PEM and Reduced Cement Paving Mixes in Iowa

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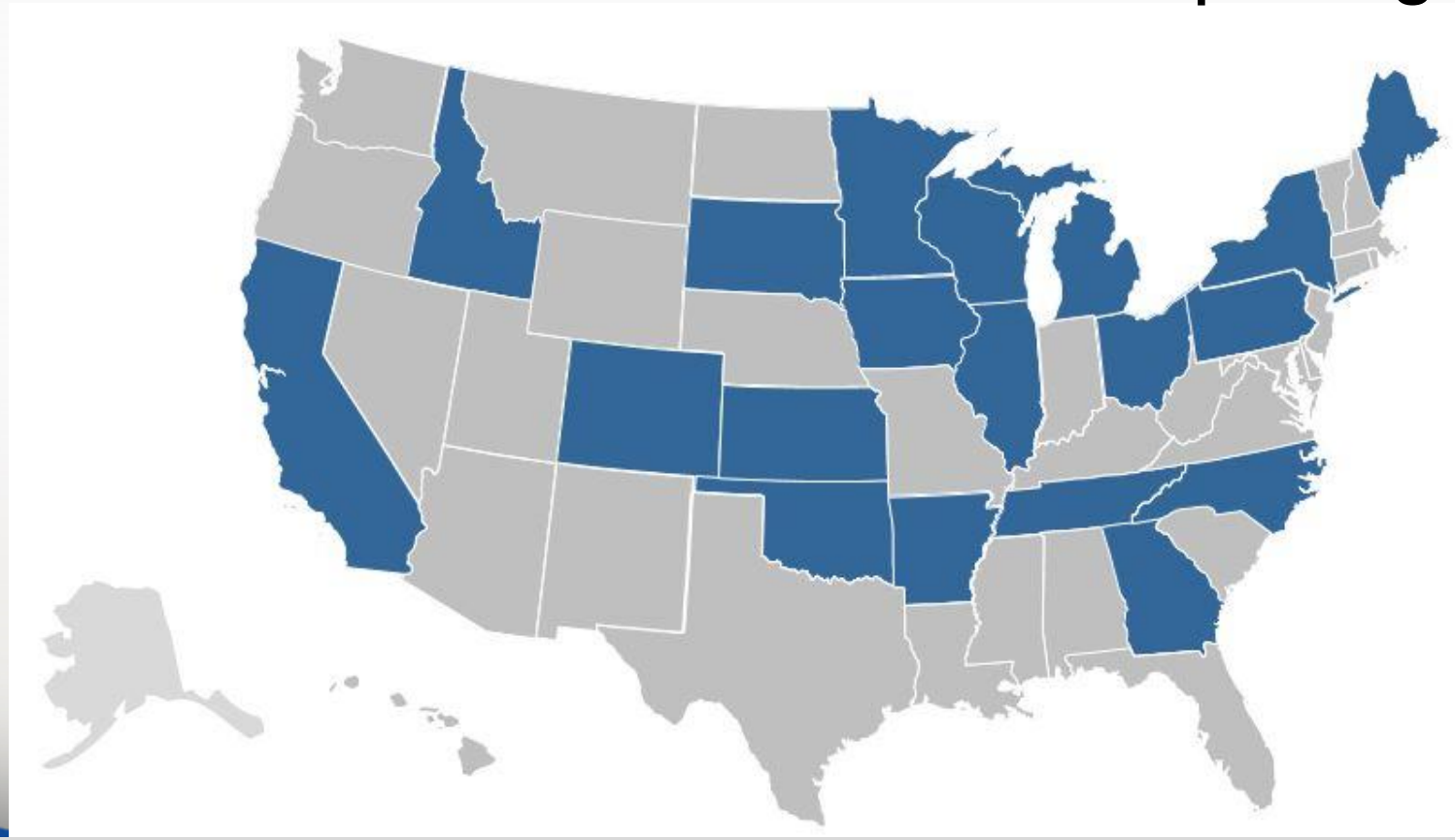
Introduction

- Overview of PEM Program
- Iowa Paving Mixes and PEM Interest
- FHWA Trailer Visit
- PEM Shadow Testing 2019
- I-29 Harrison County Project PEM
- Future Outlook for PEM

Performance Engineered Mixtures

- Pooled fund study led by CP Tech Center uniting FHWA, champion state DOTs, and the concrete paving industry



https://cptechcenter.org/performance-engineered-mixtures-pem/

Performance Engineered Mixtures

- Implementing current best practices and new methods for:
  - Designing and specifying concrete pavement mixtures for maximum long-term durability
  - Measuring and relating early age concrete properties to performance

Performance Engineered Mixtures

- Prepare the mixture for the application
  - Use what you need (and no more) from the materials you have
  - Control cementitious content
- Require the things that matter
  - What do we need to design for to maximize durability in our environment?
  - What tests/measurements do we perform to make sure we meet our goals?

What matters to us?

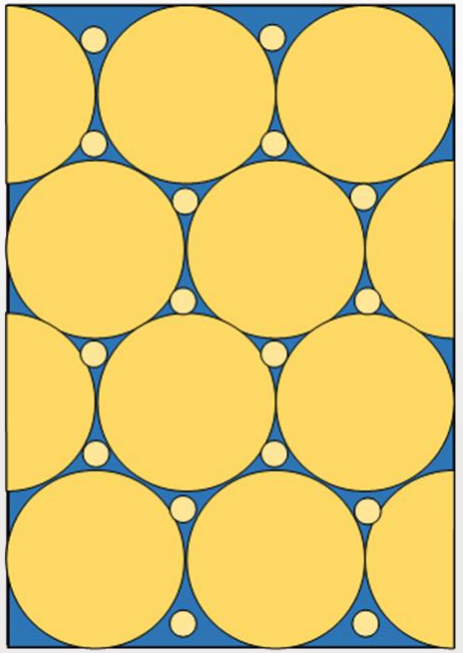
- Cold weather resistance (cold locations)
  - SAM Air Meter, LTDSC- Salt Resistance
- Transport properties/permeability (everywhere)
  - Resistivity/Formation Factor
- Aggregate stability (everywhere)
  - ASR/D-Cracking
- Workability (everywhere)
  - Box Test/V-Kelly
- Strength (everywhere)
  - Flexural or Compressive
- Shrinkage (dry locations)
  - Ring Test

How do we proportion to achieve design goals?

		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	✓	-	-	-	✓✓	-

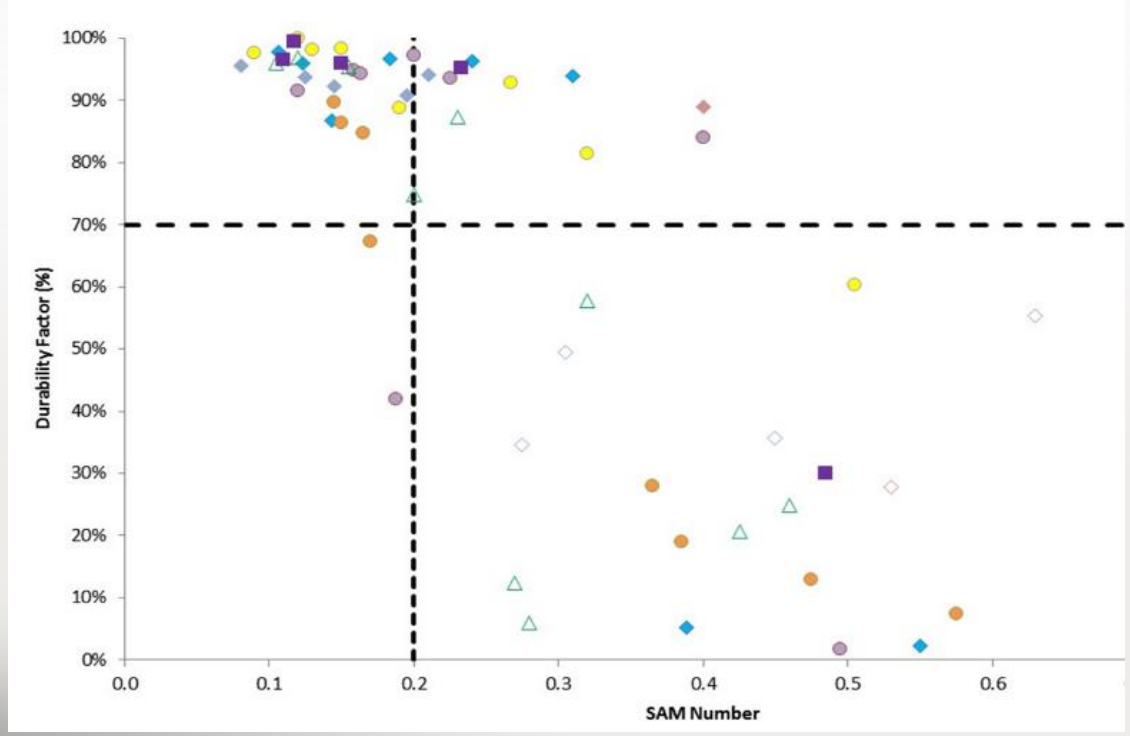
Controlled mixtures

- Control the cementitious content
  - Excess has a:
    - Negative effect on permeability, shrinkage, cost
    - Small negative effect on strength
  - “Optimum” depends on:
    - Aggregate type
    - Gradation
    - Aggregate shape



Super Air Meter (SAM)

- Test at 14.5, 30 & 45 psi
  - Release and repeat
- Air content & SAM number
- SAM number correlates to spacing factor => F/T Test
- Mix Design SAM # <0.20
- Field SAM # <0.30 & Air>6%

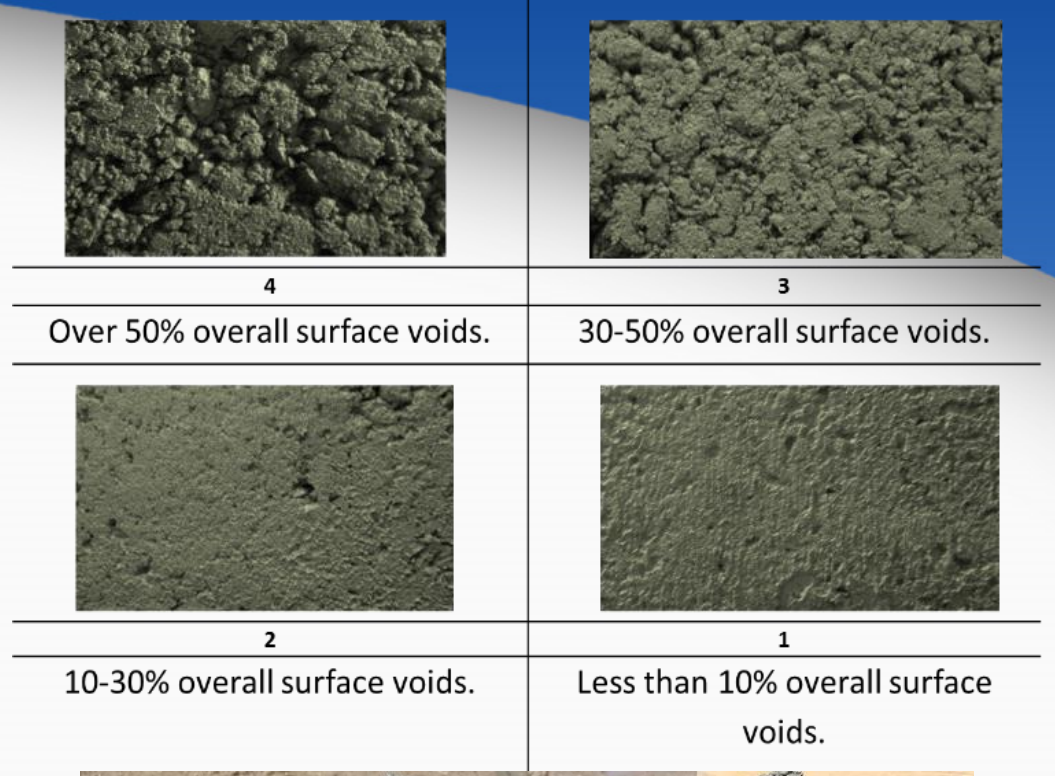


Workability

- Slump Test
  - Uniformity Test tells nothing about response to vibration
- Box Test and V-Kelly
  - Response to Vibration
- Factors in Workability
  - Aggregate Gradation
  - Paste Content
  - Admixtures

Workability - Box Test

- Fill box to 9.5 inches
- Insert vibrator 12,500 vpms
  - 3 seconds to bottom
  - 3 seconds out
- Edges of box are removed and inspected
- PEM Limits <30% Voids or Rating of 2 or less



Transport Properties - Resistivity

- Cast Two Cylinders
- Place in bucket with (Ca, Na, K) hydroxide solution
- Test Resistivity at 3, 7, 28, 56 and 91 days

Calcium Oxychloride Potential

- Salts can cause chemical attack
  - Reaction between $Ca(OH)_2$ & $CaCL_2$ or $MgCl_2$ expands ~30% & forms above 32F
- Low temperature differential scanning calorimetry (LT-DSC)
  - 10 gms hydrated paste ground, mix w 10 mg 20% CaCl2 solution, low temperature cycling
- Limit the CaOXY formation to < 0.15 (g/100g) reduces oxychloride formation
- Potential reduced by use of SCMs

Iowa Paving Specifications

- In many ways, the goals and ideas of the PEM program are familiar to Iowa
- In recent decades, we've seen the introduction of QMC and C-SUD paving mixes

Development of QMC Specification

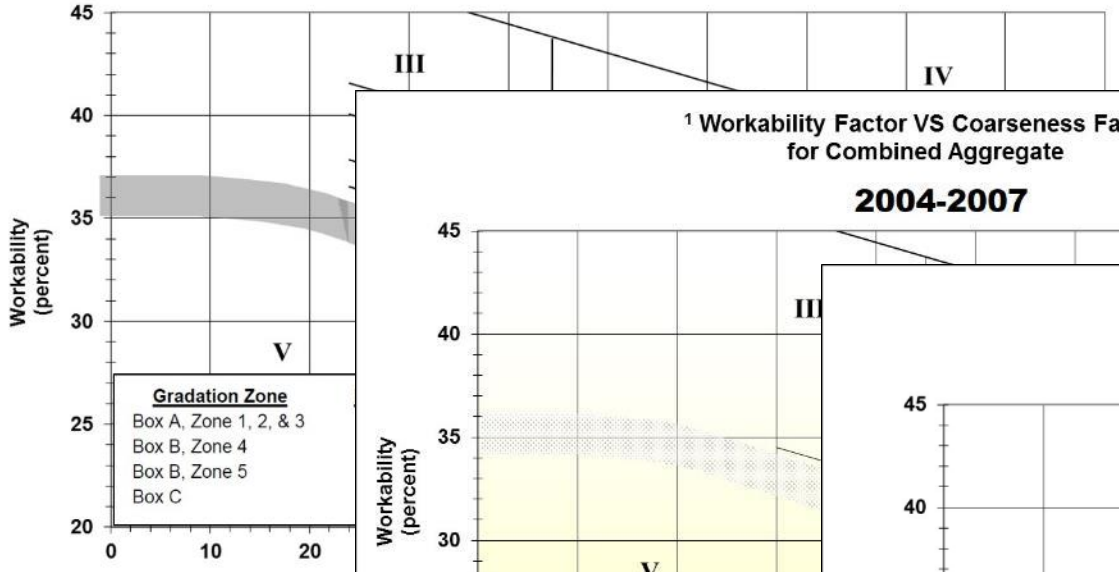
- 1997 First (QMC) project
  - Incentive Compressive Strength
- 1998 -1999 12 projects
  - Incentive Third Point flexural
- No Correlation of Strength to Durability
- Minimal Mix Improvement

Development of QMC Specification

- In 2000, Incentive based on Shilstone Gradation Chart
- Variations of incentive boxes
- 2016 Incentive removed
  - Provide proportions in Zone II
- Minimal workability issues past 20 years
  - Aggregate Shape Effect

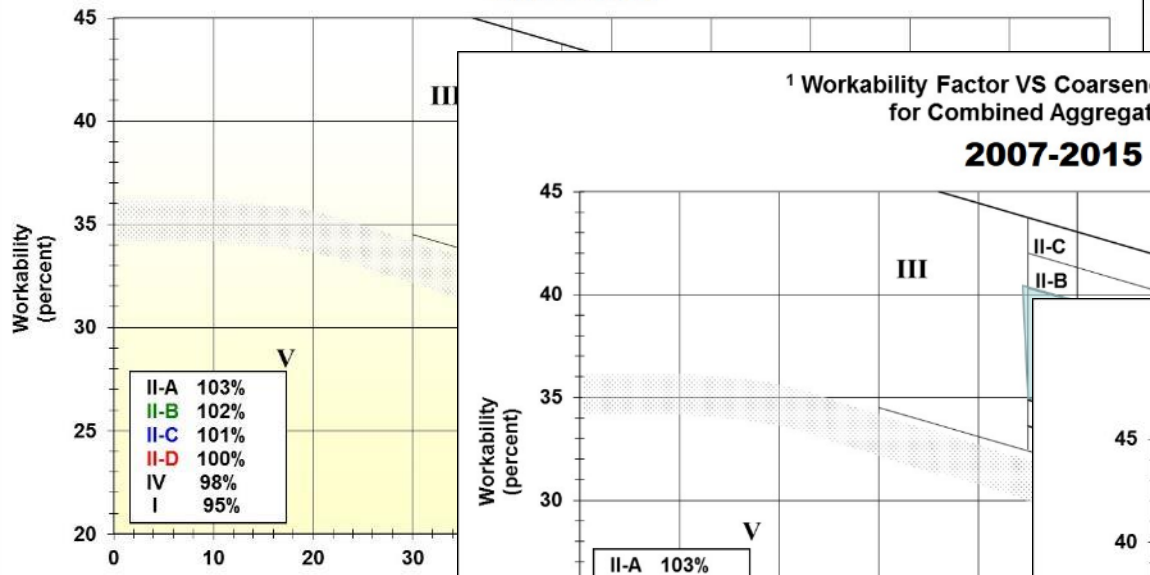
[1] Workability Factor VS Coarseness Factor for Combined Aggregate

2000-2004



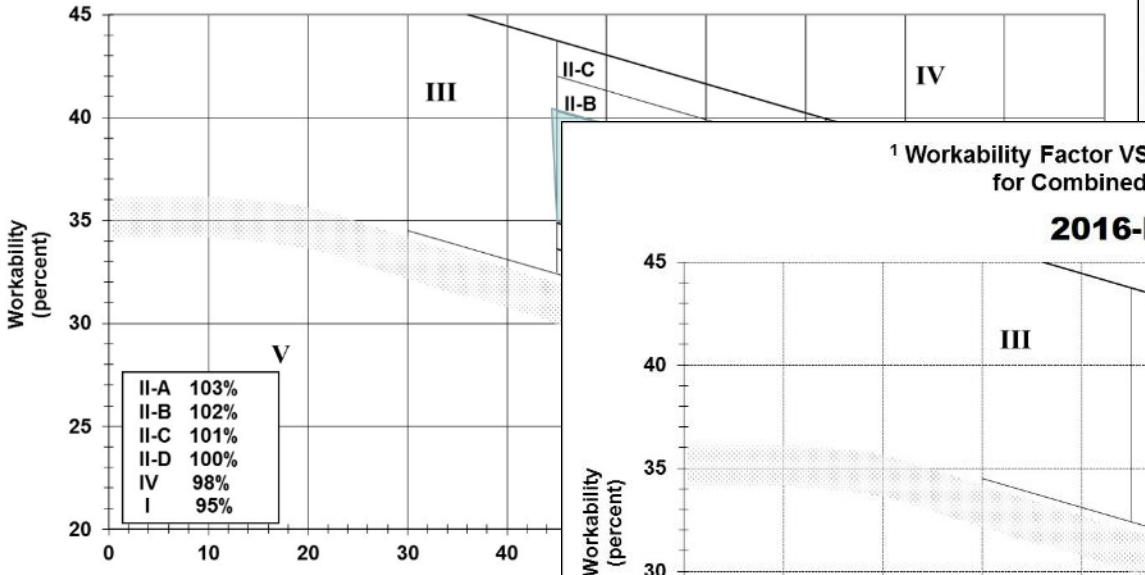
[1] Workability Factor VS Coarseness Factor for Combined Aggregate

2004-2007



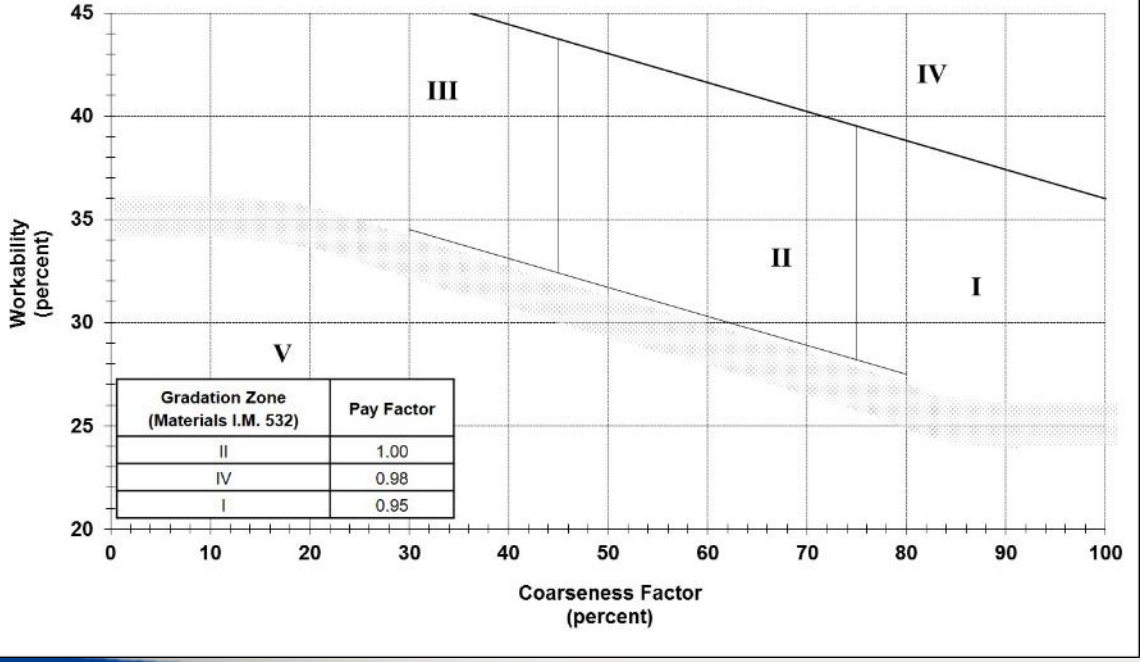
[1] Workability Factor VS Coarseness Factor for Combined Aggregate

2007-2015



[1] Workability Factor VS Coarseness Factor for Combined Aggregate

2016-Present



QMC – Aggregate Shape

- US 75 Woodbury Co. 2000
- Quartzite CA & IA
  - 45.5% CA/ 19.5% IA/ 35% FA
- Very Coarse w Angular Aggregates
  - Finishing difficulties
  - edge tear
  - slow production rates

QMC 20 Years Lessons Learned

- Partnership with contractors expedited changes
- Placement impacts durability
- Excessive handling with soft aggregates affect strength
- Well graded aggregates improve placement
- Aggregate shape and texture affect placement
- Slag and fly ash reduce permeability
- Optimized gradation allows for reduction in cementitious content and w/cm

C-SUD Paving Mixes

- While QMC was implemented by the DOT, local agencies in Iowa also needed to adapt their mixes to new trends
  - Greater de-icing demands, impacting long-term durability

C-SUD Paving Mixes

- The C-SUD specification allows local agencies to optimize the gradation according to the QMC specification
- Plus additional options:
  - Greater allowable fly ash & SCM substitution rates (35-40%)
    - Additional protection against CaOXY formation from de-icing salts
  - Further lowering of maximum w/cm (0.42)
    - This lower w/cm was adopted for QMC a few years ago, too

How does QMC mix compare with PEM?

DS-15038
(Replace DS-15031)

IOWADOT

DEVELOPMENTAL SPECIFICATIONS
FOR
QUALITY MANAGEMENT CONCRETE (QM-C)

Effective Date
April 19, 2016

THE STANDARD SPECIFICATIONS, SERIES 2015, ARE AMENDED BY THE FOLLOWING MODIFICATIONS AND ADDITIONS. THESE ARE DEVELOPMENTAL SPECIFICATIONS AND THEY PREVAIL OVER THOSE PUBLISHED IN THE STANDARD SPECIFICATIONS.

15038.01 DESCRIPTION.

A. This specification identifies a concrete mixture design with an optimum combined aggregate gradation, and the Contractor's testing and quality control responsibilities. Optimization of the aggregates should produce concrete with low water requirement as well as improved workability and finishing characteristics. While concrete strength is important and is measured, it is not the basis for optimization of the concrete mixture design.

B. Testing and quality control apply to all Contractor produced concrete using the Concrete Design Mixture (CDM). The CDM applies to mainline slip form pavement. At the Contractor's option, the CDM may apply to any other slip form paving.

15038.02 MATERIALS.

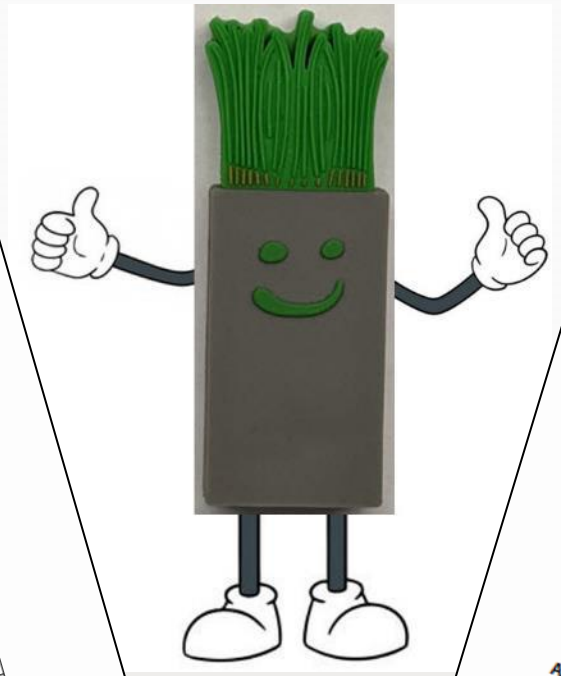
For all materials, meet the quality requirements for the respective items in Division 41 of the Standard Specifications. Compatibility of all material combinations is the Contractor's responsibility based on acquired field experience with proposed materials.

15038.03 ~~LABORATORY~~ CONCRETE DESIGN MIXTURE.

A. An Iowa DOT PCC Level III Certified Technician is responsible for the development of the CDM. Develop a CDM based on a unit volume of 1.000 according to industry standard practice, and containing proportions of materials, including admixtures. Base the proportions upon saturated surface dry aggregates to produce a workable concrete mixture meeting the constraints of Table DS-15038.03-1:

Table DS-15038.03-1: Concrete Mixture Constraints

Nominal Maximum Coarse Aggregate Size	Greater than or equal to 1 inch
Gradation	Materials I.M. 532
Cementitious Content	Minimum, 560 pounds per cubic yard*
Fly Ash Substitution Rate	See Article 2301.02, B, 6
Water/Cementitious Ratio	Maximum, ~~0.45~~ 0.42
Air Content	6% ± 1%, Design Absolute Volume = 0.060
28 Day Flexural Strength, Third Point	Minimum, 640 pounds per square inch



Standard Practice for

Developing Performance Engineered Concrete Pavement Mixtures

AASHTO Designation: PP 84-19[1]
Tech Subcommittee: 3c, Hardened Concrete
Release: Group 1 (April)

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

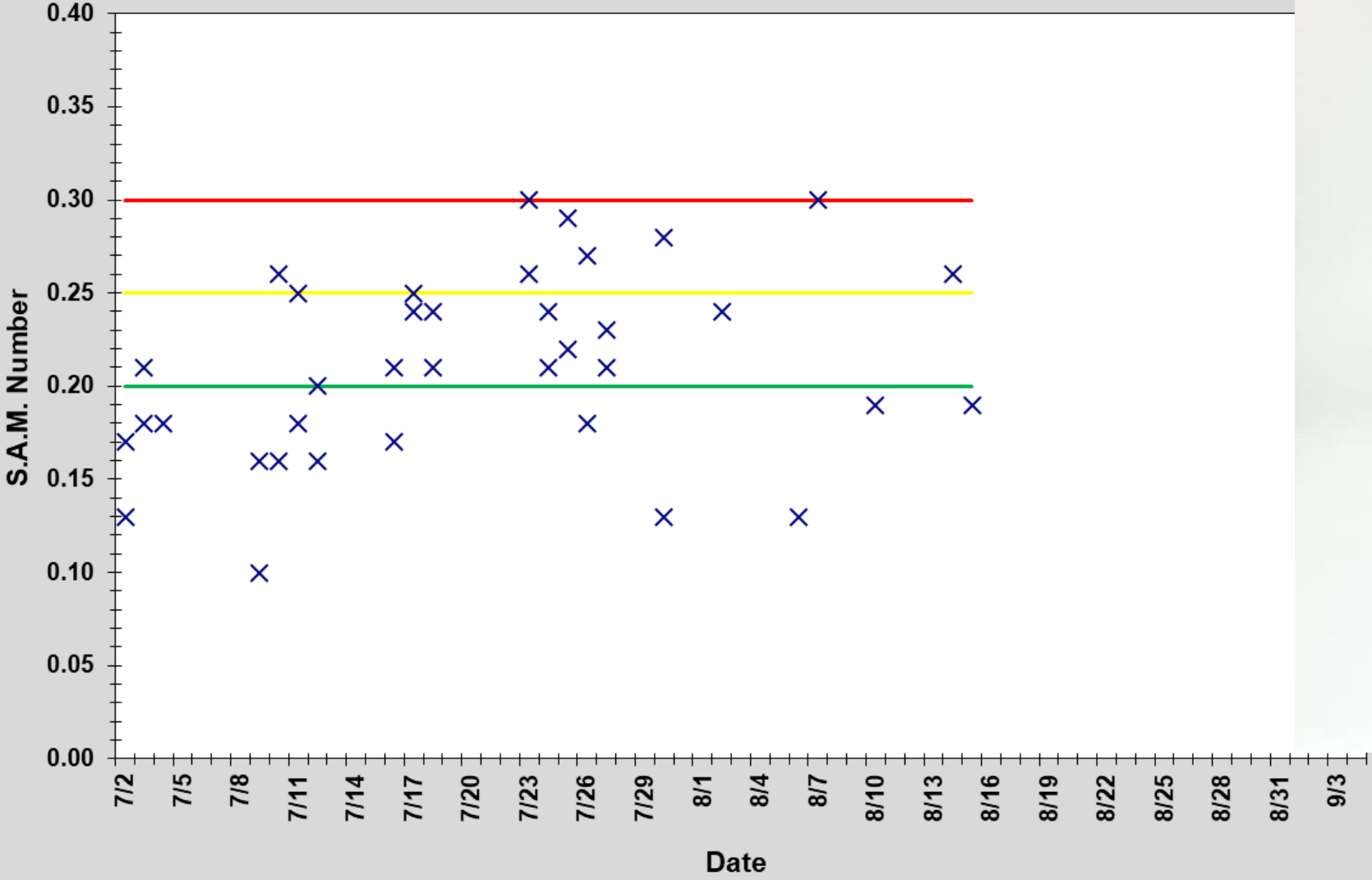
2018 PEM Pooled Fund Research Project

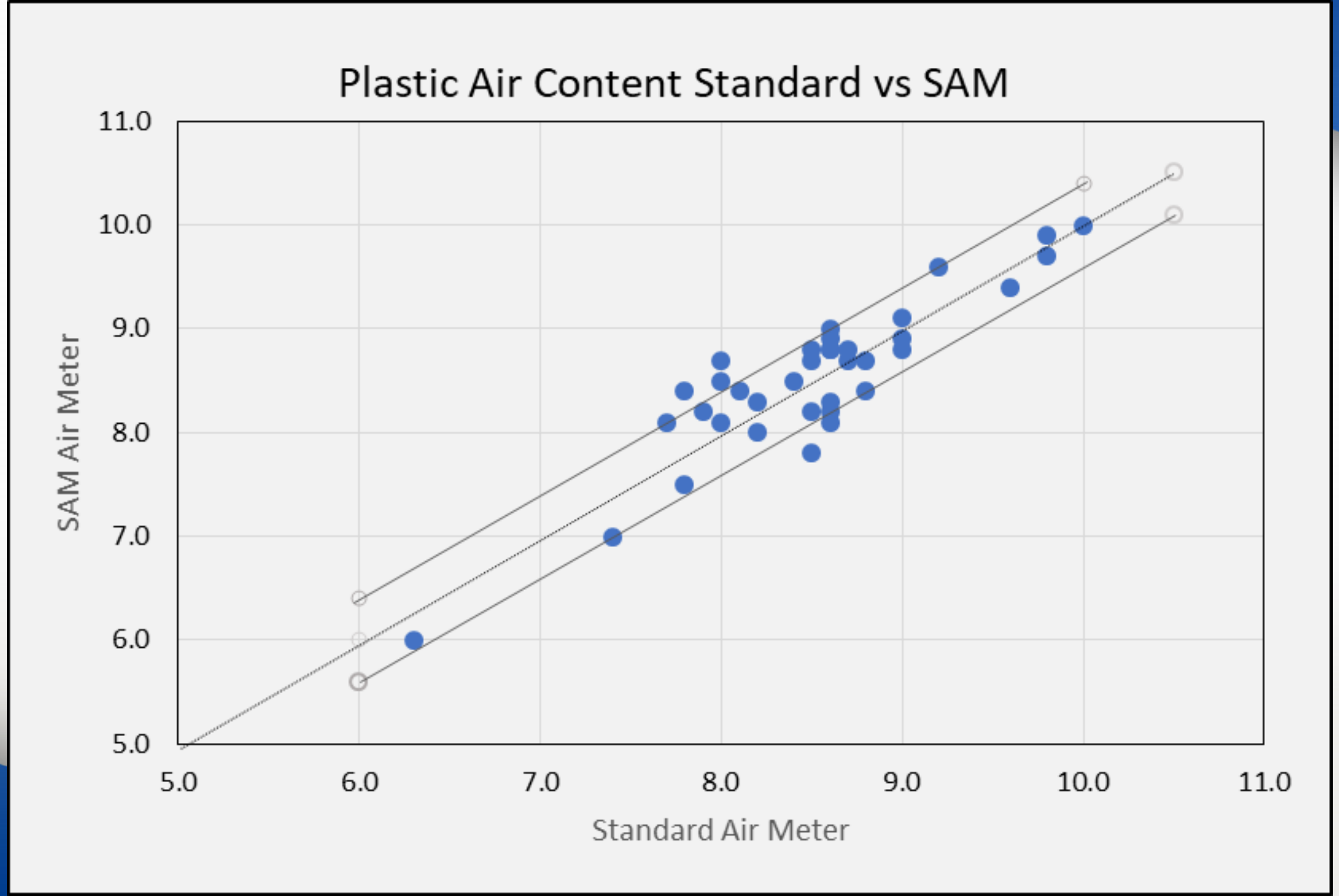
- Shadow projects
- Investigate ruggedness of test methods
- Develop specification limits
- Collect data for modelling
- Contractor QC Testing
- FHWA Mobile Concrete Trailer

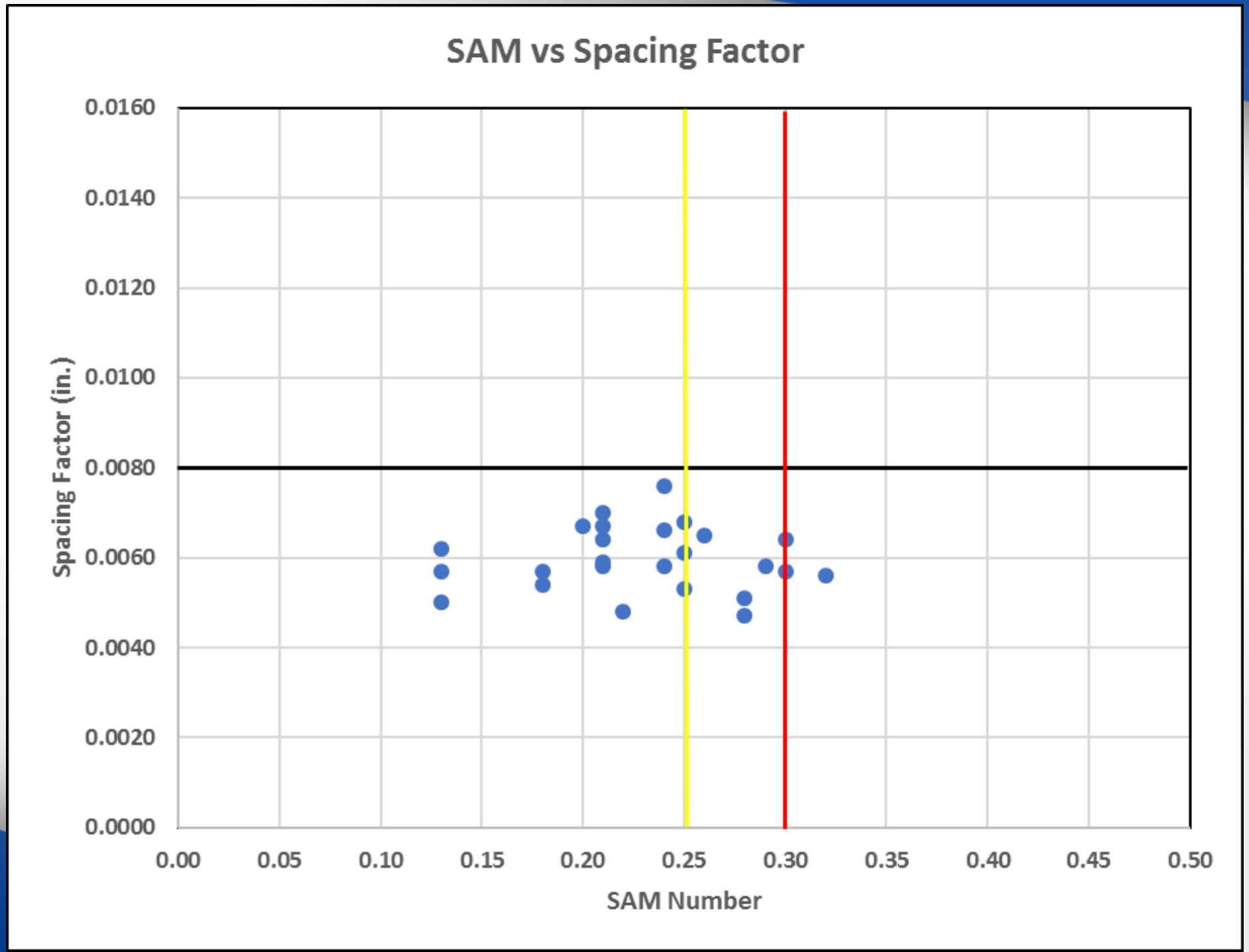
Iowa PEM Shadow Project

- Cedar Valley Corp volunteered
- US 20 Woodbury Co. 2018
- Comprehensive QC Plan
  - Control Charts
  - Air PWL
  - SAM Test
  - Box Test
  - Resistivity/Formation Factor
  - Calcium Oxychloride Potential
  - Trial batch mix design reduced cement

S.A.M. Number
Before Paver

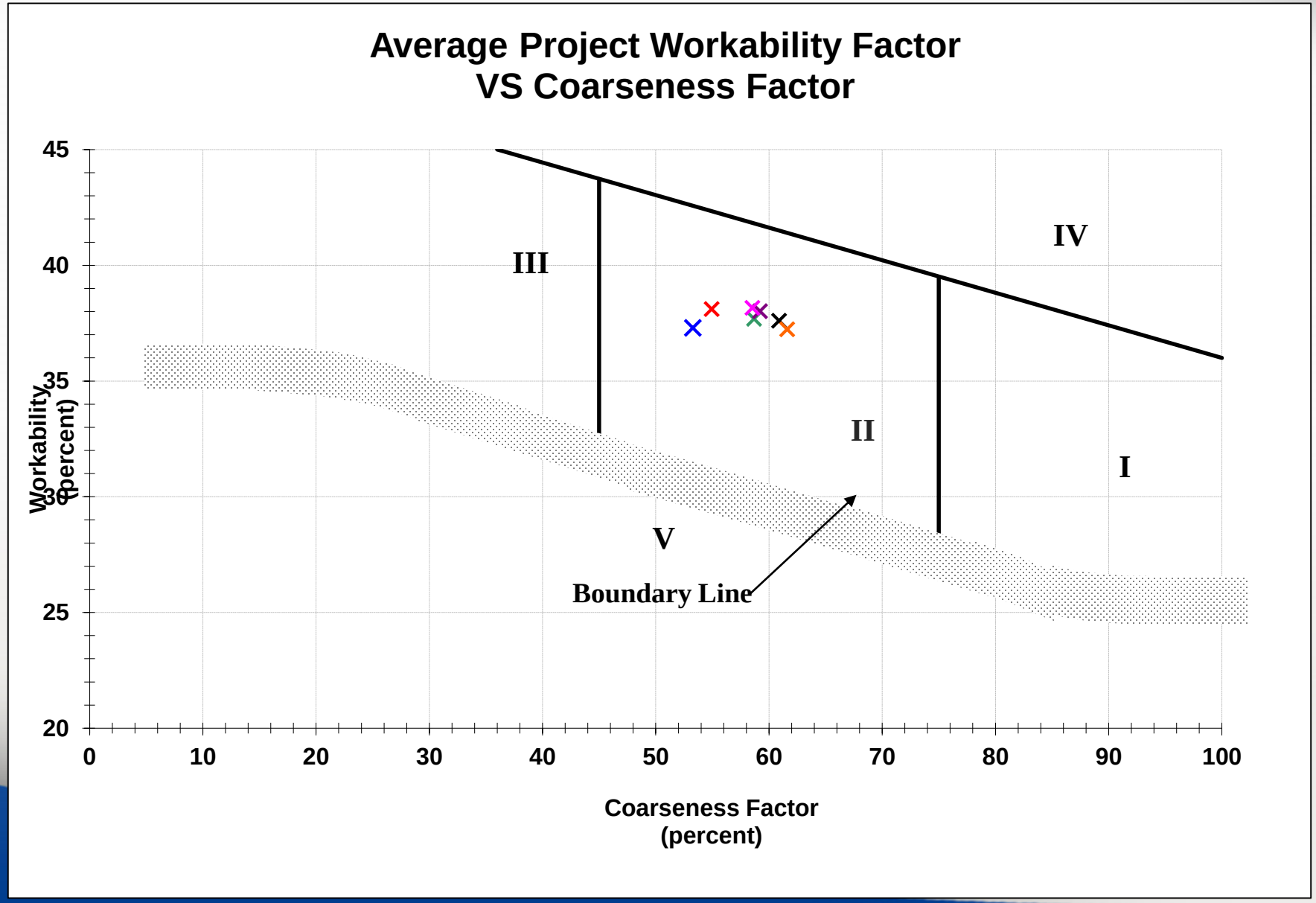



Plastic Air Content Standard vs SAM
SAM Air Meter
Standard Air Meter
11.0
10.0
9.0
8.0
7.0
6.0
5.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0

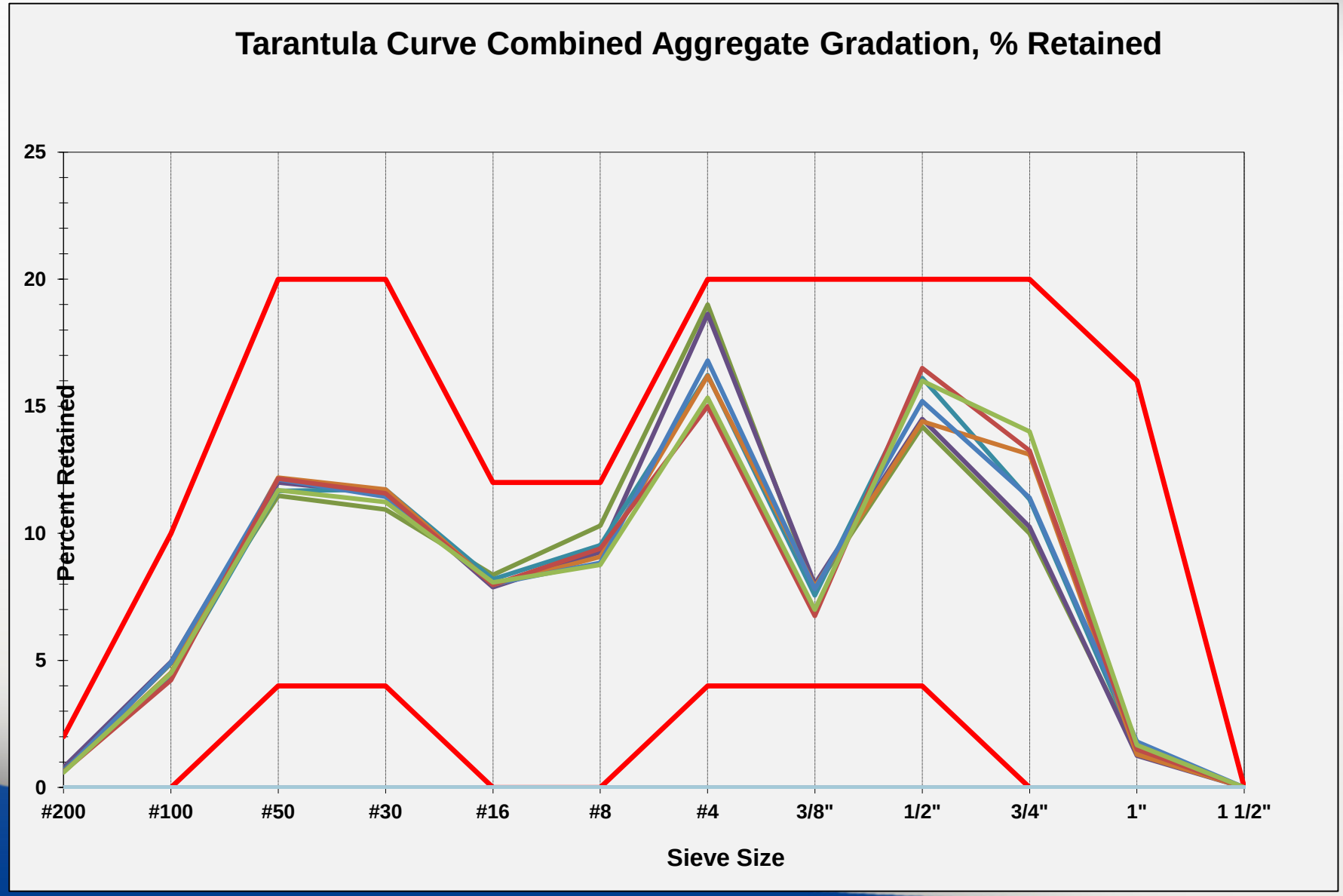

SAM vs Spacing Factor
Spacing Factor (in.)
0.0160
0.0140
0.0120
0.0100
0.0080
0.0060
0.0040
0.0020
0.0000
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
SAM Number

Box Test Ranking

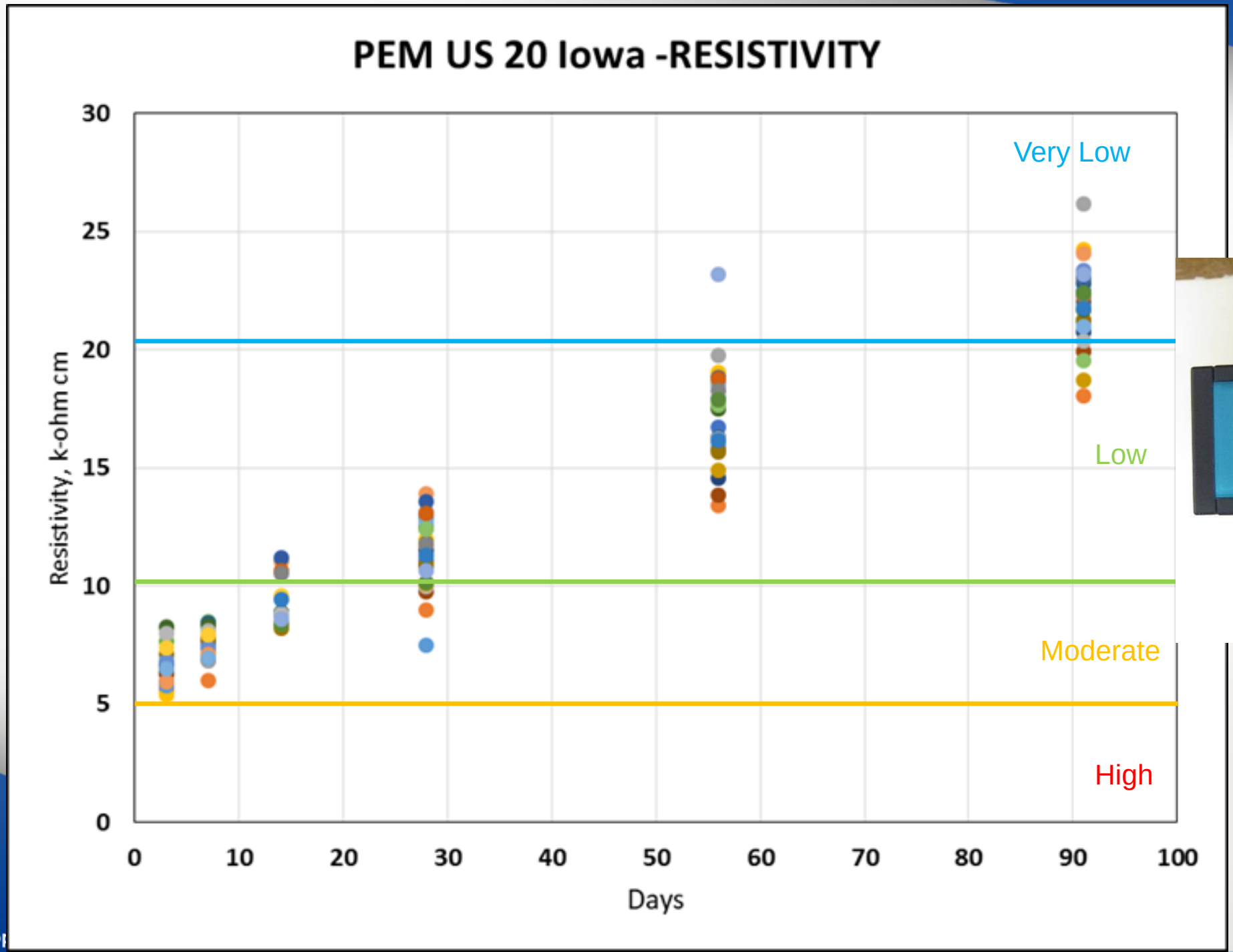
Combined Aggregate Gradation



Combined Aggregate Gradation

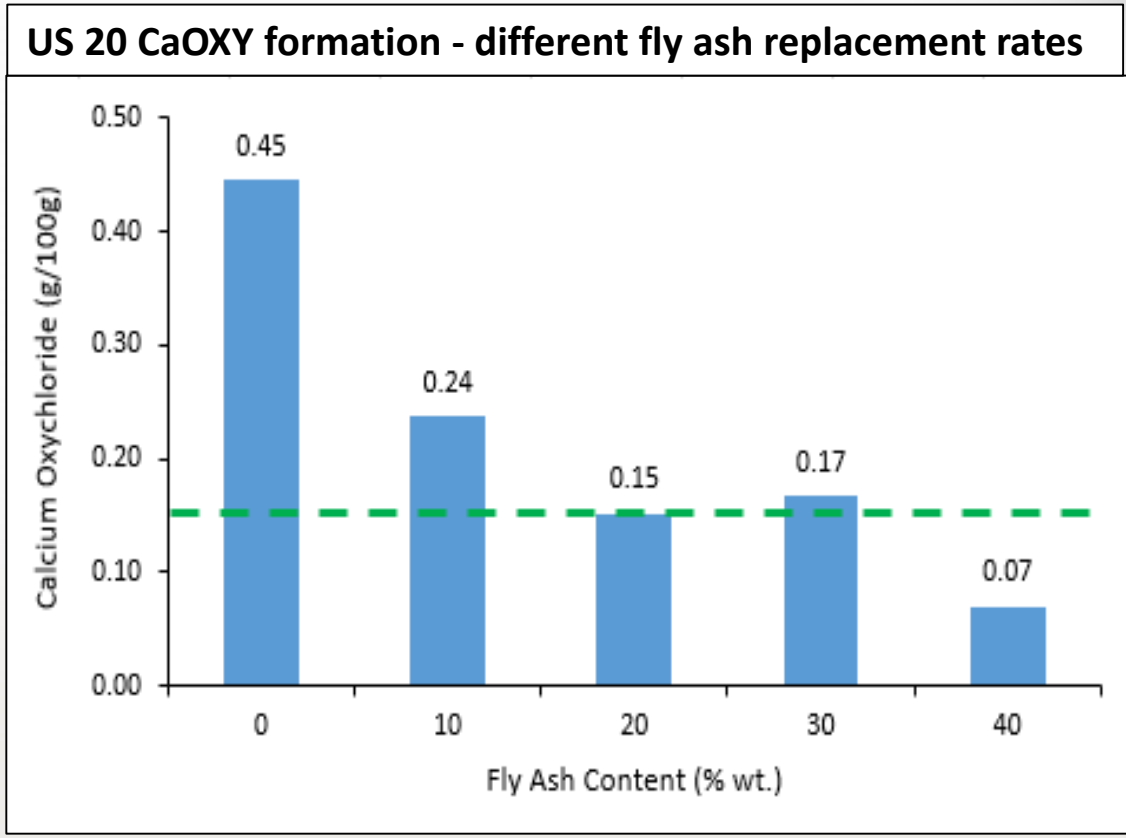


PEM US 20 Iowa -RESISTIVITY



Calcium Oxychloride Potential

- Limiting CaOXY formation to less than 0.15 (g/100g)
- 20% Class C fly ash replacement met the limit
- Higher percent slag/ fly ash replacement will further reduce potential



PEM Mix Design w Lower Cement Content

- Investigate lower cement mix on shoulders
  - 4 ft. by 6 in. thick
- Validate mix using PEM tests

A-2-C20 Mix	Abs. Vol.	lbs/CY
CEMENT:	0.083	440
FLY ASH:	0.025	110
WATER: w/c=0.474	0.155	261
FINE AGGREGATE:	0.305	1357
COARSE AGGREGATE:	0.372	1680
INTERMEDIATE AGG.:	0	0
AIR:	0.06	0
Paste Content, %	26.3	

550 lbs

PEM Mix – US 20 Shoulders	Abs. Vol.	lbs/CY
CEMENT:	0.078	412
FLY ASH:	0.024	103
WATER: w/c=0.40	0.122	206
FINE AGGREGATE (44%):	0.315	1401
COARSE AGGREGATE (44%):	0.315	1422
INTERMEDIATE AGG. (12%):	0.086	387
AIR:	0.06	0
Paste Content, %	22.4	

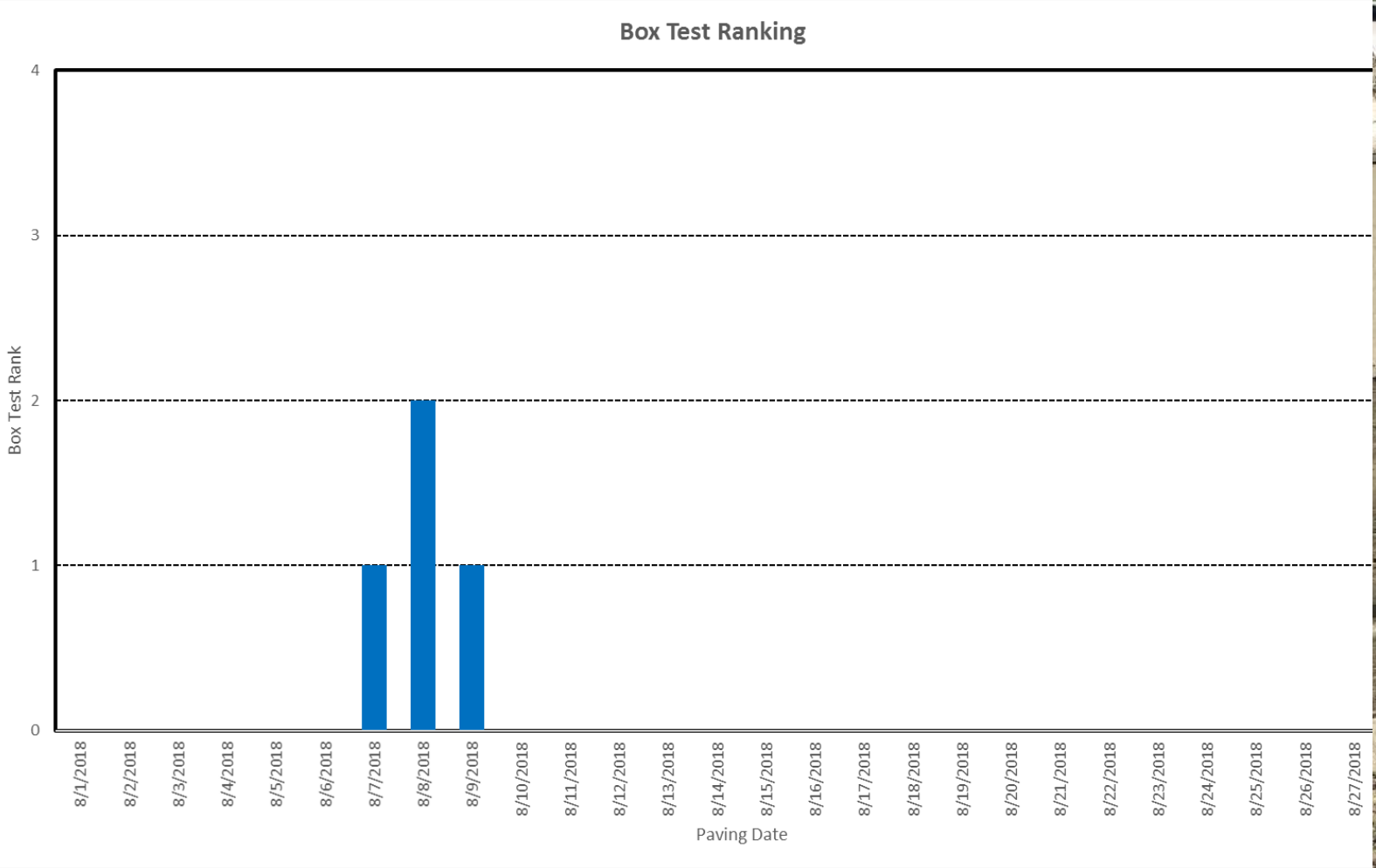
515 lbs

Dr. Taylor estimated cement content based on dry rodded unit weight of combined aggregate.

PEM Mix Design

- Some concerns lowering cement content of standard A mix for shoulder
  - Used QMC proportions
- Performed trial batch
  - Box Test
- Placement went very well
- Average w/c 0.42

PEM Mix Design



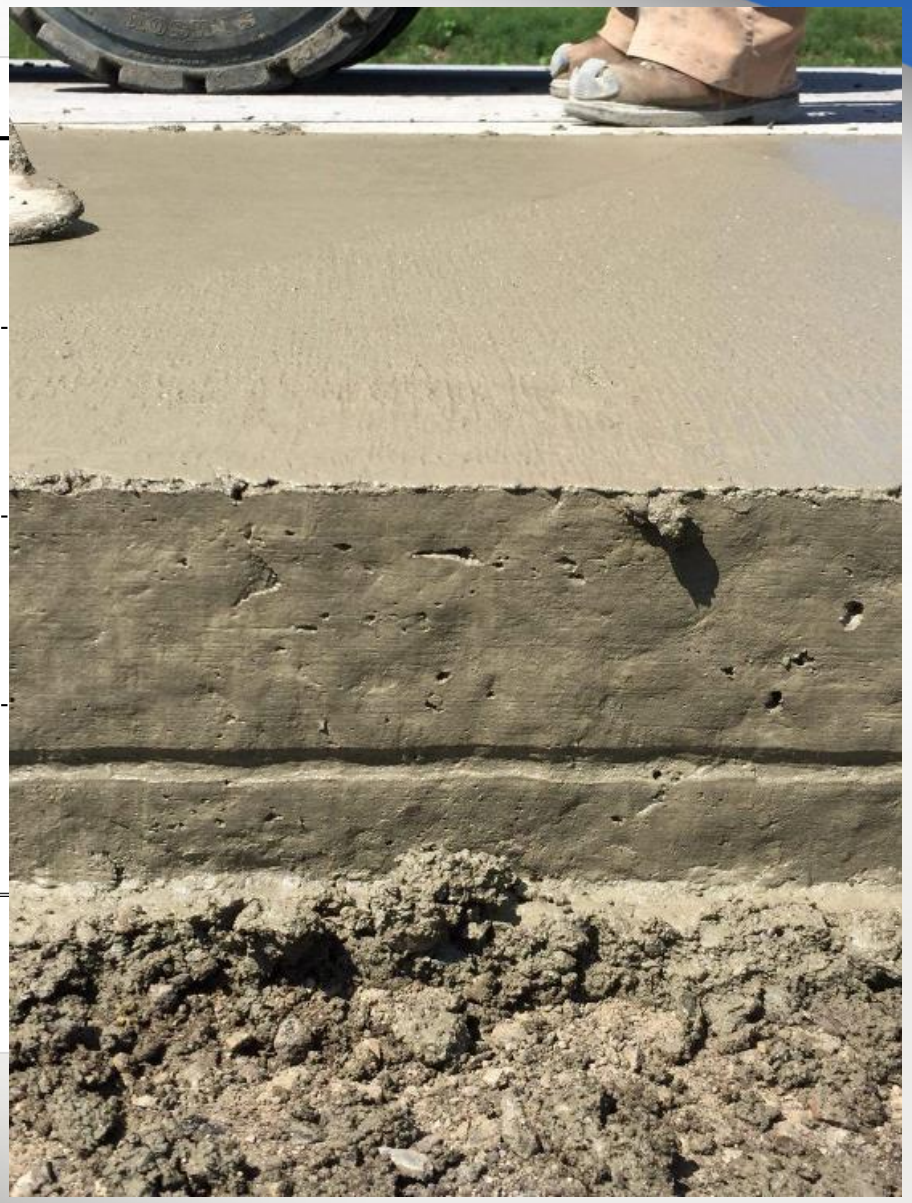


Table 3—Specification Worksheet

Section	Property	Specified Test	Specified Value		Mixture Qualification	Acceptance	Selection Details
			6.3 Concrete Strength				
6.3.1	Flexural Strength	T 97	4.1 MPa	600 psi	Yes	Yes	Choose either or both
6.3.2	Compressive Strength	T 22	24 MPa	3500 psi	Yes	Yes	
			6.4 Reducing Unwanted Slab Warping and Cracking Due to Shrinkage (if cracking is a concern)				
6.4.1.1	Volume of Paste	—	25%		Yes	No	Choose only one
6.4.1.2	Unrestrained Volume Change	ASTM C157	420 με	At 28 days	Yes	No	
6.4.2.1	Unrestrained Volume Change	ASTM C157	360, 420, 480 με	At 91 days	Yes	No	
6.4.2.2	Restrained Shrinkage	T 334	Crack free	At 180 days	Yes	No	
6.4.2.3	Restrained Shrinkage	TP XXX	$\Sigma < 60\% f'_r$	At 7 days	Yes	No	
6.4.2.4	Probability of Cracking	Appendix X1		As specified	Yes	No	
Commentary	Quality Control Check	—	—	—	No	Yes	
			6.5 Durability of Hydrated Cement Paste for Freeze–Thaw Durability				
6.5.1.1	Water to Cementitious Ratio	—	0.45	—	Yes	Yes	[a]
6.5.1.2	Fresh Air Content	T 152, T 196, TP 118	5 to 8	%	Yes	Yes	Choose only one
6.5.1.3	Fresh Air Content/SAM	T 152, T 196, TP 118	≥4% air; ≤0.2	%, psi	Yes	Yes	
6.5.2.1	Time of Critical Saturation	"Bucket Test" Specification	30	yr	Yes	No	[a, b]
6.5.3.1	Deicing Salt Damage	—	35%	SCM	Yes	Yes	Choose only one
6.5.3.2	Deicing Salt Damage	M 224	—	Topical treatment	Yes	Yes	
6.5.4.1	Calcium Oxychloride Limit	Test sent to AASHTO	<0.15 g CaOXY/g paste		Yes	No	
			6.6 Transport Properties				
6.6.1.1	Water to Cementitious Ratio	—	≤0.45 or ≤0.50	—	Yes	Yes	Choose only one
6.6.1.2	Formation Factor	Table 1	≥500 or ≥1000	—	Yes	Yes	
6.6.2.1	Ionic Penetration, *F* Factor	Appendix X2	25 mm at 30 yr		Yes, F	Through ρ	
			6.7 Aggregate Stability				
6.7.1	D Cracking	T 161, ASTM C1646	—	—	Yes	No	
6.7.2	Alkali Aggregate Reactivity	R 80	—	—	Yes	No	
			6.8 Workability				
6.8.1	Box Test	Appendix X3	<6.25 mm, <30% surface void			No	
6.8.2	Modified VKelly Test	Appendix X4	15–30 mm/root s			No	

Notes:

QMC vs PEM - What We Learned

Iowa DOT Current Practices QMC

- Strength – avg 640 PSI Flexural
- Volume of Paste = 24.3%
- w/c Ratio = 0.42 max.
- Air Content 6 to 10%
- SAM Results all below 0.30
- Ca Oxychloride Limit =0.15 g/100g
- Formation Factor ~1000
  - 20% C ash
- Aggregates – Iowa DOT Methods
- Workability Good
  - Combined Aggregate Grading

QMC vs PEM - What We Learned

- FHWA Mobile Concrete Lab closeout session
- Current QMC practices pretty good
- Possibly add resistivity testing
- Investigate Reduced Cement Mixes

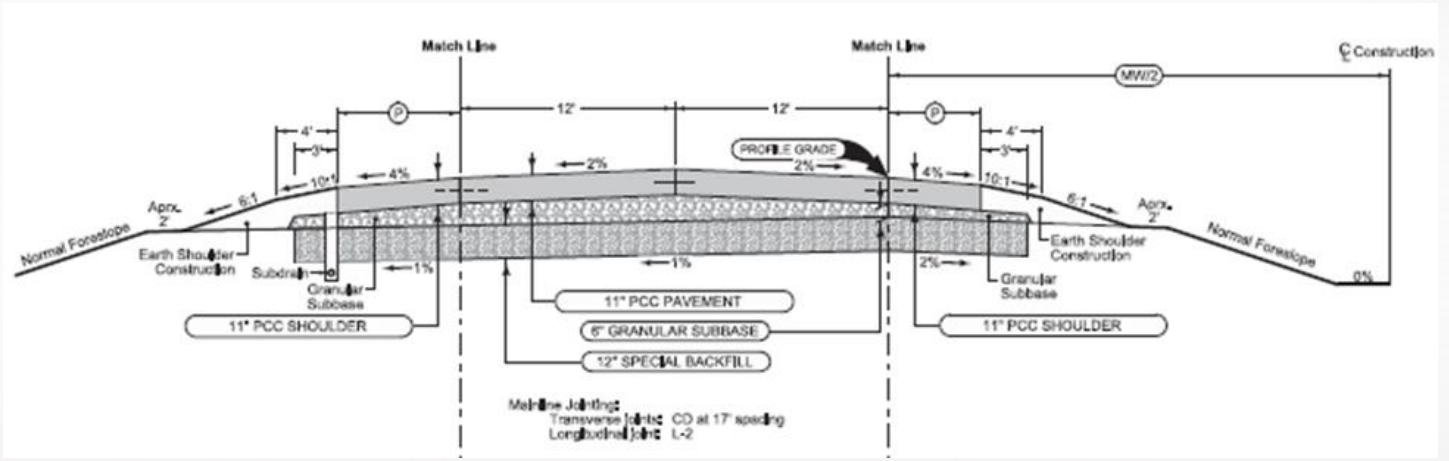
2019 PEM Data

	2019 PROJECT AVERAGES			
Location	**SAM #**	**BOX #**	**W/C**	**Resistivity**
Polk I35	0.23	1.2	0.39	11.89
Harrison I29	0.22	1.1	0.40	15.67
Black Hawk US 20	0.18	1.4	0.40	7.15*
Plymouth US 75	0.20	1.3	0.40	12.64

*Aggregates with high absorption affect results

2019 I-29 Harrison County

- With success of reduced cement mix in 2018
- Trial reduced cement mix on I-29 outside shoulder
  - 10ft wide, 11 inch thick
  - Mainline 24’ & Inside 6’ Shoulder paved integral
- Trial Batch
  - Box Test & SAM Test



2019 I-29 Harrison County Shoulders

A-6-C20 Mix	Abs. Vol.	lbs/CY
CEMENT:	0.092	463
FLY ASH:	0.027	116
WATER: w/c=0.474	0.163	274
FINE AGGREGATE:	0.395	1744
COARSE AGGREGATE:	0.263	1188
INTERMEDIATE AGG.:	0	0
AIR:	0.06	0
Paste Content, %	28.2	

579 lbs

PEM Mix – I-29 Shoulders	Abs. Vol.	lbs/CY
CEMENT:	0.077	387
FLY ASH:	0.022	97
WATER: w/c=0.419	0.120	203
Cl. V AGGREGATE (55%):	0.399	1761
COARSE AGGREGATE (45%):	0.327	1476
INTERMEDIATE AGG.:	0	0
AIR:	0.06	0
Paste Content, %	21.9	

484 lbs

2019 I-29 Harrison County Shoulders

A-6-C20

- 579 lbs/cy
- Avg w/c ratio = 0.392

PEM

- 484 lbs/cy
- Avg w/c ratio = 0.413

- Mainline 2020 decided to increase cement content due to w/c ratio
  - Later, found out a water reducer was not included in the mix.

I-29 Harrison QMC vs PEM

QMC Mix Design 2019	
Material	Weight (lbs/yd^3)
Ash Grove IP Cement	426
Nebraska City Fly Ash (20%)	107
Weeping Water CA (45%)	1427
N. Valley Cl. V. Aggregate (55%)	1708
Water (basic w/c=0.40) 0.42 max	213

533 lbs

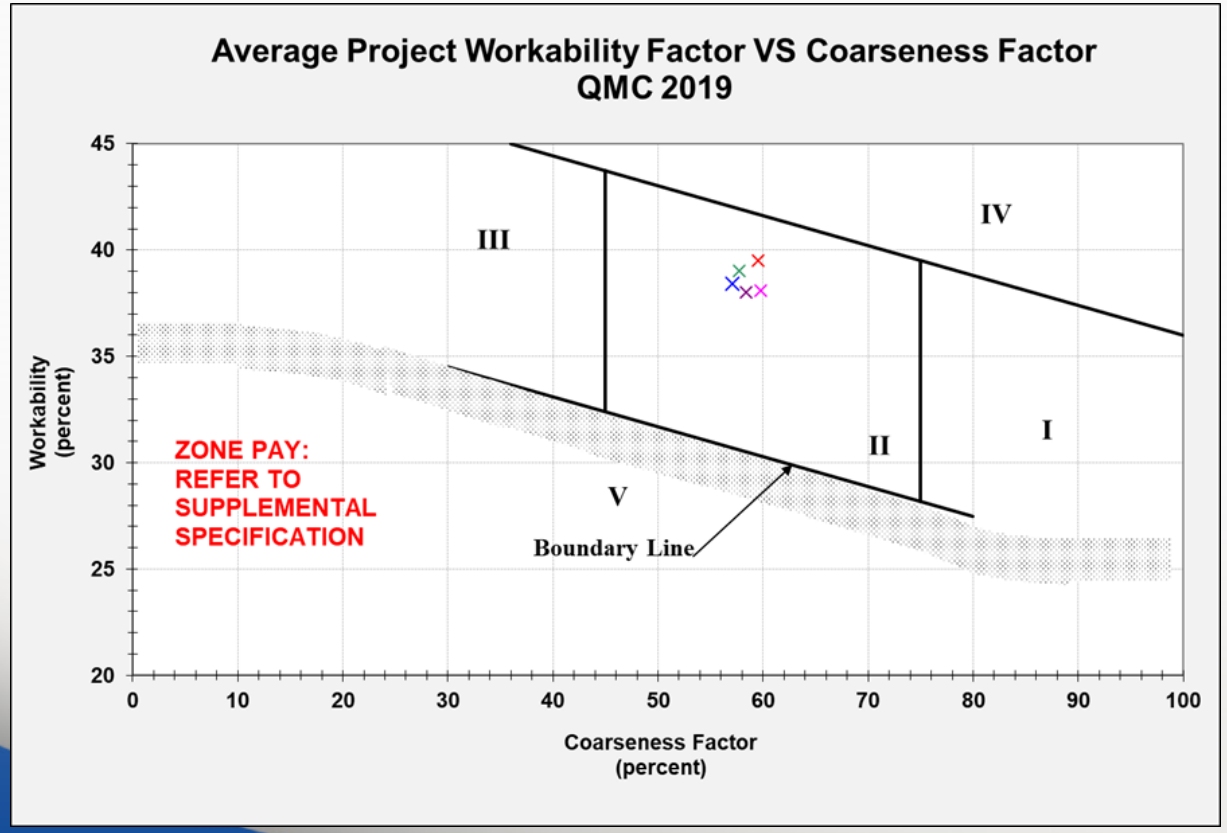
PEM Mix Design 2020	
Material	Weight (lbs/yd^3)
Ash Grove IP Cement	399
Nebraska City Fly Ash (20%)	100
Ft. Calhoun CA (45%)	1441
N. Valley Cl. V. Aggregate (55%)	1752
Water (basic w/c 0.40, 0.42 max.	200

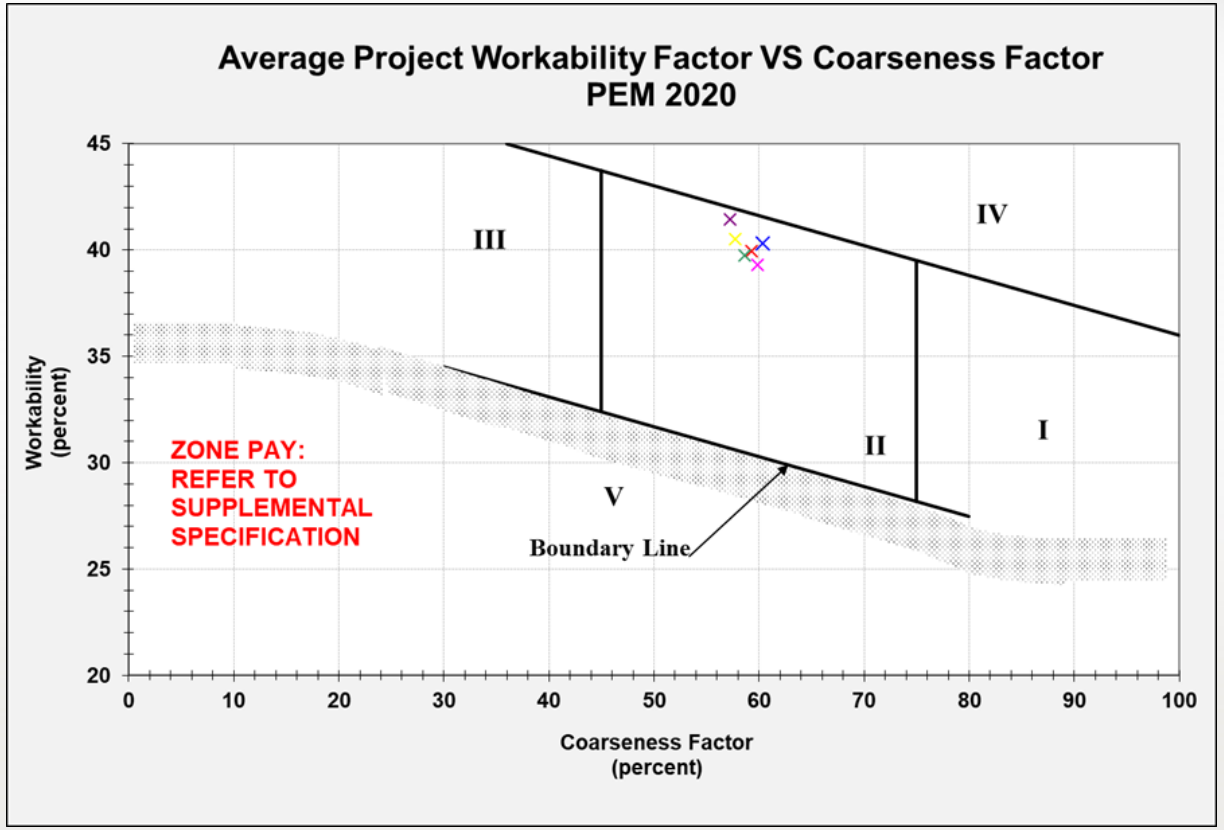
499 lbs

I-29 Harrison QMC vs PEM

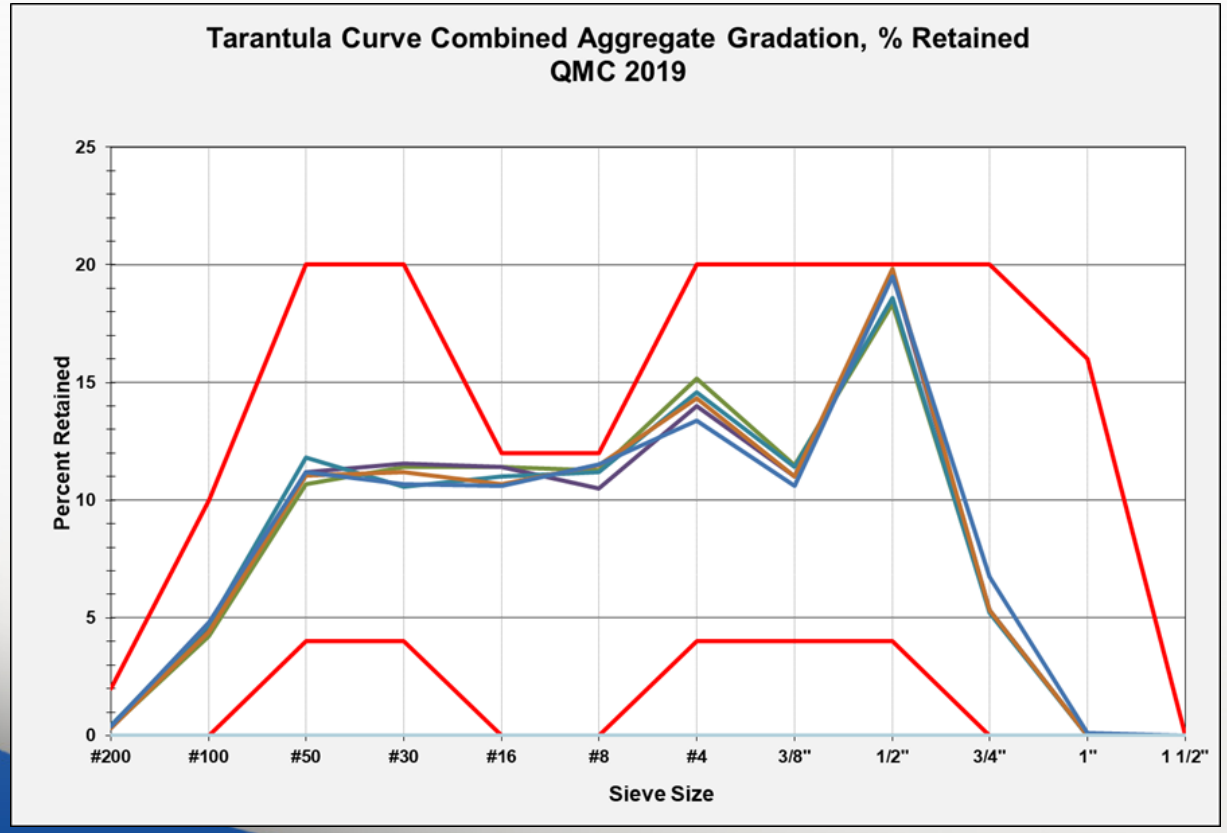
- Trail batch 2020 mix for mainline
- Mixed at plant and hauled to grade
- Paving began after trial batch
- 2019 – wet conditions
- 2020 – hot, dry

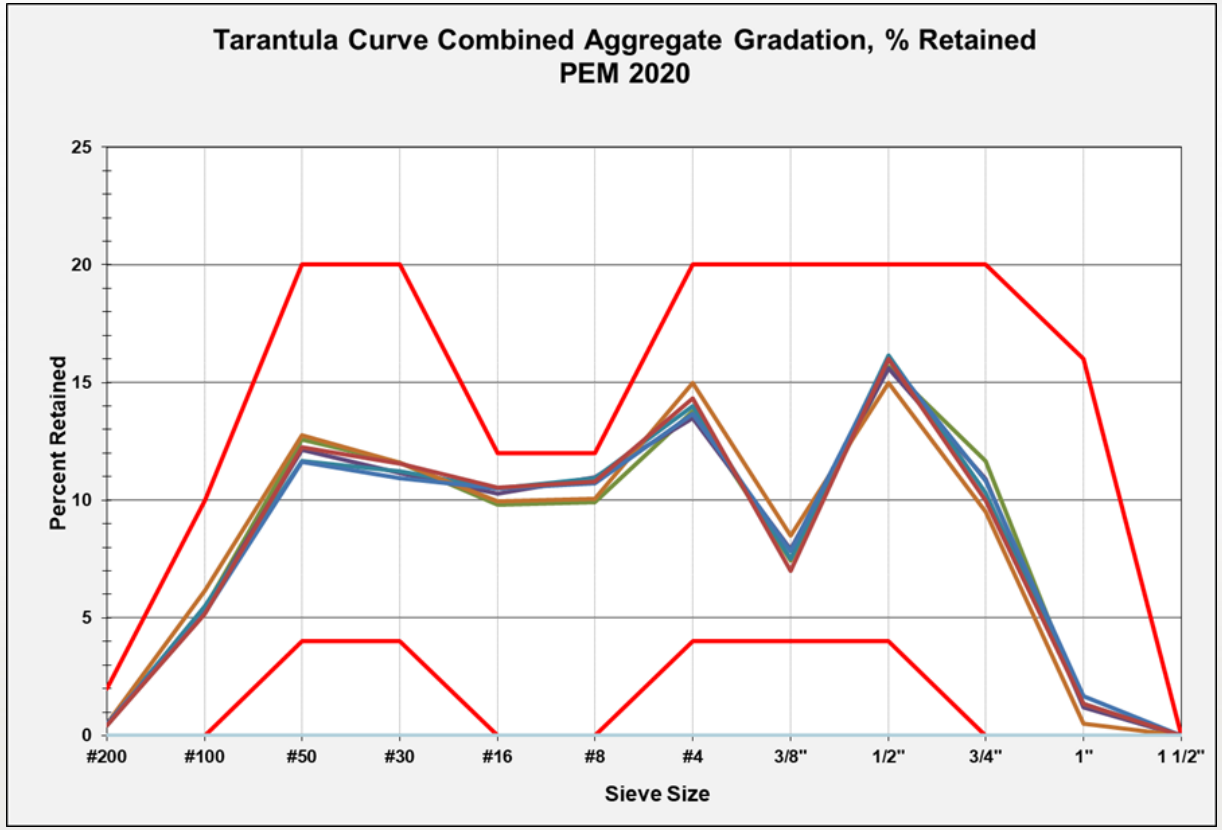
I-29 Harrison QMC vs PEM



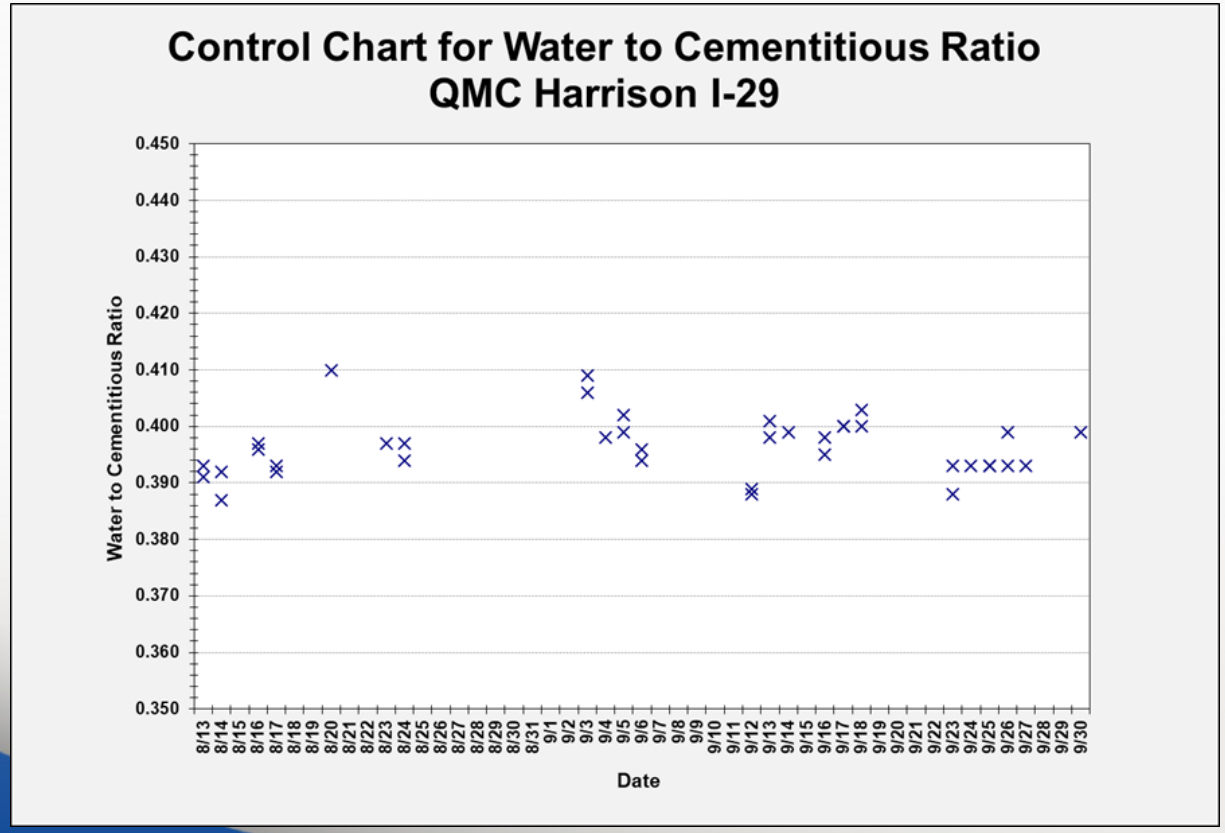


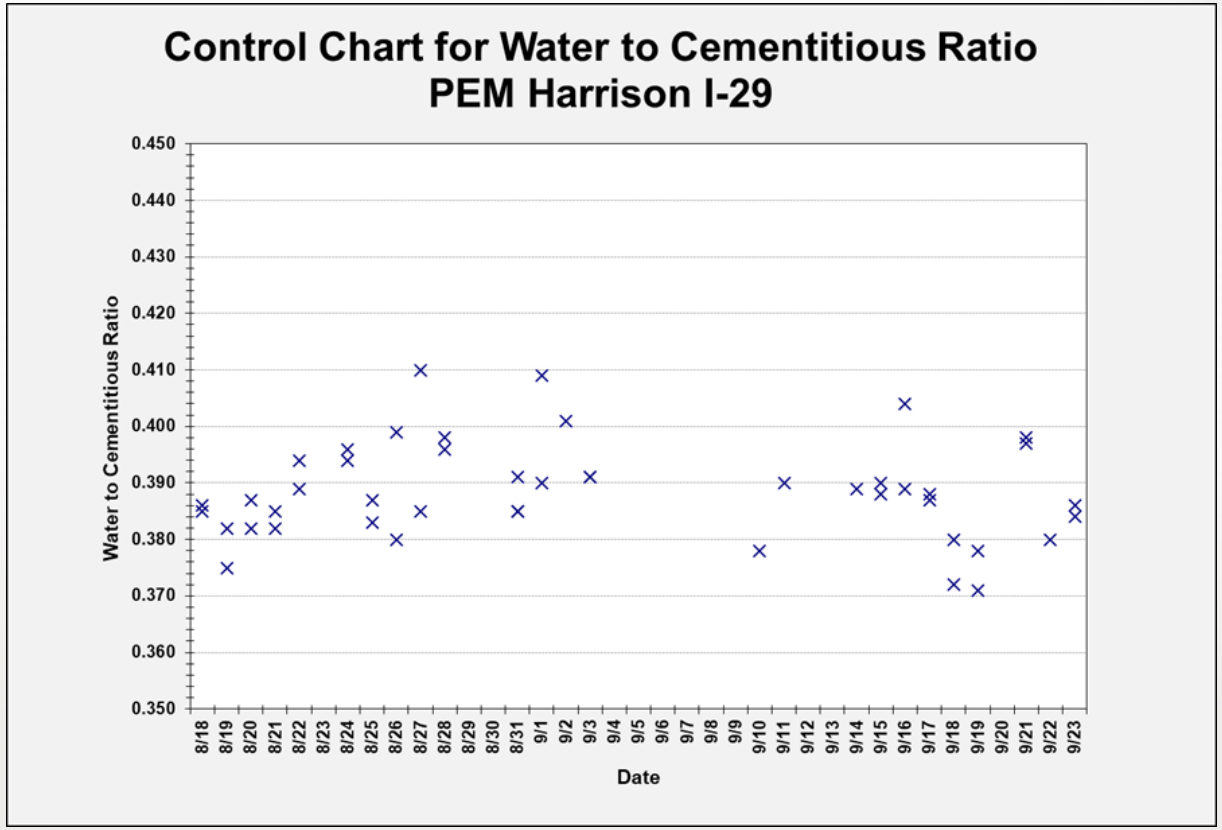
I-29 Harrison QMC vs PEM





I-29 Harrison QMC vs PEM





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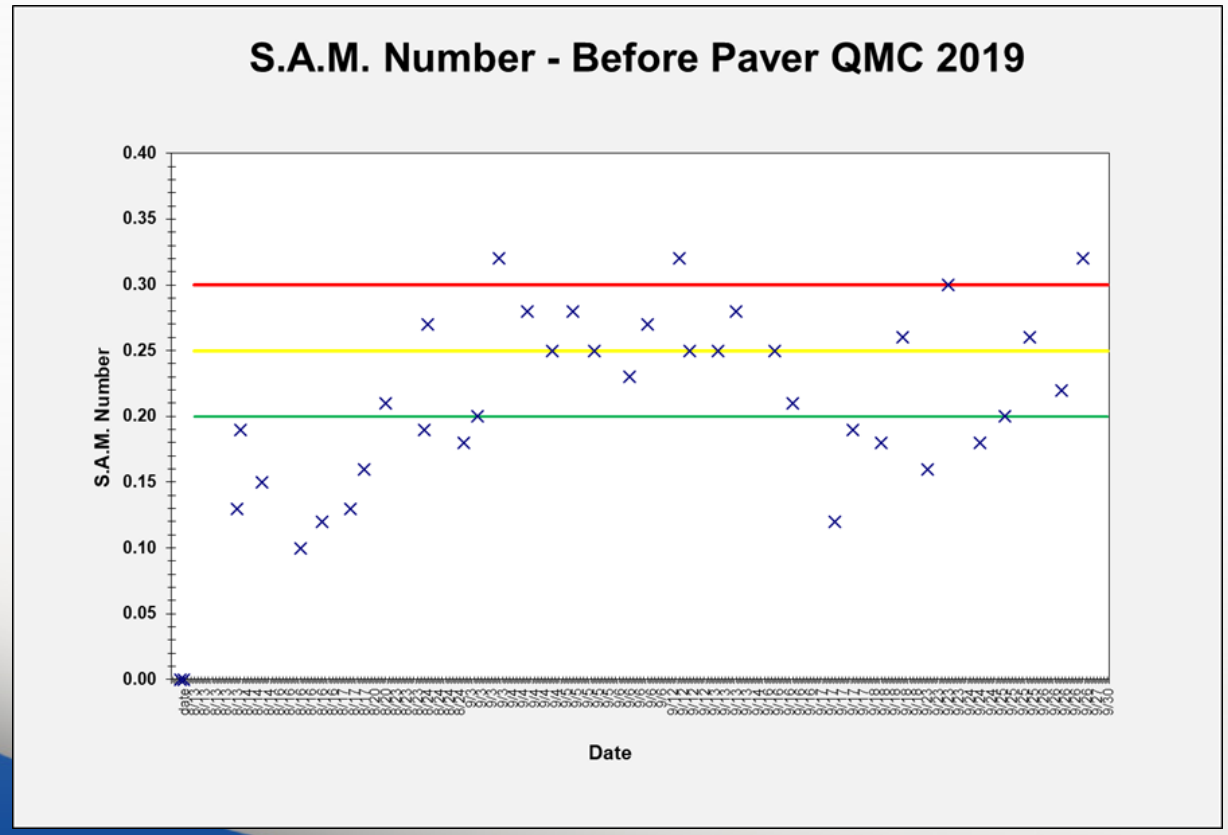
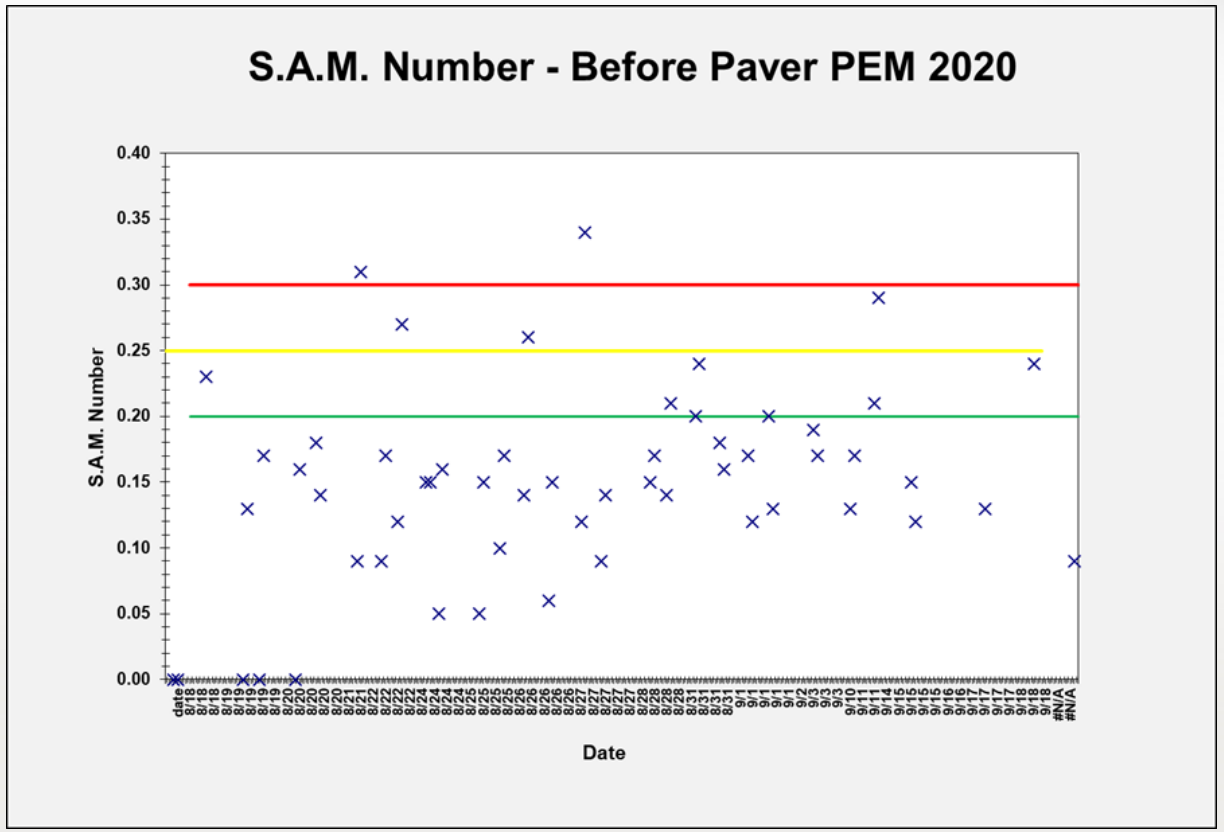
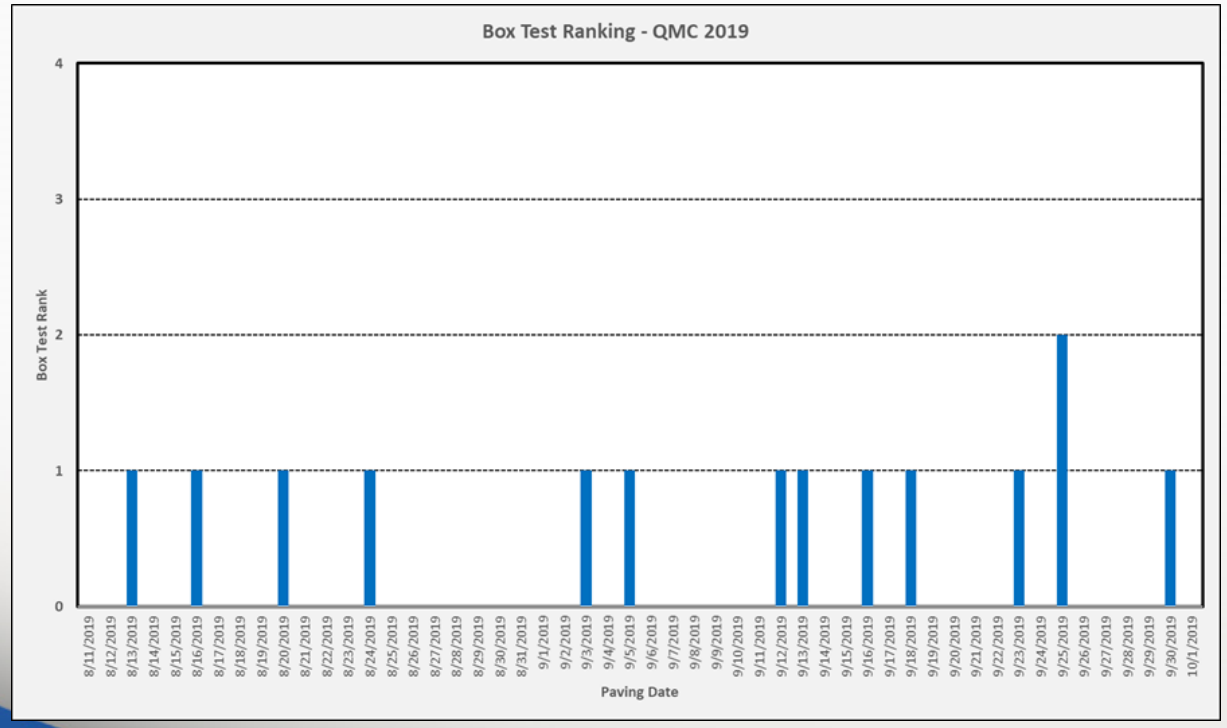
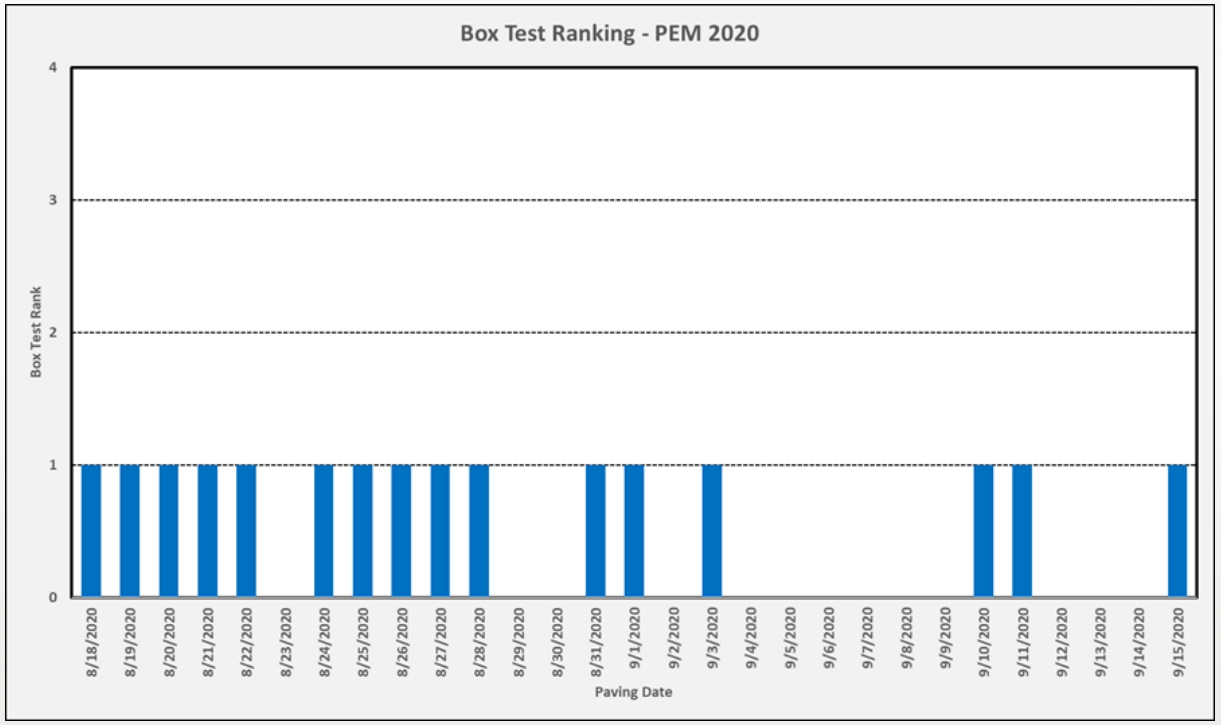


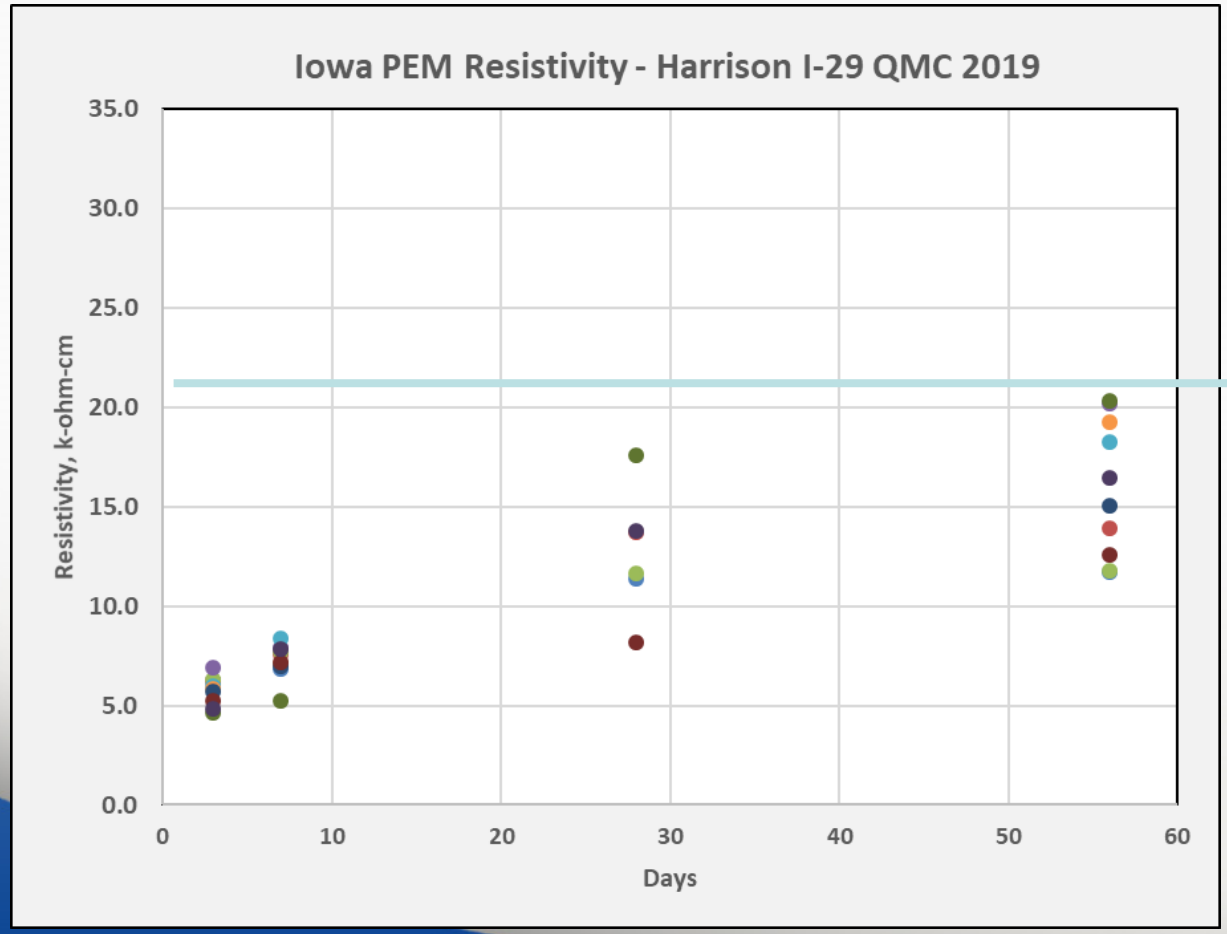


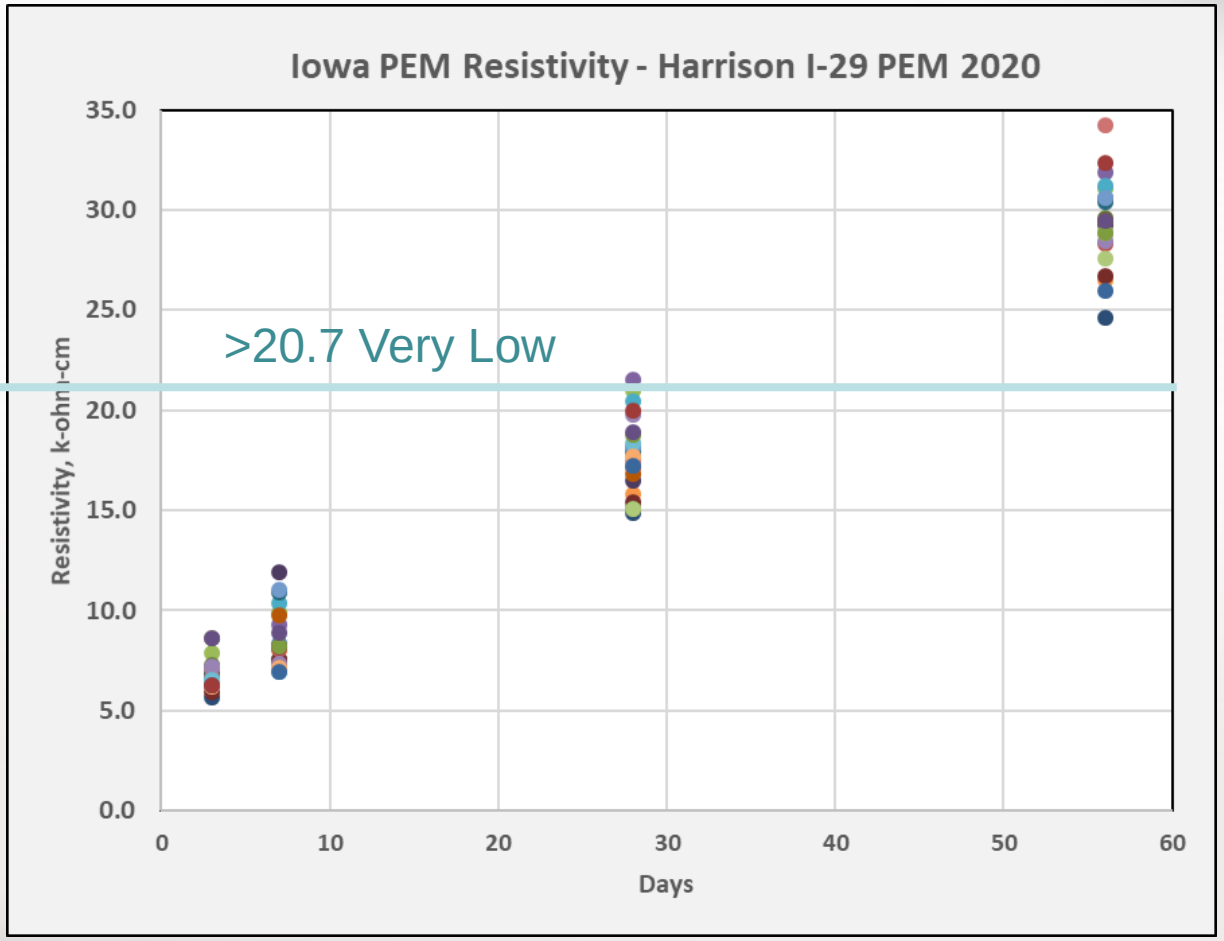
I-29 Harrison QMC vs PEM





I-29 Harrison QMC vs PEM





I-29 Harrison QMC – PEM Summary

- Average w/c ratio
  - QMC 2019 = 0.396
  - PEM 2020 = 0.390.
- Smoothness-Zero Band
  - QMC 2019 24.87 in/mi
    - 58.4% Max possible Incentive
  - PEM 2020 19.26 in/mi
    - 72.7% Max possible Incentive

Summary

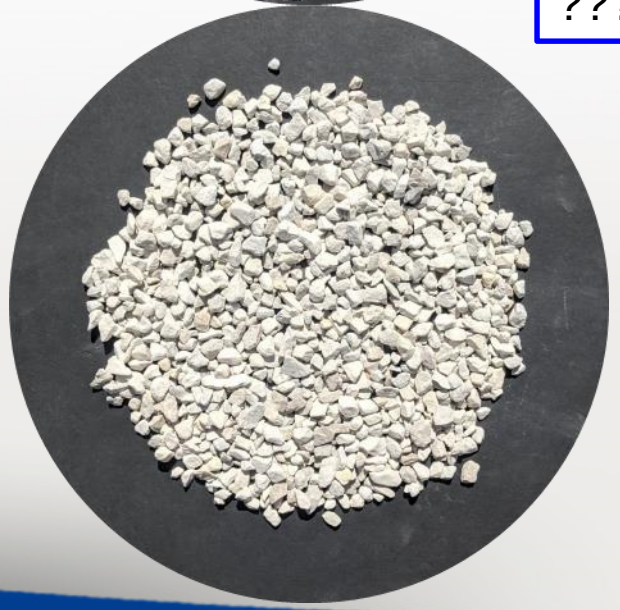
- Iowa QMC Mixes comparable with PEM Mix
- PEM testing helped validate reduced cement content QMC mixes (QMPEM)
  - 0.099 Abs Vol Cement – (1st Iteration)
    - 524 lbs/cy Type I/II
    - 517 lbs/cy Type IS(20)
    - 499 lbs/cy Type IP(25)
  - Trial Mix Design - SAM Air Test and Box Test
  - **QC** Testing - SAM Meter 1/day, Box Test – 1/day, Resistivity if available
- Influence of Aggregate Shape on cement content

Influence of Aggregate Shape

US 20 Project

I-29 Project

???



PEM - Future

- Continue gather data on SAM testing, workability, resistivity, etc.
- Get a SAM Meter and practice using
  - Purchase
  - FHWA or ICPA equipment loan
- Box Test – Build box
  - Vibrator requirements
  - https://www.minnich-mfg.com/products/vibrators/flex-shaft/csv
- Investigate lower cement mix with other aggregate combinations
- Eventually, modify QMC DS

Contractor's Perspective

Thank You !

https://intrans.iastate.edu/app/uploads/2019/03/Mixture-proportioning-2019-09.xlsx