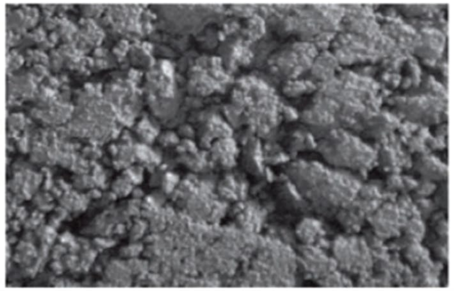
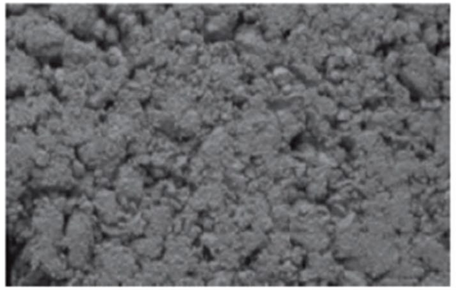
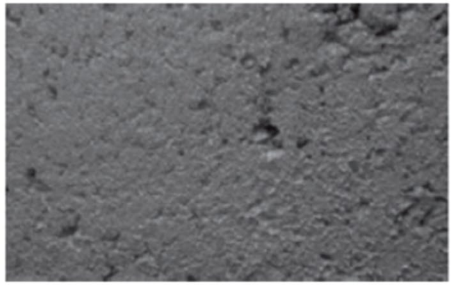
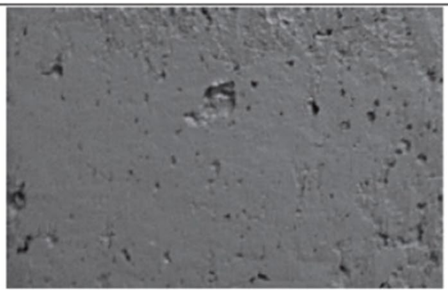
- What about the slump test?
- Does not measure how the concrete will respond to vibration
- Only measuring the slump
- Slump test good for measuring consistency
- Box Test and Modified V-Kelly Test not intended for field use
- Need to relate the Box Test or the V-Kelly test to the slump test

Box Test

- Less than 6.25 mm of edge slump (1/4 in.)
- Less than 30% surface voids

	Step 1	Gather the different components of the Box Test.
	Step 2	Construct box and place clamps tightly around box. Hand scoop mixture into box until the concrete height is 9.5" (241.3 mm).
	Step 3	Insert vibrator downward for 3 seconds and upward for 3 seconds. Remove vibrator.
	Step 4	After removing clamps and the forms, inspect the sides for surface voids and edge slumping.

Box Test Surface Voids

	
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.

Modified V-Kelly Test

- 15 – 30 mm/$s^{1/2}$ (0.6 – 1.2 in./$s^{1/2}$)

- Slope of line

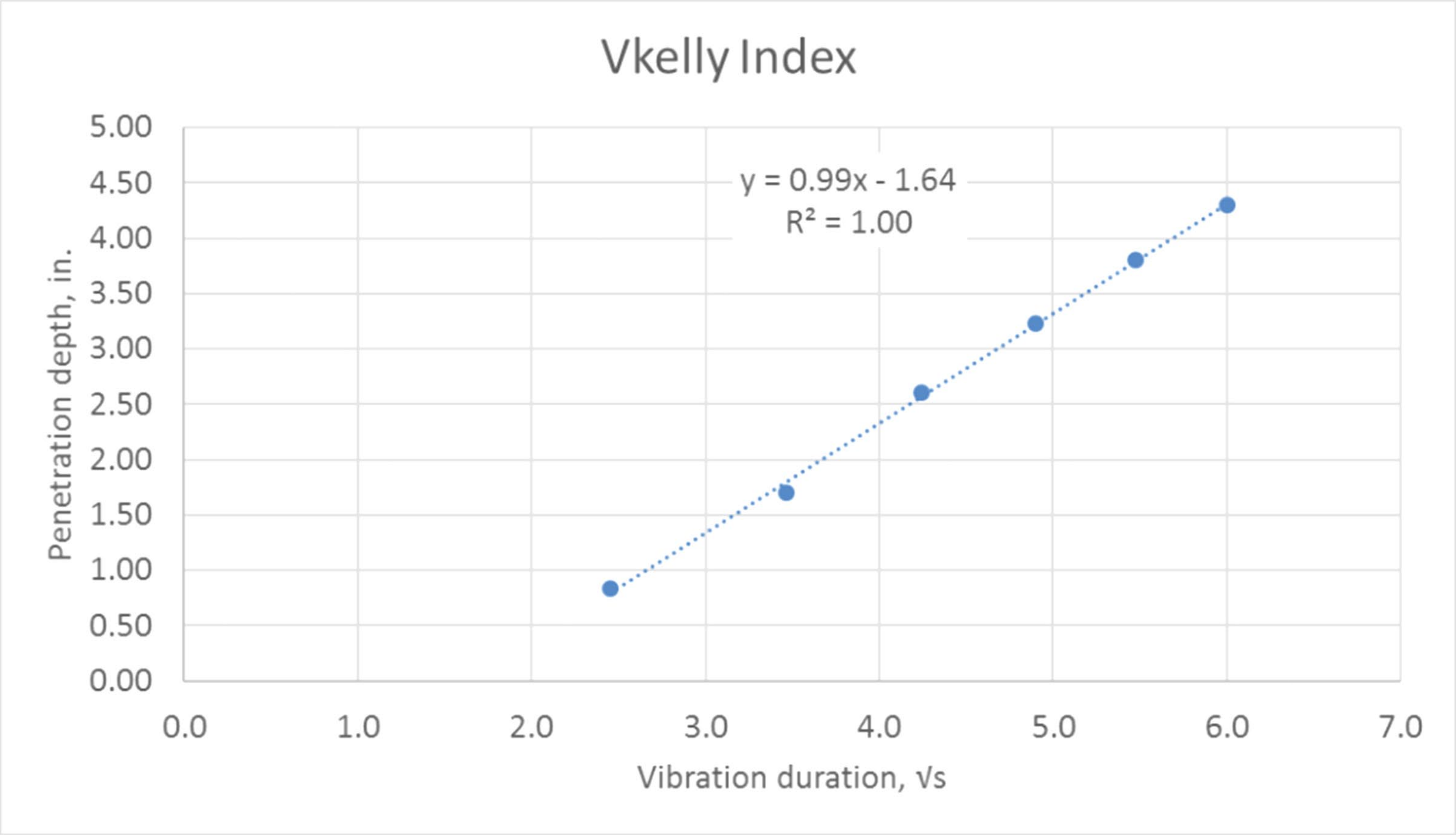


Figure 5- VKelly Index Calculation Plot

What is PEM

- What about the cement content?
- The PEM specification does not address
- No maximum or minimum amounts specified
- Use enough cement to achieve desired performance
- MoDOT has done in-house studies demonstrating less cement can enhance concrete properties

MoDOT Study

- Conducted by Research, Development, and Technology Division
- Report titled, “Laboratory Testing of Bridge Deck Mixes”
- Published in March 2003
- Wanting to reduce bridge deck cracking to increase service life
- Investigating the use of different SCM’s and reducing cement amount
- Maintain comparable slump and air content
- Utilized high quality limestone (control aggregate)

MoDOT Study

- Compressive Strength (AASHTO T 22)

Mix No.	1	2
Cement, lbs./cu. yd.	728	602
Fly Ash, %	----	15
3-day, psi	3690	3410
28-day, psi	5630	5550
56-day, psi	6260	5980
90-day, psi	6540	6530

MoDOT Study

- Permeability (AASHTO T 277)

Mix No.	1	2
Cement, lbs./cu. yd.	728	602
Fly Ash, %	----	15
28-day, coulombs	3458	2855
56-day, coulombs	2547	2172
90-day, coulombs	2387	1747

MoDOT Study

- Dry Shrinkage of Mortar (ASTM C596)

Mix No.	1	2
Cement, lbs./cu. yd.	728	602
Fly Ash, %	----	15
Shrinkage, %	0.087	0.083

MoDOT Study

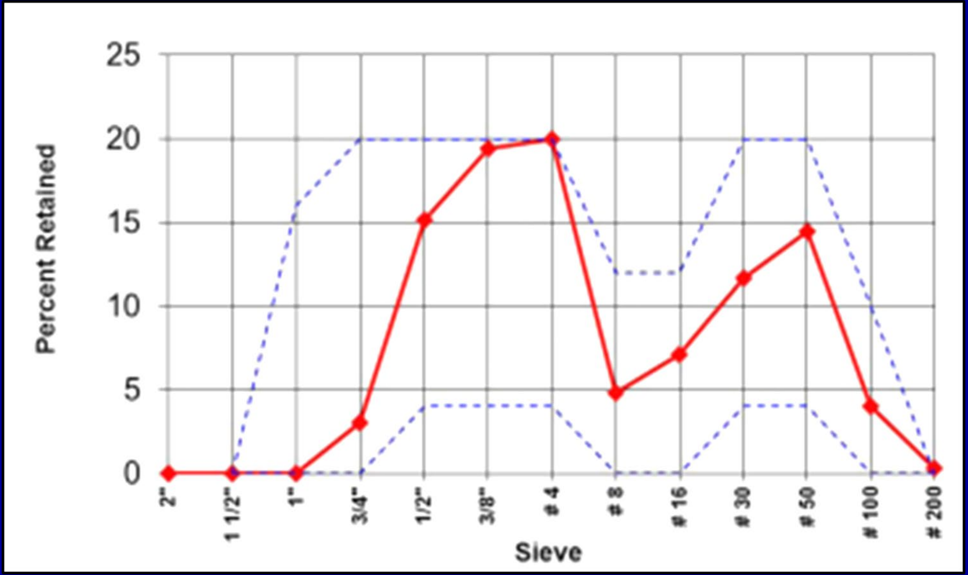
- Salt Scaling Resistance (ASTM C672)

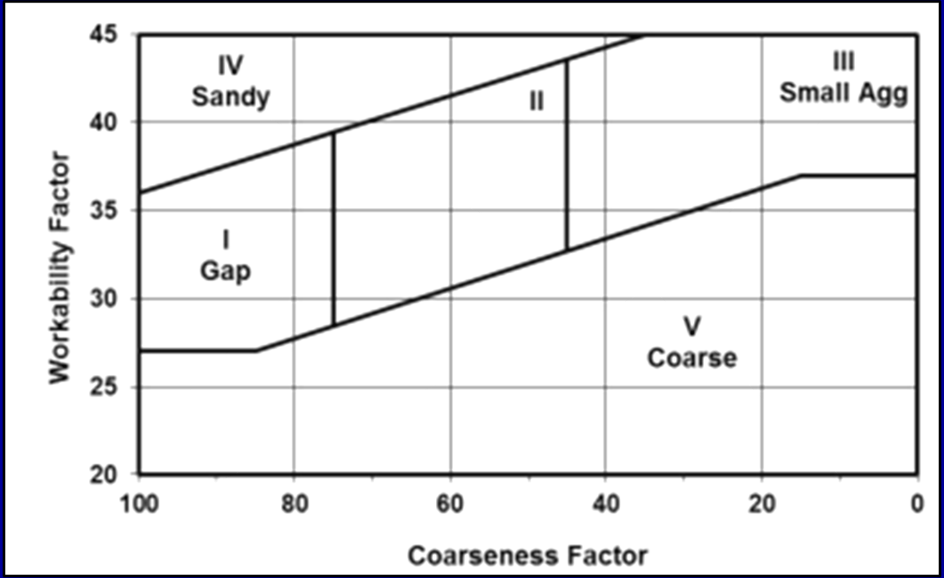
Mix No.	1	2
Cement, lbs./cu. yd.	728	602
Fly Ash, %	----	15
Rating (0 – 5)	1	2

Reducing Cement Content

- Utilize optimized aggregate gradation (i.e., well graded)
- Two design methods available

1) Tarantula Curve
2) Shilstone





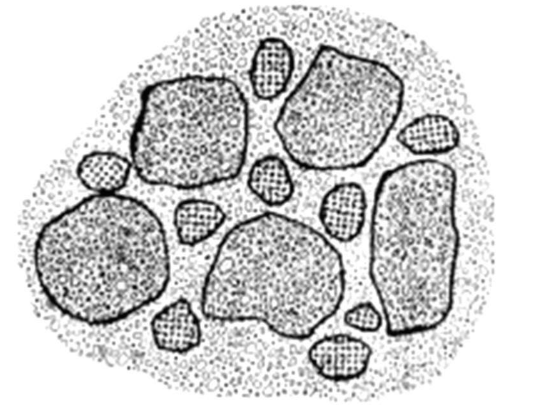


Fig. 1 — Well graded mixture.

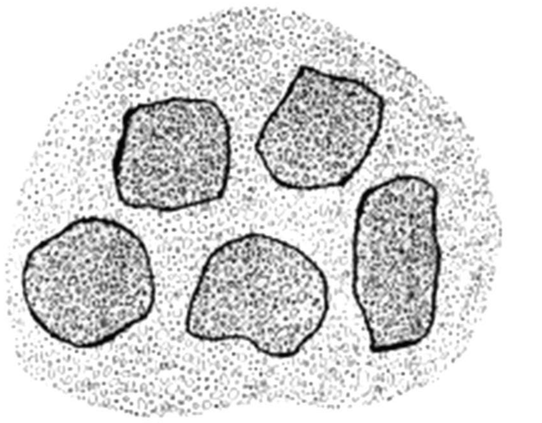


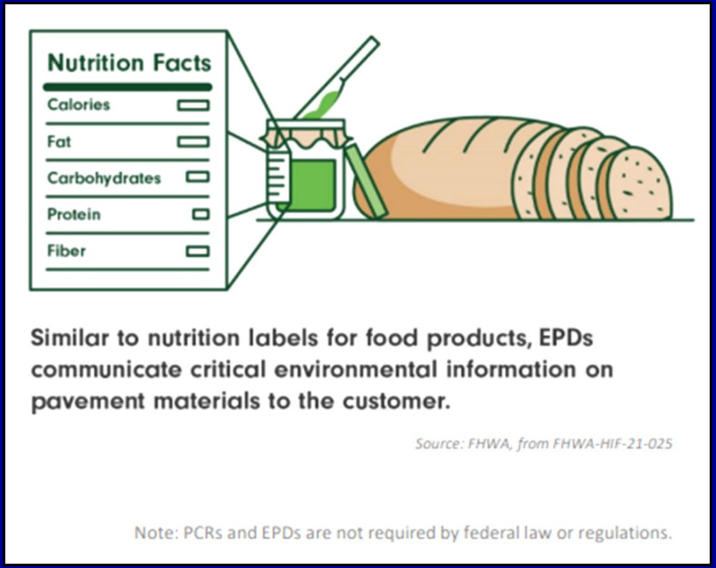
Fig. 2 — Gap graded mixture.

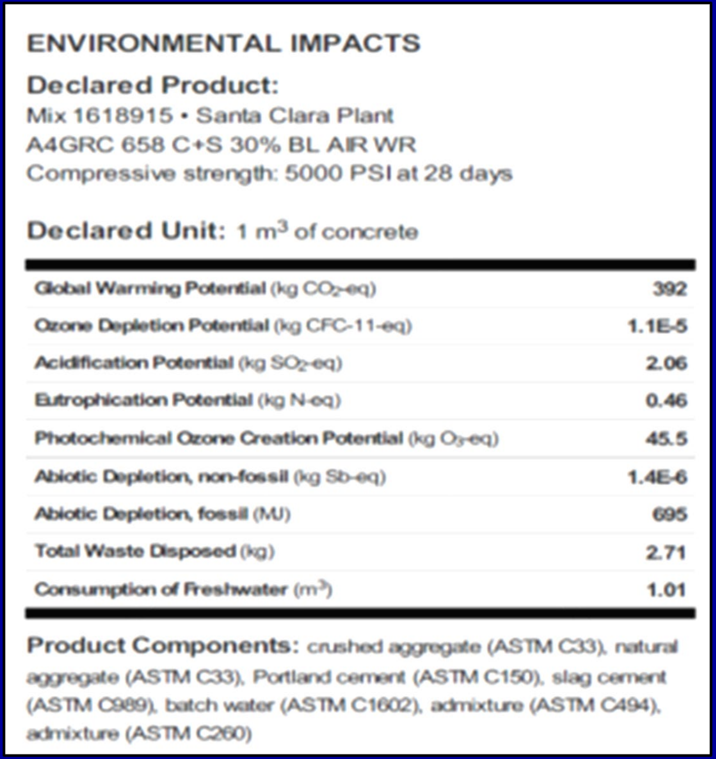
Sustainability

- Involves balancing economic, social, and environmental needs:

Sustainability

- Department of Transportation moving towards the use of Environmental Product Declarations (EPD’s) for procurement purposes
- EPD’s like nutrition labels on food
- How the product impacts the environment
- Big focus on embodied carbon





ENVIRONMENTAL IMPACTS

Declared Product:
Mix 1618915 • Santa Clara Plant
A4GRC 658 C+S 30% BL AIR WR
Compressive strength: 5000 PSI at 28 days

Declared Unit: 1 m^3 of concrete

Global Warming Potential (kg CO_2-eq)	392
Ozone Depletion Potential (kg CFC-11-eq)	1.1E-5
Acidification Potential (kg SO_2-eq)	2.06
Eutrophication Potential (kg N-eq)	0.46
Photochemical Ozone Creation Potential (kg O_3-eq)	45.5
Abiotic Depletion, non-fossil (kg Sb-eq)	1.4E-6
Abiotic Depletion, fossil (MJ)	695
Total Waste Disposed (kg)	2.71
Consumption of Freshwater (m^3)	1.01

Product Components: crushed aggregate (ASTM C33), natural aggregate (ASTM C33), Portland cement (ASTM C150), slag cement (ASTM C989), batch water (ASTM C1602), admixture (ASTM C494), admixture (ASTM C260)

EPD’s Are Just A Fad

- Department of Transportation and FHWA moving in this direction for several years
- Europe already utilizing EPD’s
- Recent events:

“So today, as we work to implement President Biden’s historic Bipartisan Infrastructure Law, which will modernize our infrastructure and create good paying jobs across the nation, the U.S. Department of Transportation will launch a Buy Clean Initiative that will assess and address the embodied **carbon emissions** that come from the **engineering**, **design**, **construction**, **procurement**, **maintenance**, and **disposal** of transportation projects.”

-- USDOT Secretary Pete Buttigieg

https://www.transportation.gov/priorities/climate-and-sustainability/policy-statement-buy-clean-initiative

2021: EO – 14057 § 303 - link

Sec. 303. Buy Clean. The Buy Clean Task Force established pursuant to section 508 of this order shall provide recommendations to the Chair of CEQ and the Director of OMB, through the Administrator of the Office of Federal Procurement Policy, on policies and procedures to expand consideration of embodied emissions and pollutants of construction materials in Federal procurement and federally funded projects, to include:

(a) identifying and prioritizing pollutants and materials, such as concrete and steel, to be covered under a Buy Clean policy, taking into account the availability of relevant data, including from environmental product declarations, and consistency with existing environmental reporting requirements;

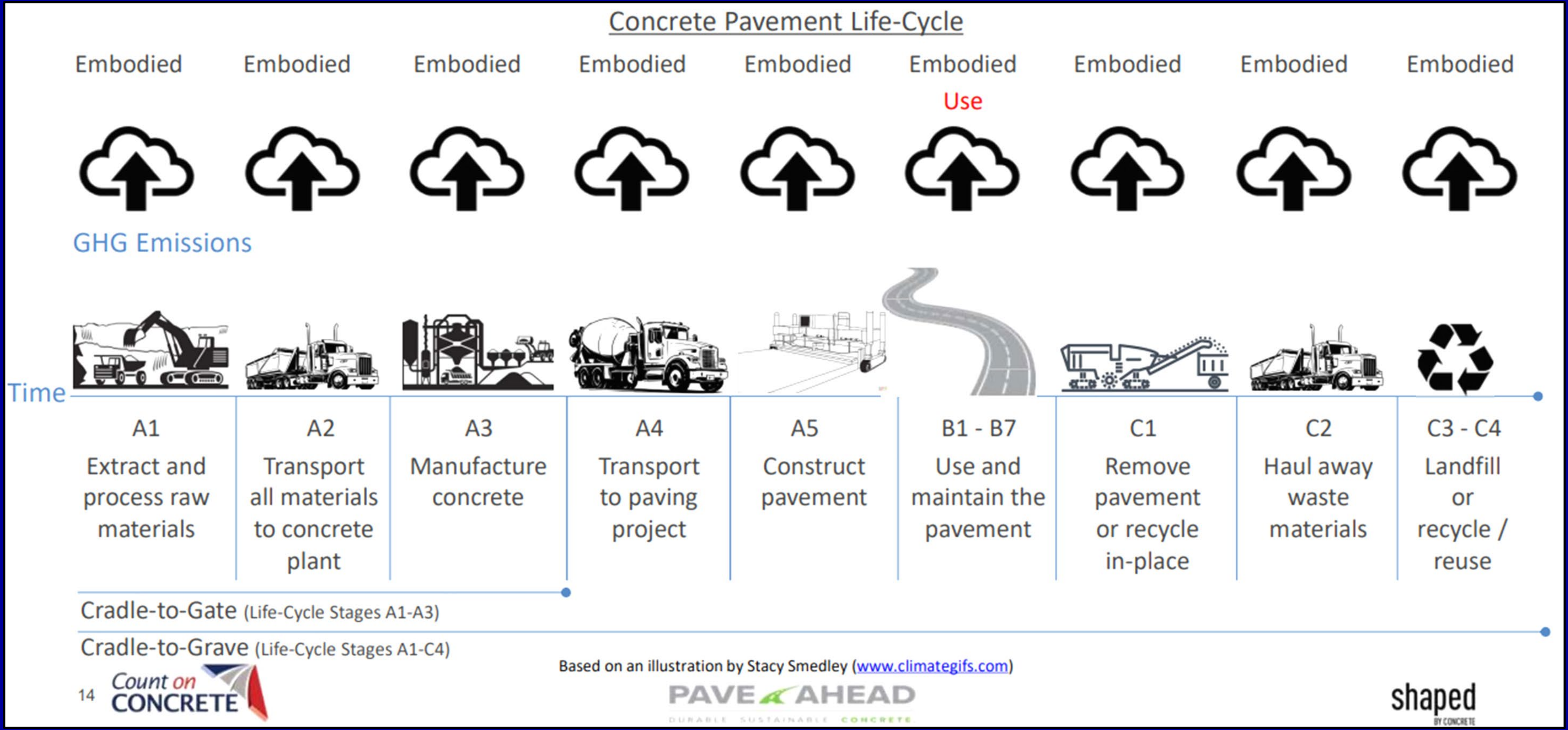
(b) providing recommendations to increase transparency of embodied emissions, including supplier reporting; procedures for auditing environmental product declarations and verifying accuracy of reported emissions data; and recommendations for grants, loans, technical assistance, or alternative mechanisms to support domestic manufacturers in enhancing capabilities to report and reduce embodied emissions in priority materials they produce; and

(c) recommending pilot programs that incentivize Federal procurement of construction materials with lower embodied emissions.

U.S. Department of Transportation
Federal Highway Administration

Developing EPD's

- Procedures developed by ISO
- Cradle to gate at this time



Do not use EPD's to compare asphalt and concrete mixes

Do not use EPD's to compare PCCP mixes to PCCM mixes

Embodied Carbon

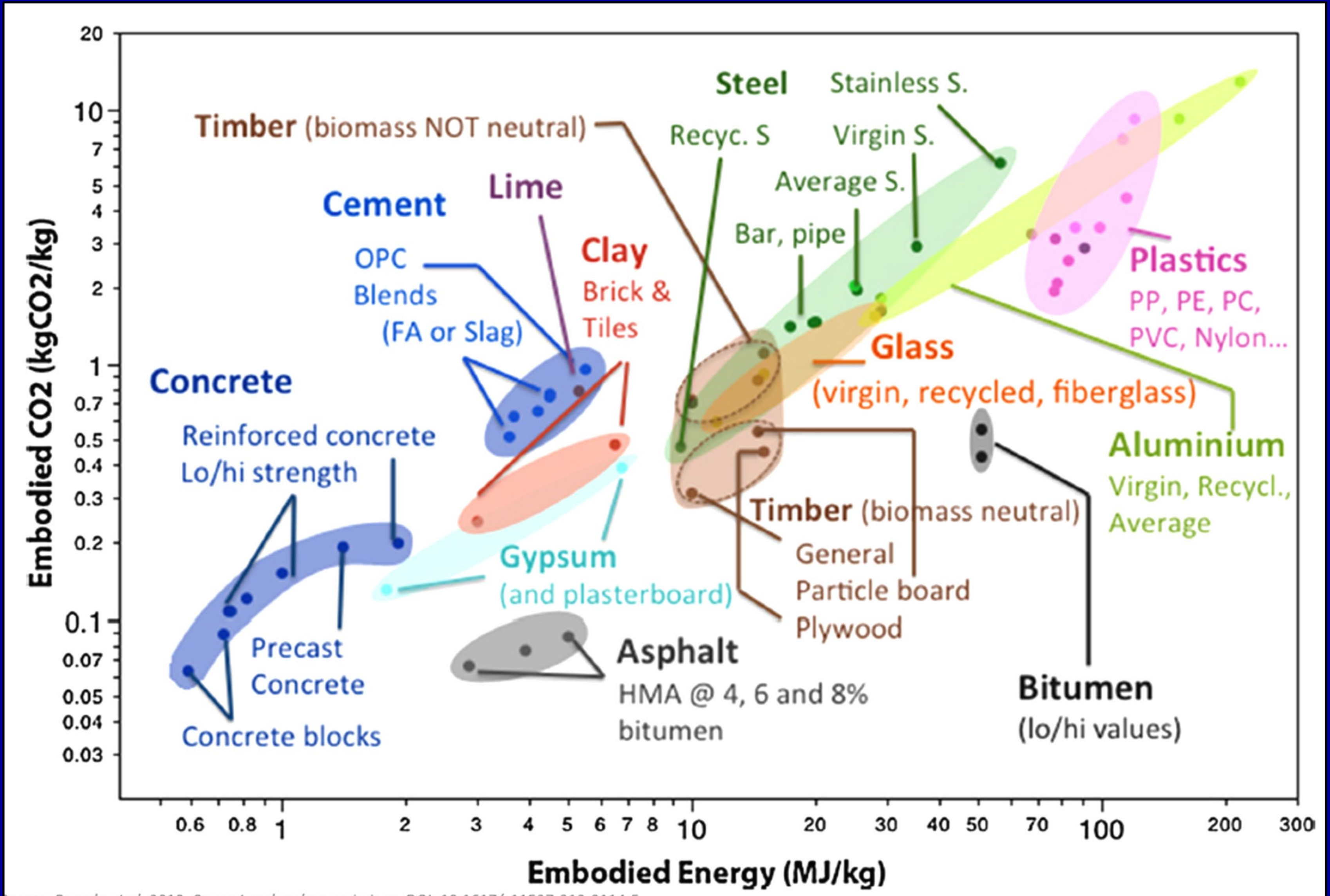
- Why the big focus on the cement industry?
- One ton of cement generates approx. 0.9 tons of CO_2
- Industry contributes about 7% of the CO_2 to the atmosphere
- Important to keep this in perspective:

1) Concrete used to build roads, bridges, and structures
2) Modern society uses concrete to build infrastructure
3) Concrete last longer than other materials (i.e., wood)
4) Concrete is one of the most used building materials in the world

Don’t Build Bridge With Wood Anymore

Embodied Carbon

- Concrete and asphalt mix similar



Source: Barcelo et al. 2019. Cement and carbon emissions. DOI: 10.1617/s11527-013-0114-5

Economics

- Reducing overall cement content and utilizing more aggregate saves money
- Cement cost approximately $150 per ton
- Coarse aggregate cost approximately $25 per ton
- River sand cost approximately $17 per ton
- Concrete quality not negatively impacted
- Require less maintenance to maintain
- Concrete last longer

Summary

- Utilizing Performance Engineered Mixes have several positive benefits:

1) Enhance concrete quality thereby extending service life
2) Reduced cost by optimizing cement content
3) Sustainable by reducing embodied carbon
4) Leads to the use by-products such as fly ash, slag, silica fume

Questions

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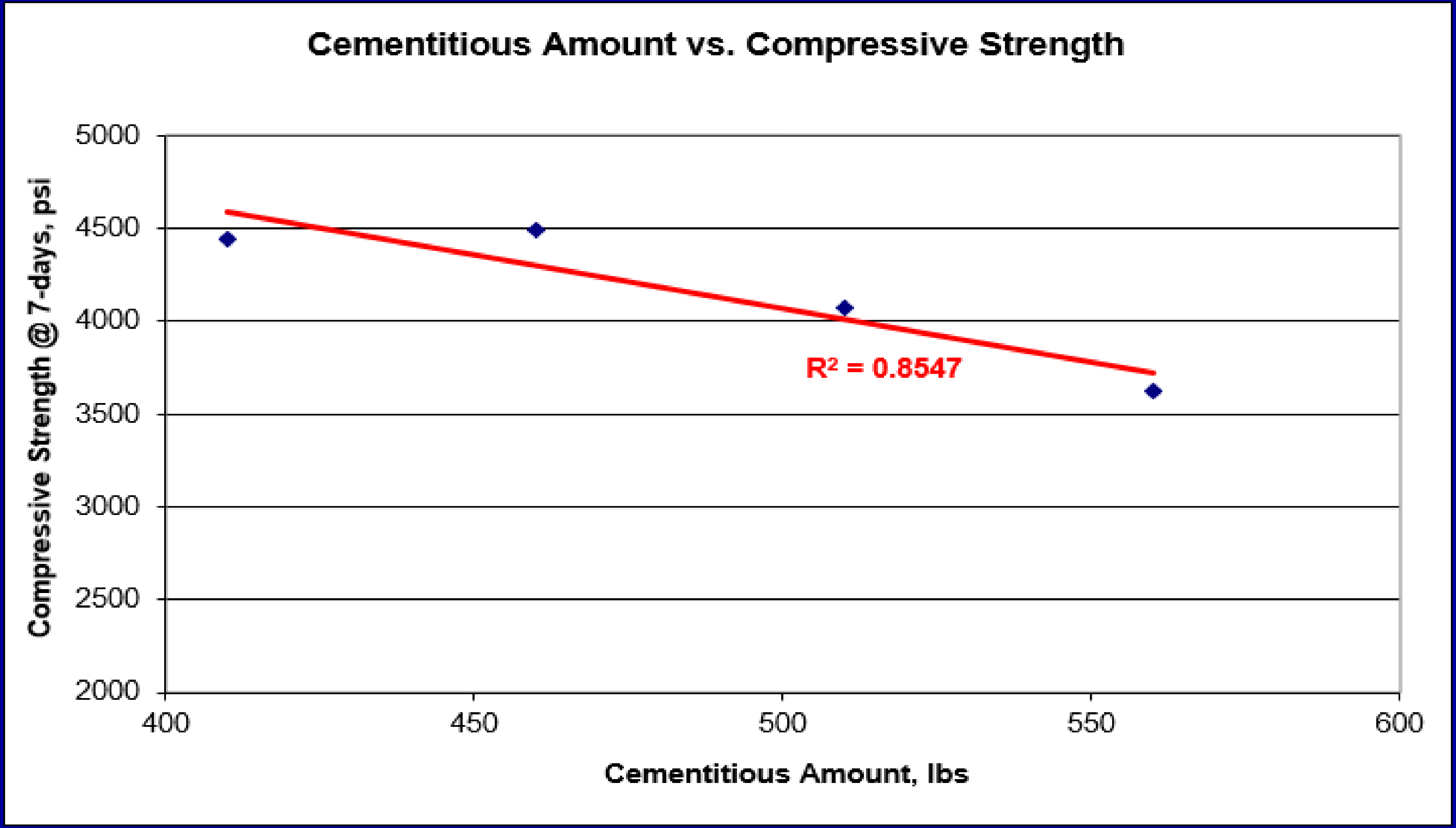
Email: Brett.Trautman@modot.mo.gov

MoDOT Study No. 2

- Conducted by Construction and Materials Division
- Performed in 2008
- Wanting to see how concrete properties would be impacted by reducing the amount of cementitious materials
- As cement amount reduced utilized fly ash, water reducers, and more river sand to maintain workability
- Maintain the same water to cement ratio
- Maintain comparable slump and air content
- Utilized high quality limestone (control aggregate)

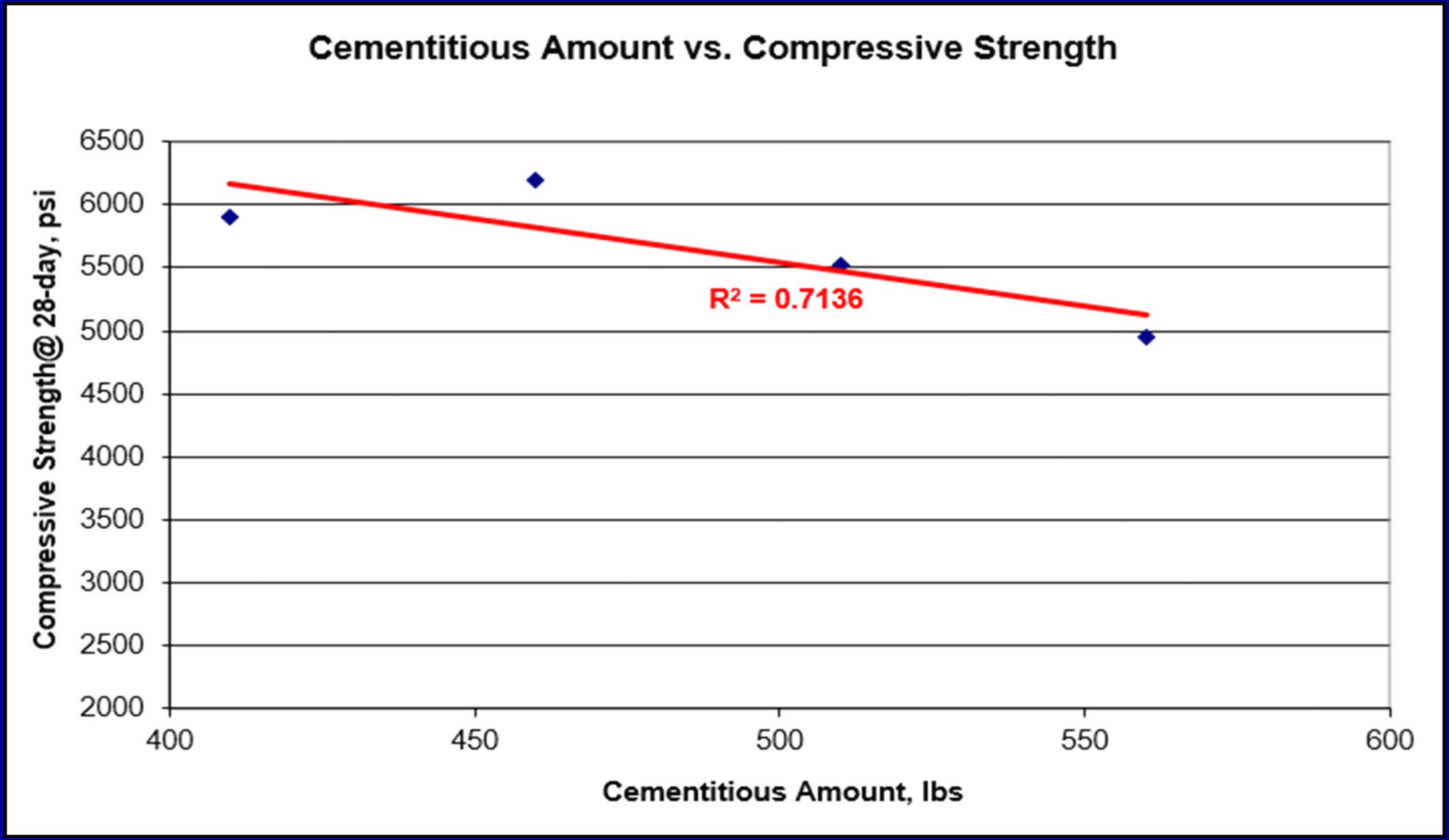
MoDOT Study No. 2

- Compressive Strength @ 7 days



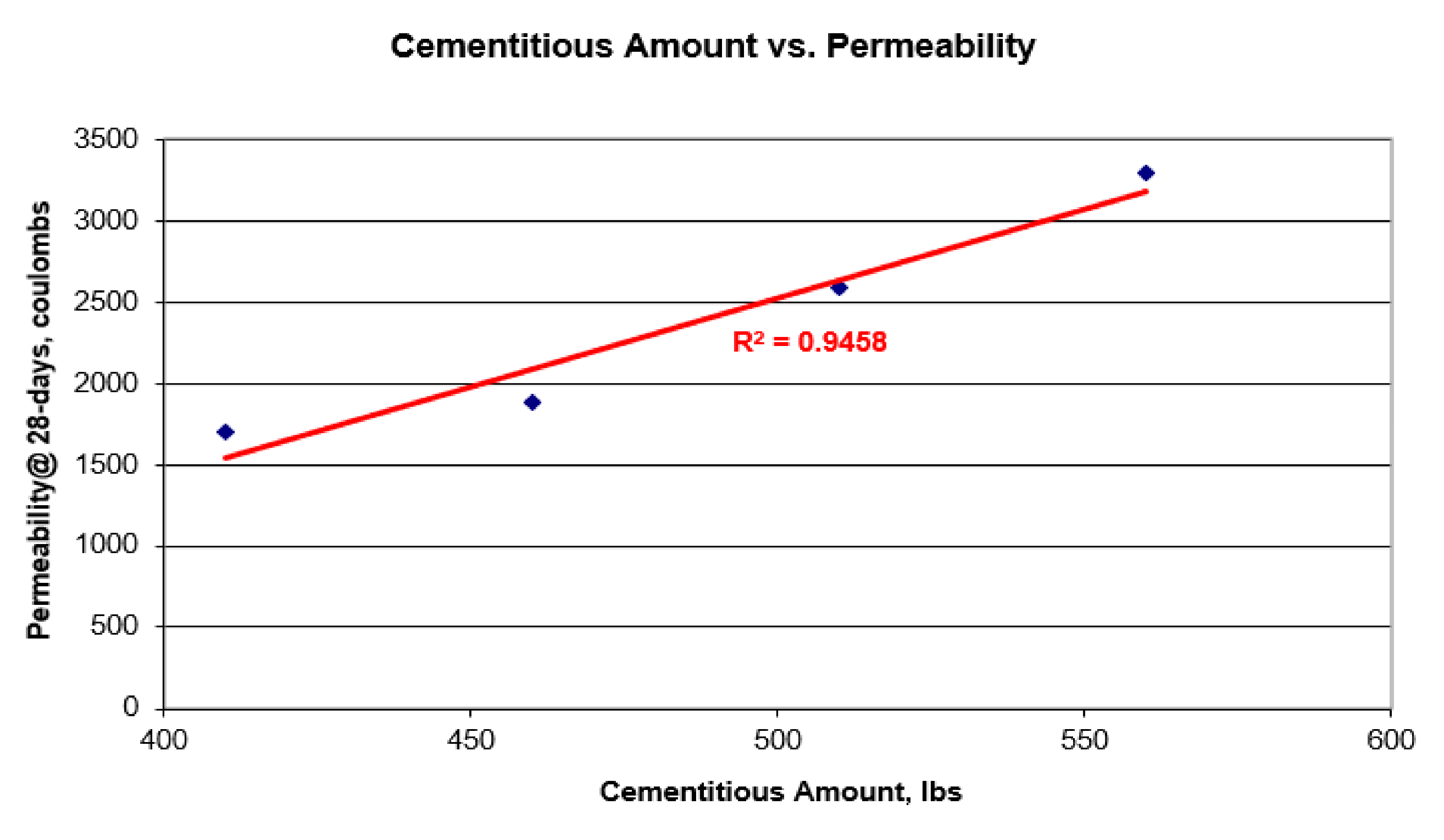
MoDOT Study No. 2

- Compressive Strength @ 28 days



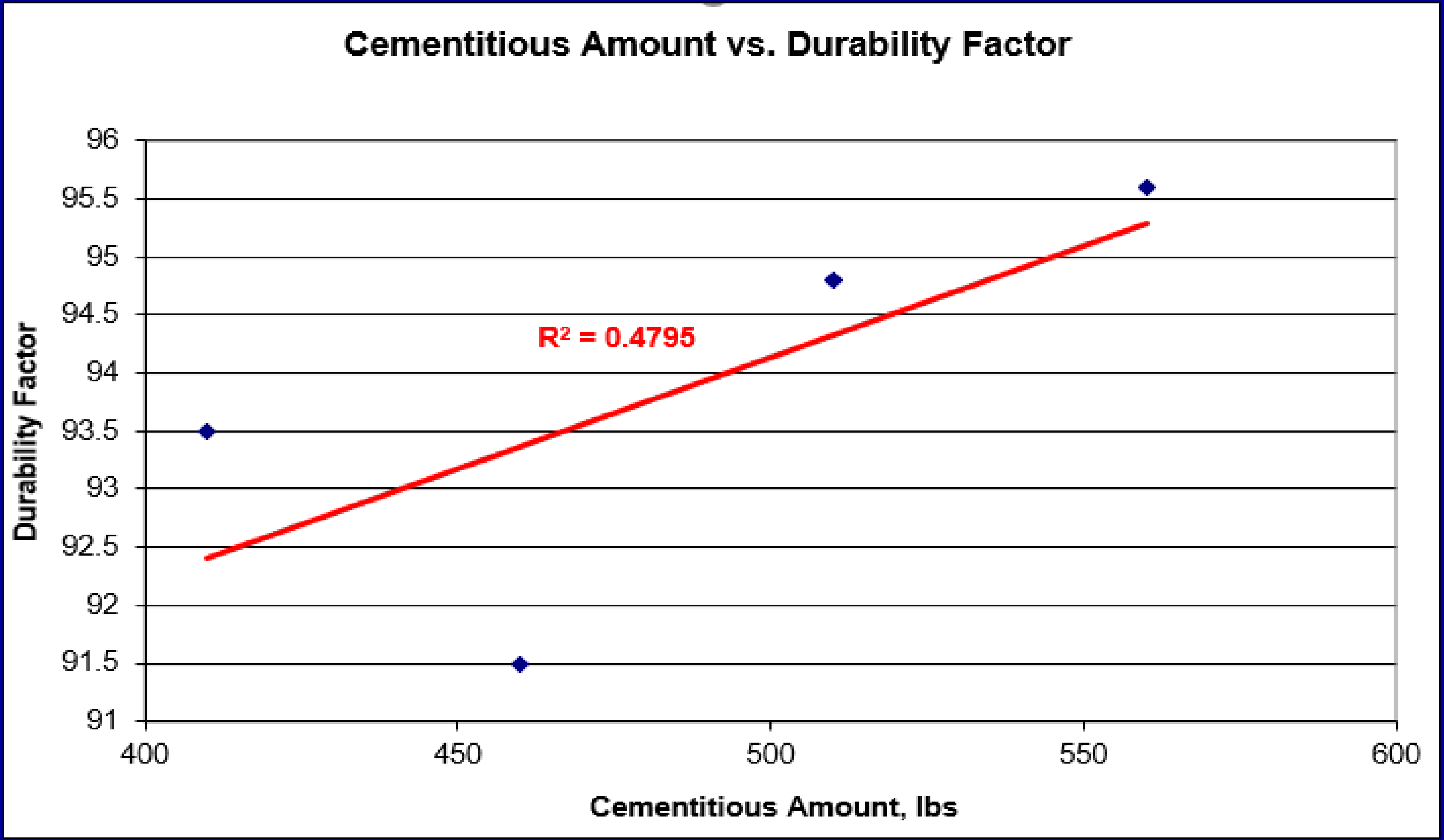
MoDOT Study No. 2

- Permeability @ 28 days



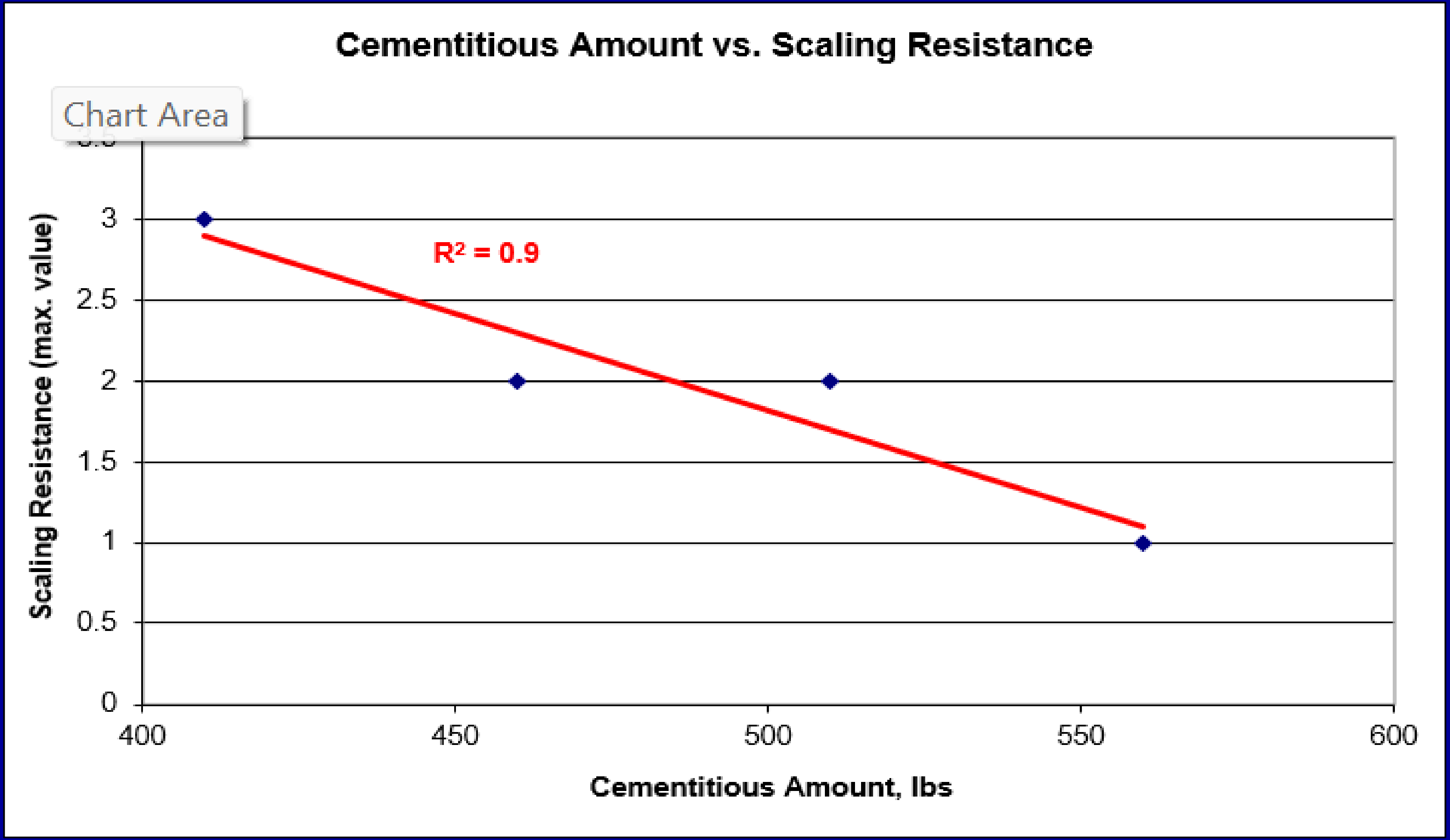
MoDOT Study No. 2

- Freeze/Thaw Durability @ 300 cycles



MoDOT Study No. 2

- Salt Scaling Resistance @ 50 cycles



What is PEM

- Three main areas:

		Workability	Transport	Strength	Cold weather	Shrinkage	Aggregate stability
Aggregate System	Type, gradation	✓✓	-	-	-	-	✓✓
Paste quality	Air, w/cm, SCM type and dose	✓	✓✓	✓✓	✓✓	✓	✓
Paste quantity	Vp/Vv	✓	-	-	-	✓✓	-

Roman Empire