Performance Engineered Mixtures for Durable and Sustainable Concrete Infrastructure:

Update on Research and Pilot Projects

NCDOT Research Projects 2018-14, 2019-41, 2020-13

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NC Concrete Pavement Conference
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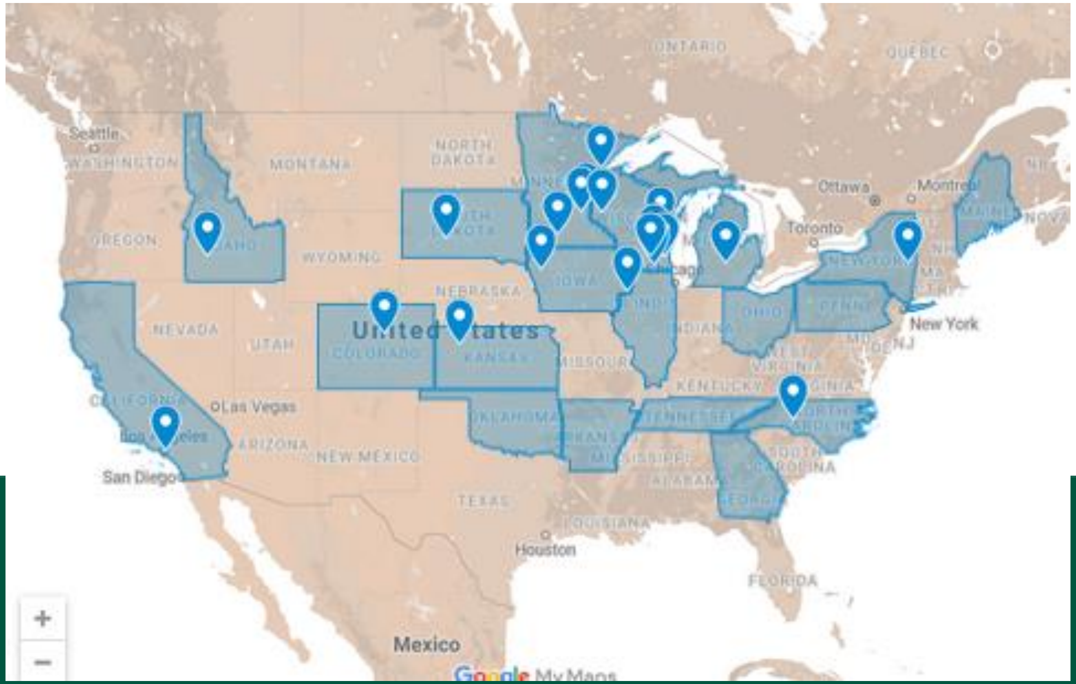
UNIVERSITY OF NORTH CAROLINA
CHARLOTTE
THE WILLIAM STATES LEE
COLLEGE OF ENGINEERING

Performance Engineered Concrete Initiative

- For almost a century, concrete has been specified and accepted based on:
  <u>strength, slump and air content</u>.

These measurements often do not correlate to
future performance and durability over the service life.

- Decades of research on concrete materials have supported development of new testing technologies that provide information that better predicts concrete performance.



- FHWA, 19 state agencies, and 4 national associations supported a Transportation Pooled Fund to support movement towards adoption of these test methods and performance-based specification provisions.

AASHTO PP 84 (now R 101) was/is the centerpiece of the PEM effort

Standard Practice for

Developing Performance Engineered Concrete Pavement Mixtures

AASHTO Designation: R 101-22[1]

Adopted: 2022

Technical Subcommittee: 3c, Hardened Concrete

AASHTO

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

- Introduces performance engineered concrete mixtures (PEM)
- Provides prescriptive and performance approaches to meet key objectives
    - Strength
    - Susceptibility to slab warping and shrinkage cracking
    - Susceptibility to shrinkage
    - Cracking potential
    - Freeze-thaw durability
    - Aggregate stability (ASR, D-cracking)
    - Workability

What is Performance Engineered Concrete?

- Concrete that does what you want it to do:
  - during construction (workable and constructable)
  - over the service life (adequate strength and good durability performance)
- Meets other needs
  - Construction challenges
    - pumpable
    - highly flowable
    - high early strength
    - many other kinds of project-specific needs
  - Sustainability goals
    - lower emissions/carbon footprint
    - use of recycled materials
    - use of local materials

Moving specifications away from slump, strength, and air content...

and towards
materials and tests that support long term performance.

Background

From Brian Hunter, NCDOT M&T

- NCDOT specifications for concrete have changed little over the past 85 years
  - Prescriptive specification
  - Little room for innovation
  - Mixtures typically over-designed for strength

- Resource reductions drive the need to reduce maintenance cost, increase service life

- Desire fly ash in most of our mixtures because of the benefits
  - Encounter fly ash shortage throughout the years
  - Need to find equivalent performance of mixtures without fly ash (“what if” scenario)

- Recently (2018) increased allowable fly ash substitution rate from 20% to 30%
  - Needed data to support/encourage use of higher substitution rate, account for slower early age strength gain

- Needed data to support decision to allow use of portland limestone cement (see NCDOT RP 2015-03 report)

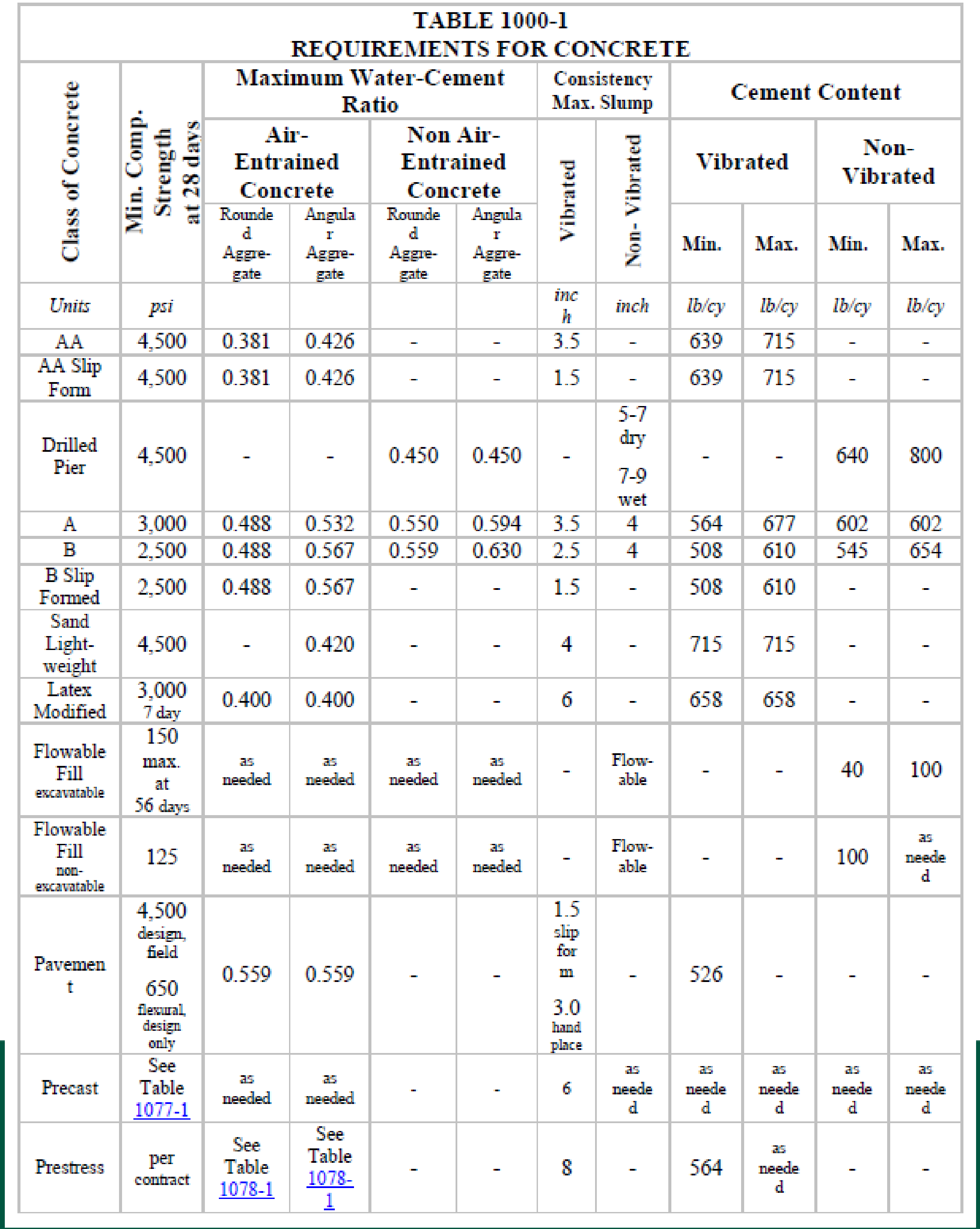


TABLE 1000-1
REQUIREMENTS FOR CONCRETE

Class of Concrete	Min. Comp. Strength at 28 days	Maximum Water-Cement Ratio				Consistency Max. Slump		Cement Content			
		Air-Entrained Concrete		Non Air-Entrained Concrete		Vibrated	Non-Vibrated	Vibrated		Non-Vibrated	
		Rounded Aggregate	Angular Aggregate	Rounded Aggregate	Angular Aggregate			Min.	Max.	Min.	Max.
Units	*psi*					*inch*	*inch*	*lb/cy*	*lb/cy*	*lb/cy*	*lb/cy*
AA	4,500	0.381	0.426	-	-	3.5	-	639	715	-	-
AA Slip Form	4,500	0.381	0.426	-	-	1.5	-	639	715	-	-
Drilled Pier	4,500	-	-	0.450	0.450	-	5-7 dry 7-9 wet	-	-	640	800
A	3,000	0.488	0.532	0.550	0.594	3.5	4	564	677	602	602
B	2,500	0.488	0.567	0.559	0.630	2.5	4	508	610	545	654
B Slip Formed	2,500	0.488	0.567	-	-	1.5	-	508	610	-	-
Sand Light-weight	4,500	-	0.420	-	-	4	-	715	715	-	-
Latex Modified	3,000 7 day	0.400	0.400	-	-	6	-	658	658	-	-
Flowable Fill excavatable	150 max. at 56 days	as needed	as needed	as needed	as needed	-	Flow-able	-	-	40	100
Flowable Fill non-excavatable	125	as needed	as needed	as needed	as needed	-	Flow-able	-	-	100	as needed
Pavement	4,500 design, field 650 flexural, design only	0.559	0.559	-	-	1.5 slip form 3.0 hand place	-	526	-	-	-
Precast	See Table 1077-1	as needed	as needed	-	-	6	as needed	as needed	as needed	as needed	as needed
Prestress	per contract	See Table 1078-1	See Table 1078-1	-	-	8	-	564	as needed	-	-

What if...

- Emphasis on durability
- Sustainability considerations

- Flexibility for innovation
- Buffer against material shortages
- Opportunity for cost-savings

Preventing issues, rather than spending money/effort monitoring or addressing them

Resistivity testing for permeability
(rapid electrical test)

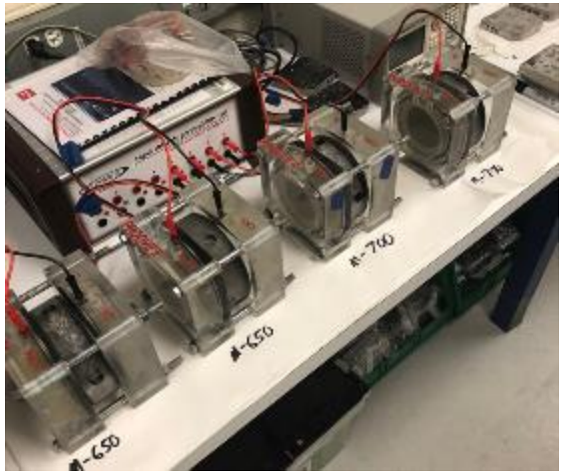
vs.

Drilled powder samples tested for chloride content
(chemical testing)

Implementing new, rapid testing technologies to replace tests that are slow, destructive, or unreliable.

Permeability

Surface Resistivity Test
AASHTO T 358



Rapid Chloride
Permeability Test
AASHTO T 277

Freeze-thaw durability

Super Air Meter
AASHTO T 152

vs.

Freeze Thaw Testing
ASTM C666

Tests specified for use in targeted applications.
Use of tests during prequalification to predict/improve performance.

Photo: Humboldt

Resistance to cracking

- Volumetric shrinkage (drying shrinkage)
- Target length change established
- Likely used for bridge applications
- Would typically be used to prequalify mixtures, not during construction

NCDOT PEM efforts so far…

- Participation in Pooled Fund
- Two internally funded projects
  - RP 2018-14 (2017 - 2019) "Durable and Sustainable Concrete Through Performance Engineered Concrete Mixtures."
  - RP 2020-13 (2019 - 2022) "*Continuing Towards* Durable and Sustainable Concrete Through Performance Engineered Concrete Mixtures."

- FHWA Implementation Funds
  - RP 2019-41 "Performance Engineered Concrete Mixtures – FHWA Implementation Funds" – technology transfer activities

We have collected a lot of field/lab data…
We have established proposed testing targets and shadow specifications

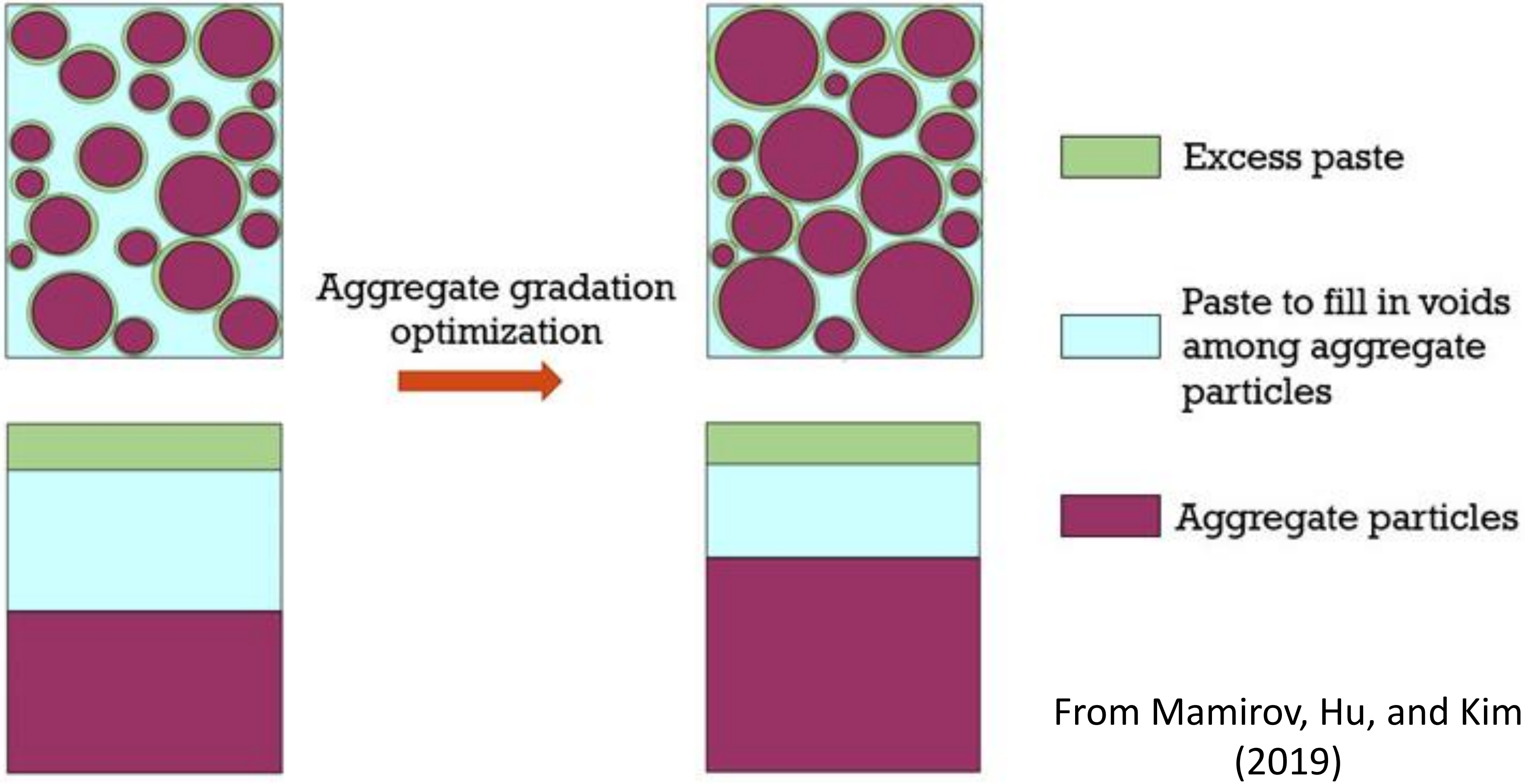
We are trying selected tests out on pilot projects
Evaluating proposed testing targets
Gathering stakeholder feedback
Finding ways to justify use of PEM approaches and technologies

Overall Objectives – NCDOT's PEM Initiatives

1. Establish preliminary specification recommendations, targets for selected PEM technologies and some prescriptive provisions
    - surface resistivity ✓ PEM 1, pavement pilot project, PEM 2, structures pilot project
    - w/cm, cementitious content (prescriptive provisions) ✓ PEM 1, PEM 2, in progress for 2024 specs
    - shrinkage ✓ PEM 1, PEM 2, structures pilot project
    - SAM ✓ PEM 1, pavement pilot project, PEM 2, structures pilot project
2. Explore ways to reduce paste/cement contents
    - optimized aggregate gradation ✓ PEM 2
    - reduced cementitious contents ✓ PEM 2
3. Support pilot project implementation
    - pavement projects ✓ FHWA Implementation Funds, RP 2019-41
    - bridge projects ✓ PEM 2
    - bridge deck overlay projects ✓ PEM 2
4. Support technology transfer to NCDOT division/regional personnel as well as industry stakeholders ✓✓✓✓ PEM 1, pavement pilot project, PEM 2, structures pilot project

5. Quantify benefits associated with use of PEM technologies and approaches

RP 2020-13
Laboratory Evaluation of Optimized Aggregate Gradation Mixtures



🟩 Excess paste

🟦 Paste to fill in voids among aggregate particles

🟪 Aggregate particles

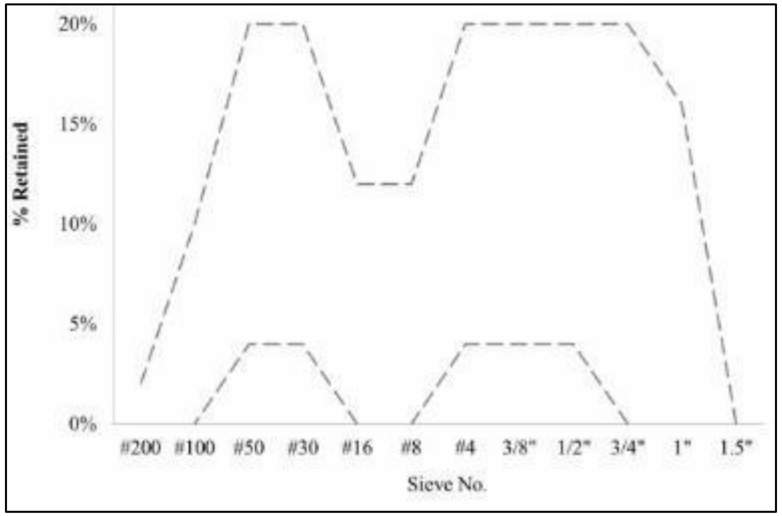
From Mamirov, Hu, and Kim (2019)

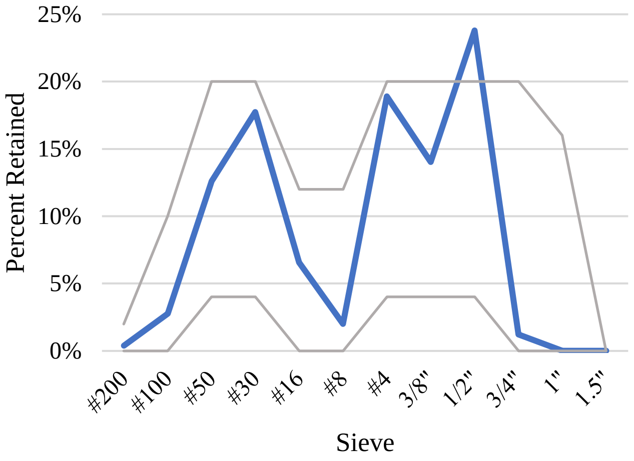
Concrete Mixture Matrix RP 2018-14

Mixture ID **W-XXX-YYY,** **W** is *w/cm* ratio, **XXX** is cement content, **YYY** is fly ash content	**Mixture Proportions, pcy**							
	Mixture type	***w/cm* ratio**	**Fly ash replacement (%)**	**Cement**	**Fly ash**	**Coarse aggregate**	**Fine aggregate**	**Water**
H-700-0	AA (high and medium cm content)	0.47	0	700	0	1659	1072	329.0
H-560-140			20	560	140	1659	1022	329.0
H-650-0			0	650	0	1659	1175	305.5
H-520-130			20	520	130	1659	1129	305.5
H-600-0			0	600	0	1659	1277	282.0
H-480-120			20	480	120	1659	1235	282.0
H-420-180			30	420	180	1659	1214	282.0
M-700-0		0.42	0	700	0	1659	1163	294.0
M-560-140			20	560	140	1659	1114	294.0
M-650-0			0	650	0	1659	1259	273.0
M-520-130			20	520	130	1659	1214	273.0
M-600-0			0	600	0	1659	1356	252.0
M-480-120			20	480	120	1659	1313	252.0
M-420-180			30	420	180	1659	1292	252.0
L-700-0	AA (low cm content) and Pavement	0.37	0	700	0	1659	1254	259.0
L-560-140			20	560	140	1659	1205	259.0
L-650-0			0	650	0	1659	1344	240.0
L-520-130			20	520	130	1659	1298	240.0
L-600-0			0	600	0	1659	1434	222.0
L-480-120			20	480	120	1659	1392	222.0
L-420-180			30	420	180	1659	1370	222.0

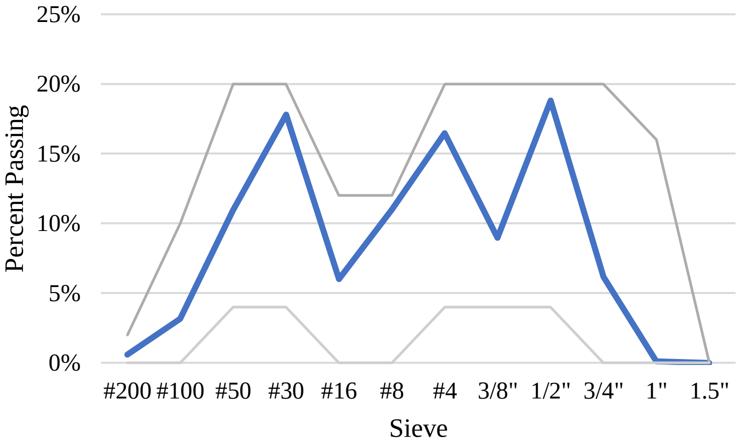
Optimized Aggregate Gradations

- 10% cementitious material reduction applied to all RP 2018-14 mixtures
- RP 2018-14 paste contents ranged from 24.5% to 33.8% (avg 28.5%)
- RP 2020-13 paste contents ranged from 22.0 to 30.3% (avg 25.6%)





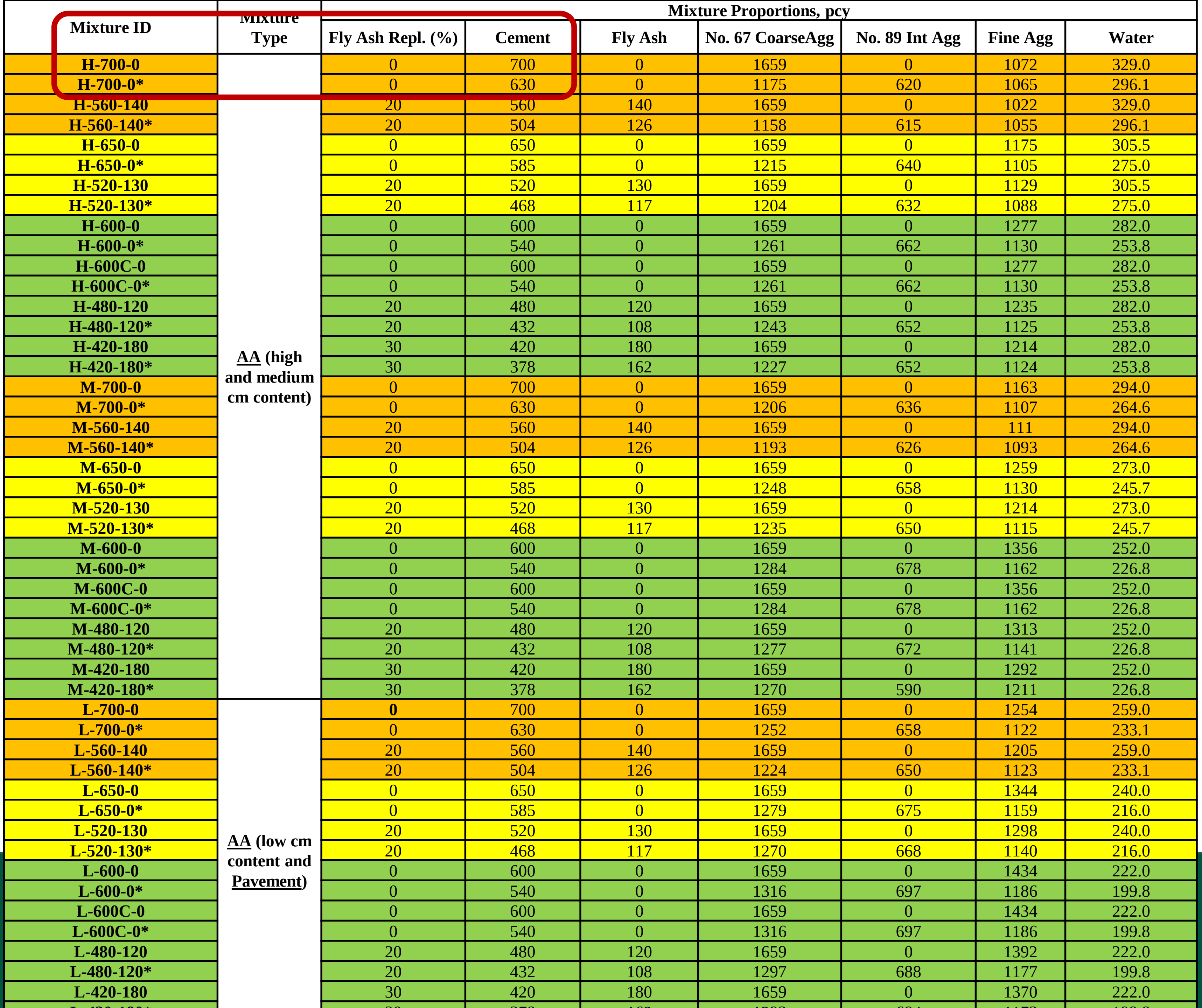
Mixture H-700-0



Mixture H-700*-0

<u>No. 89M aggregate used to achieve Tarantula Curve compliant gradation, paste contents (%) reduced.</u>

Mixture Matrices RP 2018-14 and RP 2020-13



Mixture ID	Mixture Type	Mixture Proportions, pcy						
		Fly Ash Repl. (%)	Cement	Fly Ash	No. 67 CoarseAgg	No. 89 Int Agg	Fine Agg	Water
H-700-0	AA (high and medium cm content)	0	700	0	1659	0	1072	329.0
H-700-0*		0	630	0	1175	620	1065	296.1
H-560-140		20	560	140	1659	0	1022	329.0
H-560-140*		20	504	126	1158	615	1055	296.1
H-650-0		0	650	0	1659	0	1175	305.5
H-650-0*		0	585	0	1215	640	1105	275.0
H-520-130		20	520	130	1659	0	1129	305.5
H-520-130*		20	468	117	1204	632	1088	275.0
H-600-0		0	600	0	1659	0	1277	282.0
H-600-0*		0	540	0	1261	662	1130	253.8
H-600C-0		0	600	0	1659	0	1277	282.0
H-600C-0*		0	540	0	1261	662	1130	253.8
H-480-120		20	480	120	1659	0	1235	282.0
H-480-120*		20	432	108	1243	652	1125	253.8
H-420-180		30	420	180	1659	0	1214	282.0
H-420-180*		30	378	162	1227	652	1124	253.8
M-700-0		0	700	0	1659	0	1163	294.0
M-700-0*		0	630	0	1206	636	1107	264.6
M-560-140		20	560	140	1659	0	111	294.0
M-560-140*		20	504	126	1193	626	1093	264.6
M-650-0		0	650	0	1659	0	1259	273.0
M-650-0*		0	585	0	1248	658	1130	245.7
M-520-130		20	520	130	1659	0	1214	273.0
M-520-130*		20	468	117	1235	650	1115	245.7
M-600-0		0	600	0	1659	0	1356	252.0
M-600-0*		0	540	0	1284	678	1162	226.8
M-600C-0		0	600	0	1659	0	1356	252.0
M-600C-0*		0	540	0	1284	678	1162	226.8
M-480-120		20	480	120	1659	0	1313	252.0
M-480-120*		20	432	108	1277	672	1141	226.8
M-420-180		30	420	180	1659	0	1292	252.0
M-420-180*		30	378	162	1270	590	1211	226.8
L-700-0	AA (low cm content and Pavement)	**0**	700	0	1659	0	1254	259.0
L-700-0*		0	630	0	1252	658	1122	233.1
L-560-140		20	560	140	1659	0	1205	259.0
L-560-140*		20	504	126	1224	650	1123	233.1
L-650-0		0	650	0	1659	0	1344	240.0
L-650-0*		0	585	0	1279	675	1159	216.0
L-520-130		20	520	130	1659	0	1298	240.0
L-520-130*		20	468	117	1270	668	1140	216.0
L-600-0		0	600	0	1659	0	1434	222.0
L-600-0*		0	540	0	1316	697	1186	199.8
L-600C-0		0	600	0	1659	0	1434	222.0
L-600C-0*		0	540	0	1316	697	1186	199.8
L-480-120		20	480	120	1659	0	1392	222.0
L-480-120*		20	432	108	1297	688	1177	199.8
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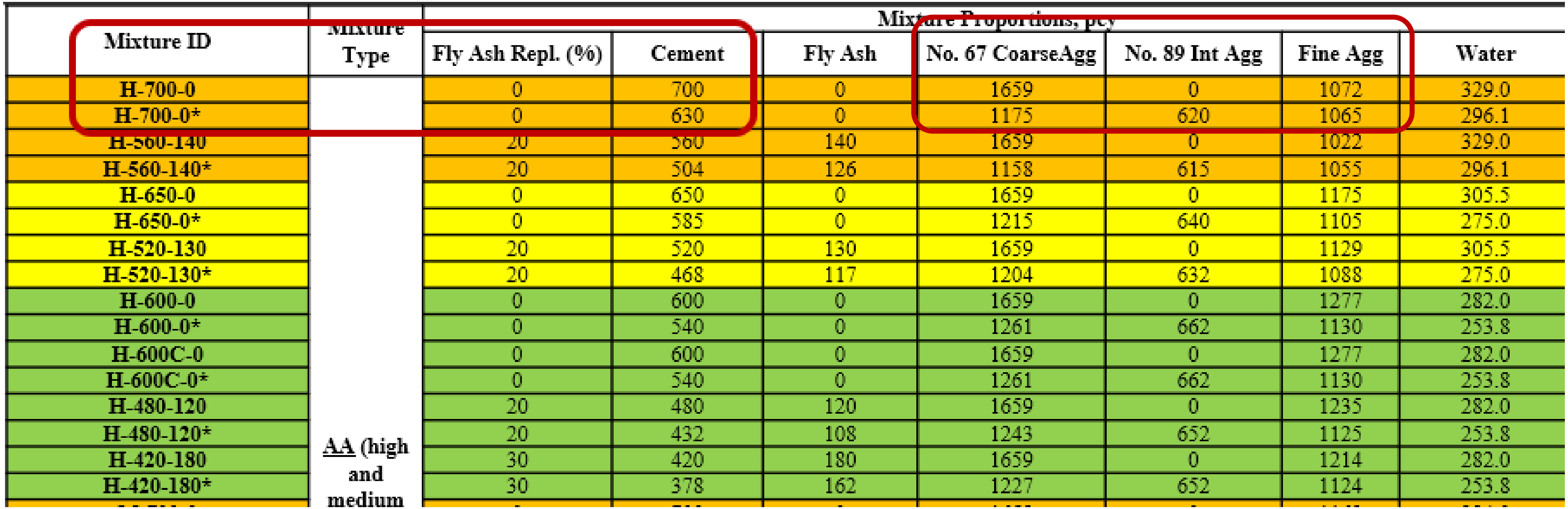
Mixture Matrices
RP 2018-14 and RP 2020-13



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H-650-0*		0	585	0	1215	640	1105	275.0
H-520-130		20	520	130	1659	0	1129	305.5
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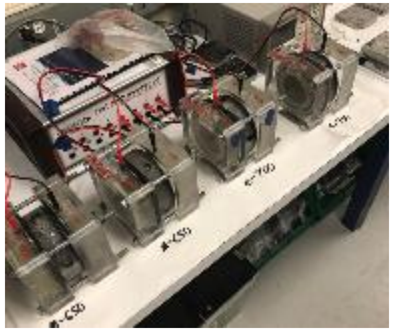
H-600-0*		0	540	0	1261	662	1130	253.8
H-600C-0		0	600	0	1659	0	1277	282.0
H-600C-0*		0	540	0	1261	662	1130	253.8
H-480-120		20	480	120	1659	0	1235	282.0
H-480-120*		20	432	108	1243	652	1125	253.8
H-420-180		30	420	180	1659	0	1214	282.0
H-420-180*		30	378	162	1227	652	1124	253.8

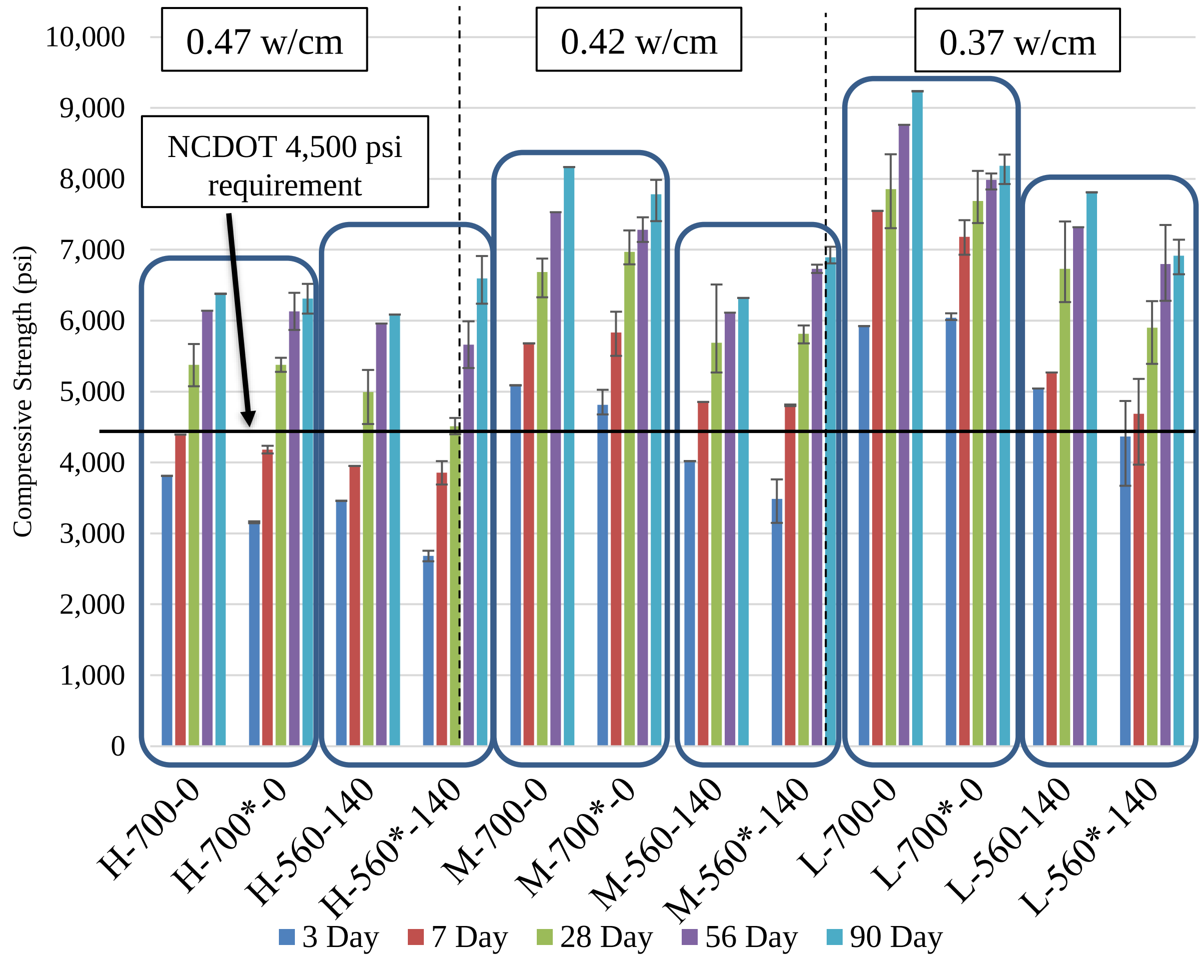
Testing Program

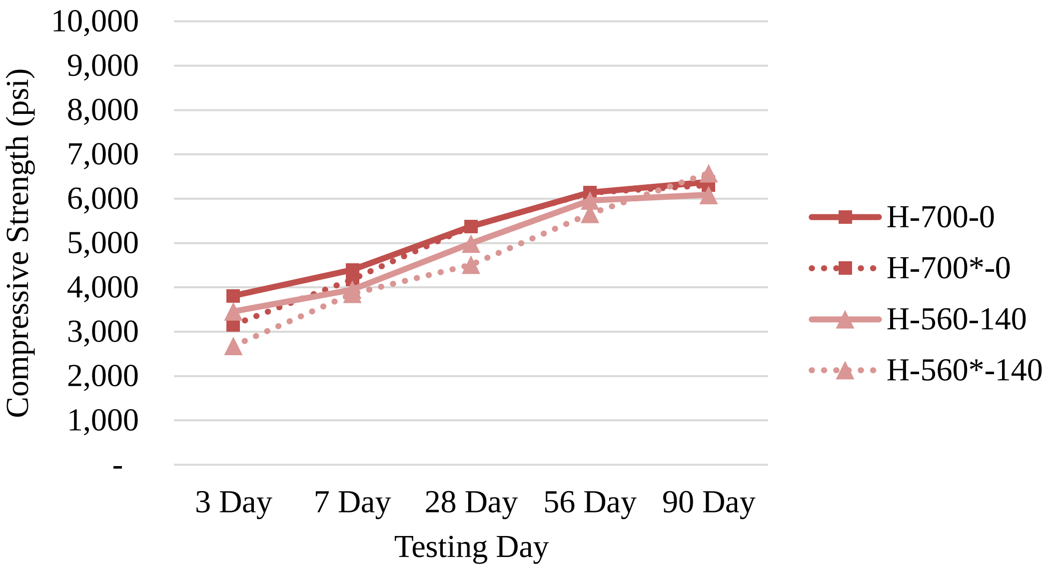
	Test name	Standard	Testing age(s) in days	Replicates
Fresh	Air content	ASTM C231	Fresh	1
	SAM number	AASHTO T 152	Fresh	1
	Slump	ASTM C143	Fresh	1
	Fresh density (unit weight)	ASTM C138	Fresh	1
	Temperature	AASHTO T 309	Fresh	1
Hardened	Compressive strength	ASTM C39	3, 7, 28, 56, 90	3 each age
	Modulus of rupture (MOR, or flexural strength)	ASTM C78	28	2
	Modulus of elasticity (MOE) and Poisson’s ratio	ASTM C469	28	2
	Surface Resistivity	AASHTO T 358	3, 7, 28, 56, 90	3 each age
	Rapid chloride permeability	ASTM C1202	28, 90	2
	Formation factor (via Bucket Test)	Protocol by J. Weiss, Oregon State University (Weiss 2018)	35	2
	Shrinkage	ASTM C157	Per standard	3
	Freeze-thaw durability	ASTM C666 (proc. A)	Per standard	3
	Hardened air content	ASTM C457 (automated)	N/A	2


Compressive/Flex Strength

- Compressive and flexural strengths were roughly equivalent between optimized and non-optimized mixtures



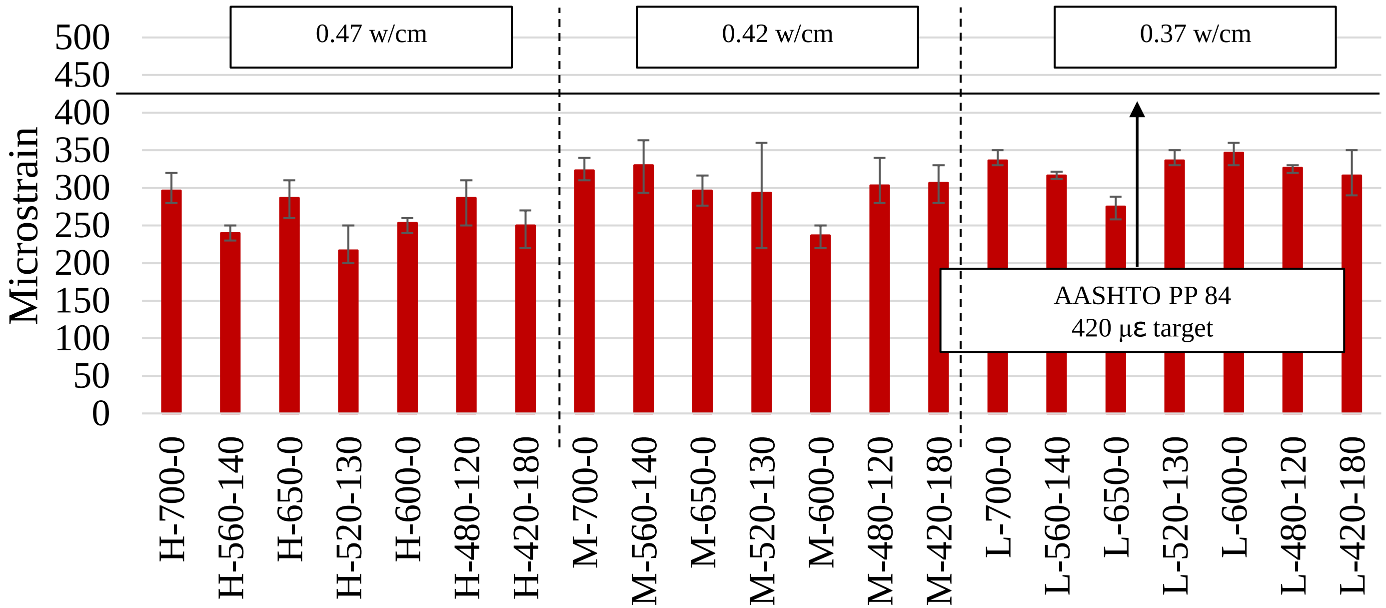


- Indicates that current NCDOT specifications could reasonably be met by mixtures containing a 10% reduction in cementitious materials and a 2-3% reduction in paste volume.

- This could offer both cost savings and other sustainability benefits.

Volumetric Shrinkage

- Optimized aggregate gradation mixtures:
  - met the AASHTO PP 84 suggested limit of 420 με at 28-days.
  - had higher average 28-day volumetric shrinkage than companion non-optimized aggregate gradation mixtures.
  - but had lower average volumetric shrinkage than non-optimized aggregate by the 32-week measurement.

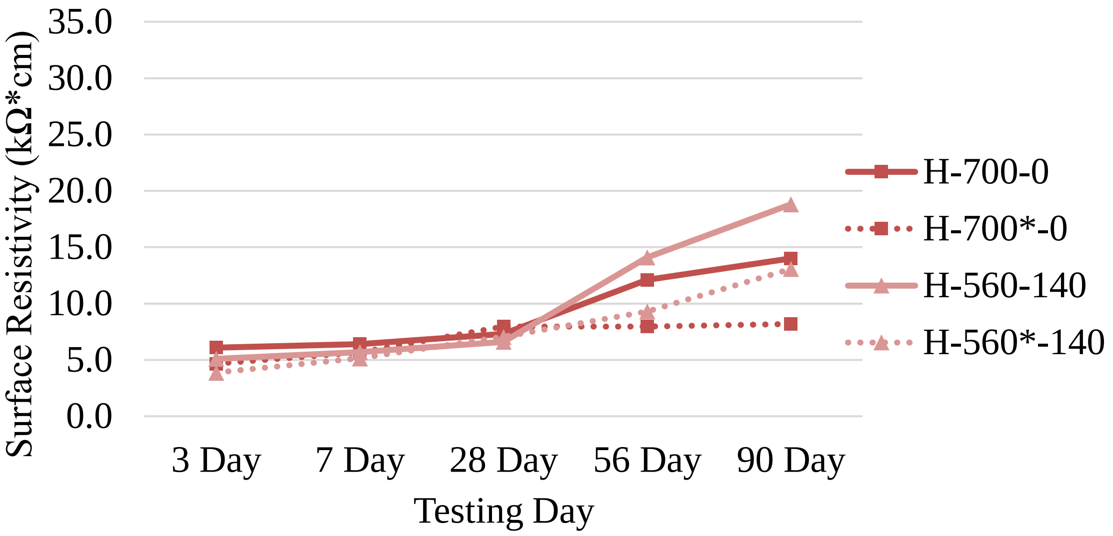


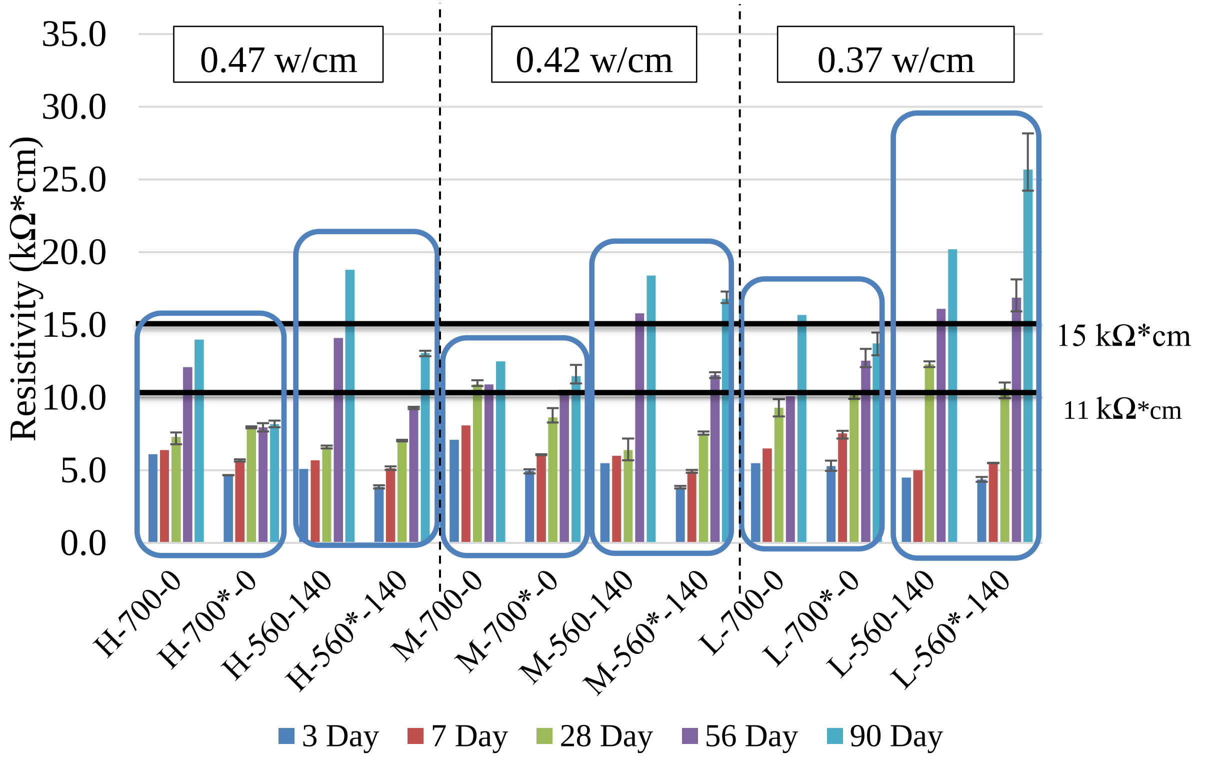
28-day volumetric shrinkage for optimized aggregate gradation mixtures

w/cm ratio	Mixture type	28 Day (με)	8 Week (με)	16 Week (με)	32 Week (με)
0.47	Non-optimized	277	348	429	709
	Optimized	342	470	550	617
	Average percent difference	17.7%	24.9%	20.8%	-17.3%
0.42	Non-optimized	300	369	427	750
	Optimized	385	502	552	592
	Average percent difference	21.4%	26.0%	22.3%	-29.5%
0.37	Non-optimized	318	398	476	852
	Optimized	388	490	554	587
	Average percent difference	18.0%	18.5%	14.0%	-94.3%

Surface Resistivity

- Average surface resistivity test results for optimized aggregate gradation mixtures were typically lower than the companion non-optimized aggregate gradation mixtures.
- Electrical test results may be influenced by the increased volume of the ITZ, the increased aggregate volume, or other factors.





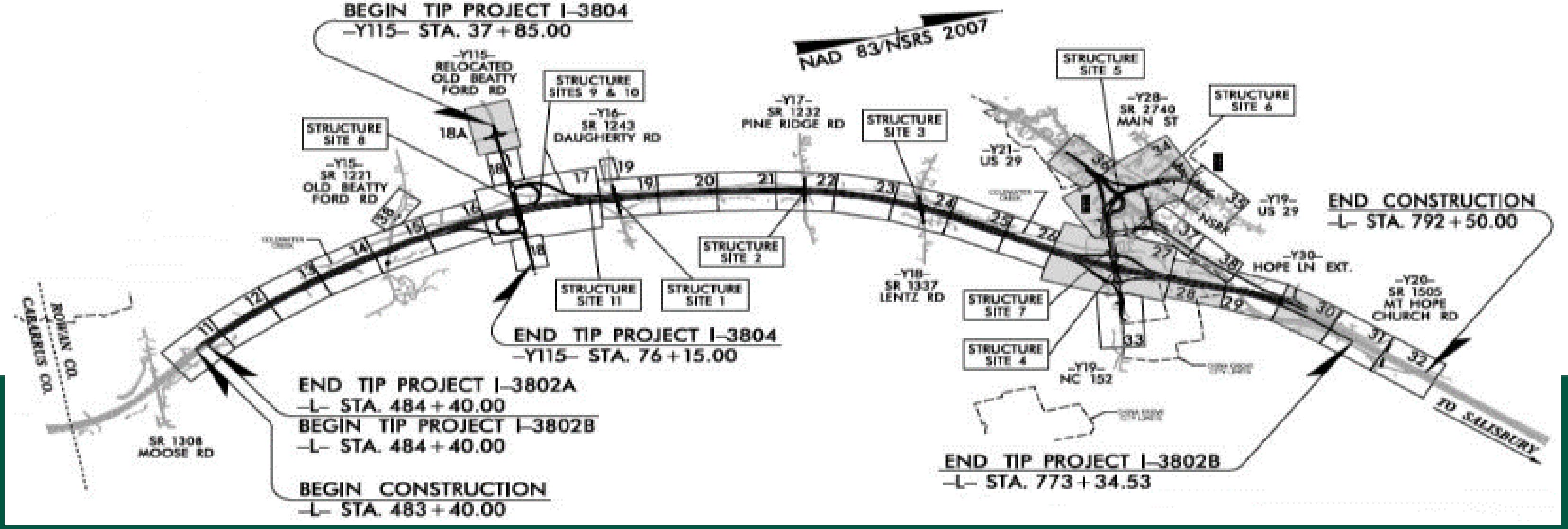
- Avg. surface resistivity of all mixtures improved as the w/cm ratio decreased at later age tests.
- Influence of fly ash in improving surface resistivity was more pronounced at lower w/cm

RP 2020-13

PEM Pilot Project – Structural Concrete

FHWA Implementation Project – Concrete Pavement

- I-85 widening project north of Charlotte, NC
  - 5.3 miles long
  - Existing 4-lane interstate widened to provide 4 additional travel lanes (2 lanes in each direction)
  - 500,000 SY of concrete pavement construction (12” thick JPCP)
  - Two phases:
    - April 2018 to September 2018
    - April 2019 to October 2019



LANE

Structural Pilot Project Implementation

- I-485 widening project south of Charlotte, NC
  - 18.2 miles long
  - High-occupancy toll (HOT) lanes along entire stretch of roadway
  - 17 structures, 15.3 miles of new sound wall
  - 3 year duration
- Concrete Supply Co. provided most structural mixtures
  - AA, Drilled Pier, A
- PEM Shadow Testing
  - SAM, surface resistivity, shrinkage
  - Spring/Summer/Fall 2021

BLYTHE

CONCRETE SUPPLY CO.

SUMMIT DESIGN AND ENGINEERING SERVICES

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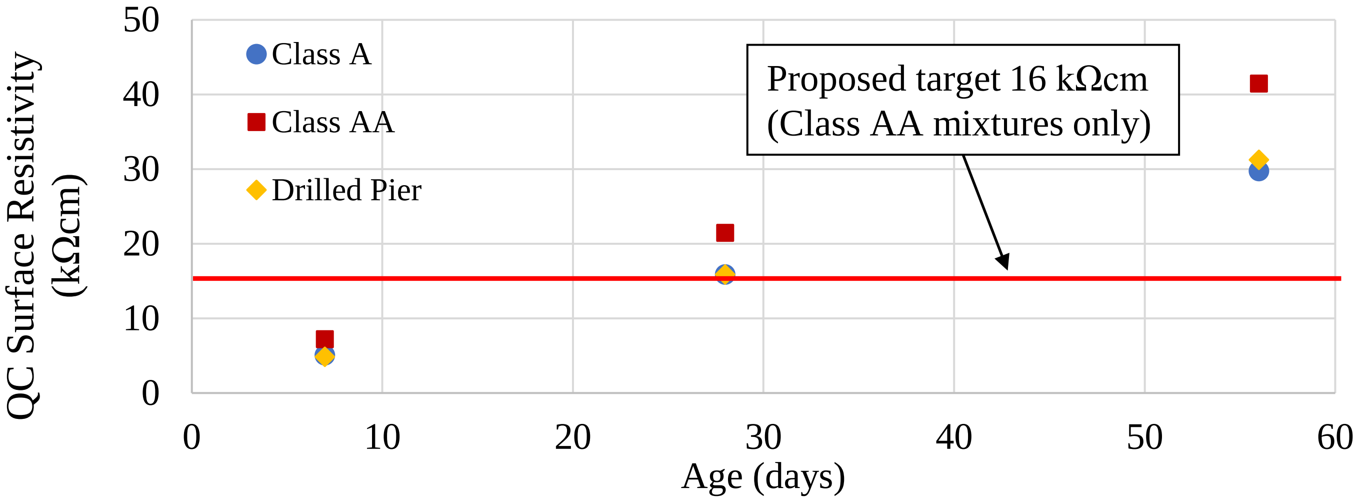
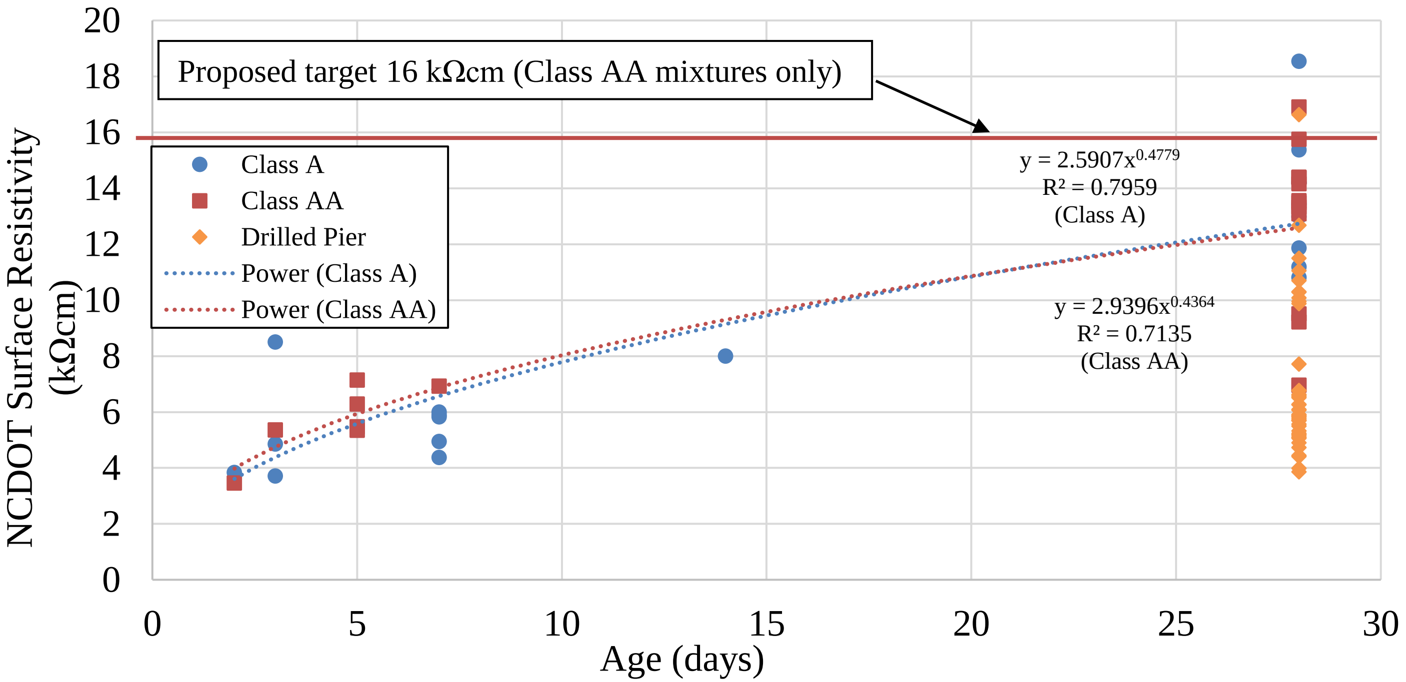
RK&K

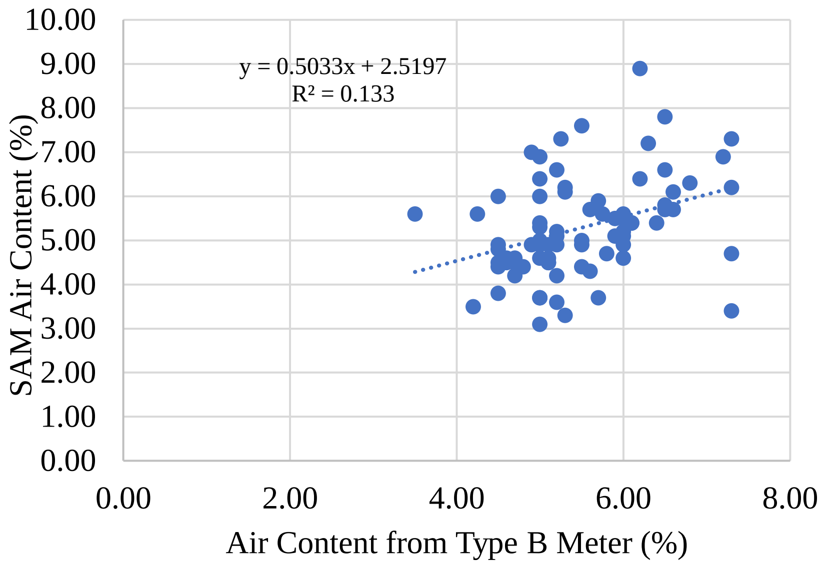
Pilot Project Implementation – Surface Resistivity

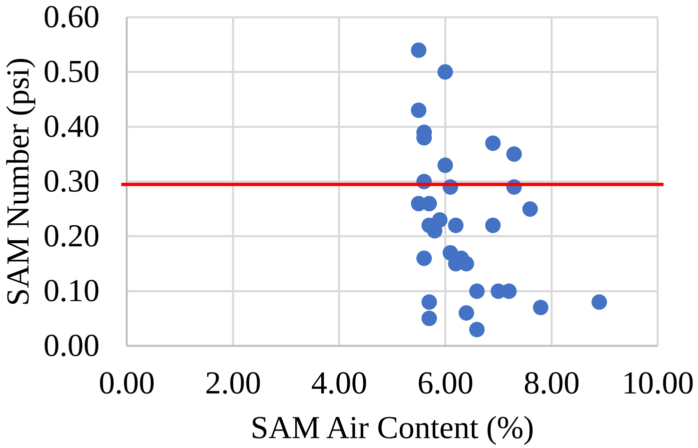

Proposed target 16 kΩcm (Class AA mixtures only)


Proposed target 16 kΩcm (Class AA mixtures only)

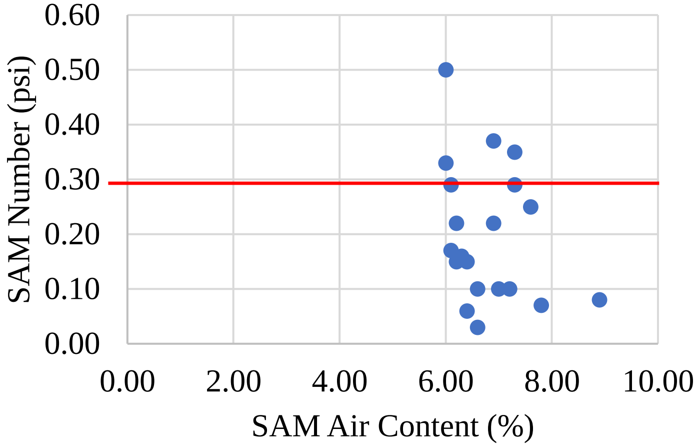
- QC tests
  - Class A, Class AA, and drilled shaft mixtures exhibit low to very low permeability to chloride ions.
  - Mixtures included approximately 20% fly ash.
  - Proposed target of 16 kΩcm was readily met by the Class AA mixture by 28 days and was nearly met by the other two mixtures at 28 days.
  - All well exceeded the target by 56 days.
- NCDOT “acceptance” tests
  - Taken up to ages of 28 days due to limitations in curing storage.
  - The 28-day resistivity measurements provide reasonable confidence that the 16 kΩcm will be met by these mixtures used on pilot project components sometime after 28 days.

Pilot Project Implementation – Super Air Meter

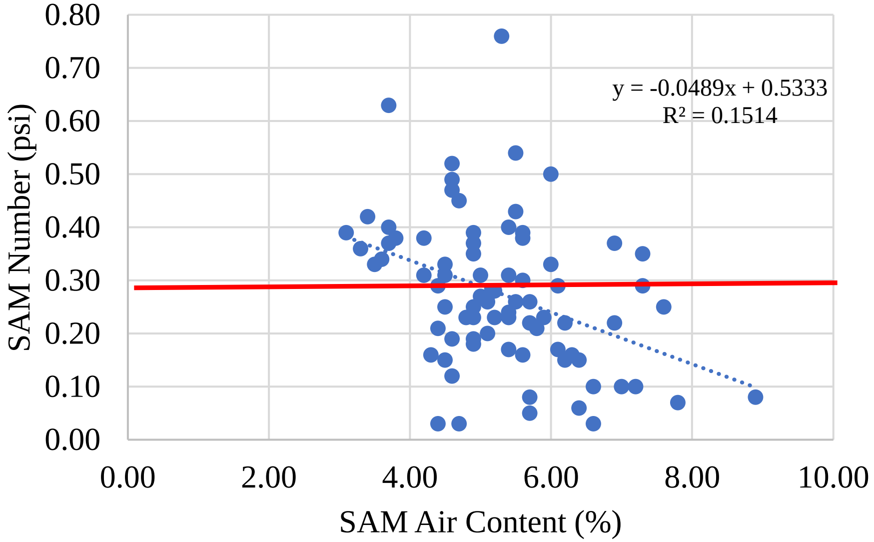




Mixtures with air content >5.5%



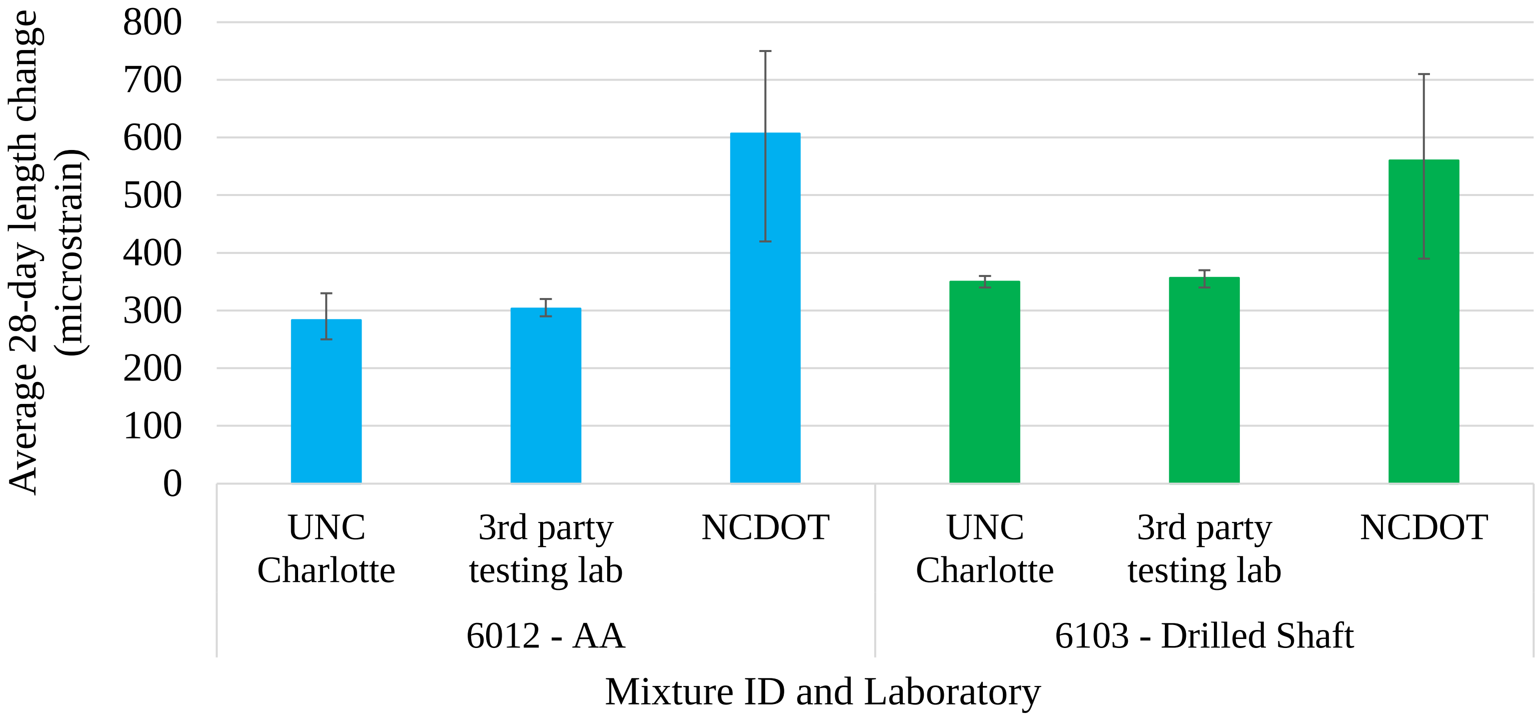
Mixtures with air content >6.0%



- Quality of data obtained from the SAM improved as part of this pilot project, with lower variability observed than during the previous pilot project.
- Likely the result of a training session provided by the device developer, with focus on training the technicians responsible for testing.
- A limited number of technicians also obtained the data.

- Proposed SAM target of 0.30 appears to have been reasonably met with mixtures with air contents greater than 6%.

Pilot Project Implementation – Shrinkage



- ASTM C157 28-day shrinkage targets (less than 400 microstrain) appeared to be reasonably met by the two structural mixtures, as tested by UNC Charlotte and a third-party laboratory.

- Additional training may be needed to support deployment of this PEM test on a wider basis.

Pilot Project Findings and Benefits

- Performance criteria for the targeted technologies (surface resistivity, SAM, and shrinkage) from previous studies appear reasonable for use in future PEM projects.

- Spreadsheet tools and other resources that can be used by NCDOT personnel, Resident Engineers, contractors and other stakeholders potentially involved in PEM.

- NCDOT and contractor insight from implementation of PEM shadow specifications and PEM tests at a structural concrete pilot project.

Recommendations

- PEM tests offer means to evaluate durability performance and proposed (targets for the most part) appear reasonable.
  - Surface resistivity is a rapid, easy test that offers many benefits.

- Encourage the use of optimized aggregate gradation approaches to achieve the durability and sustainability benefits associated with reduced cementitious materials and paste contents.

- Encourage increased use of SCMs such as fly ash at higher replacement rates to provide improved durability performance and hence, long-term economic and environmental benefits.

- Prescriptive specification provisions such as w/cm ratios and cementitious materials contents should be revisited.
  - The importance of controlling w/cm in achieving the desired mechanical properties and durability performance was demonstrated by this study, as well as previous studies. Minimum cementitious contents for many mixtures could be reduced.

Future work

1. Steps needed to support surface resistivity implementation
2. Engaging more stakeholders: learning about and using PEM approaches/technologies
3. Quantifying the benefits of PEM

- Targeted laboratory study to support surface resistivity implementation
    - 28-day surface resistivity targets that provide a high likelihood of meeting resistivity targets at later ages.
    - Resistivity targets for optimized aggregate gradation mixtures

- Economic and sustainability assessment of NCDOT concrete infrastructure.
    - Life cycle cost analysis (LCCA) would provide measures of cost savings achieved by PEM for pavement and structural concrete
    - Life cycle assessment (LCA) would provide measures of sustainability benefits (environmental, societal) achieved by PEM for pavement and structural concrete

- Additional PEM pilot projects for both pavement and structural concrete.

Thank you!

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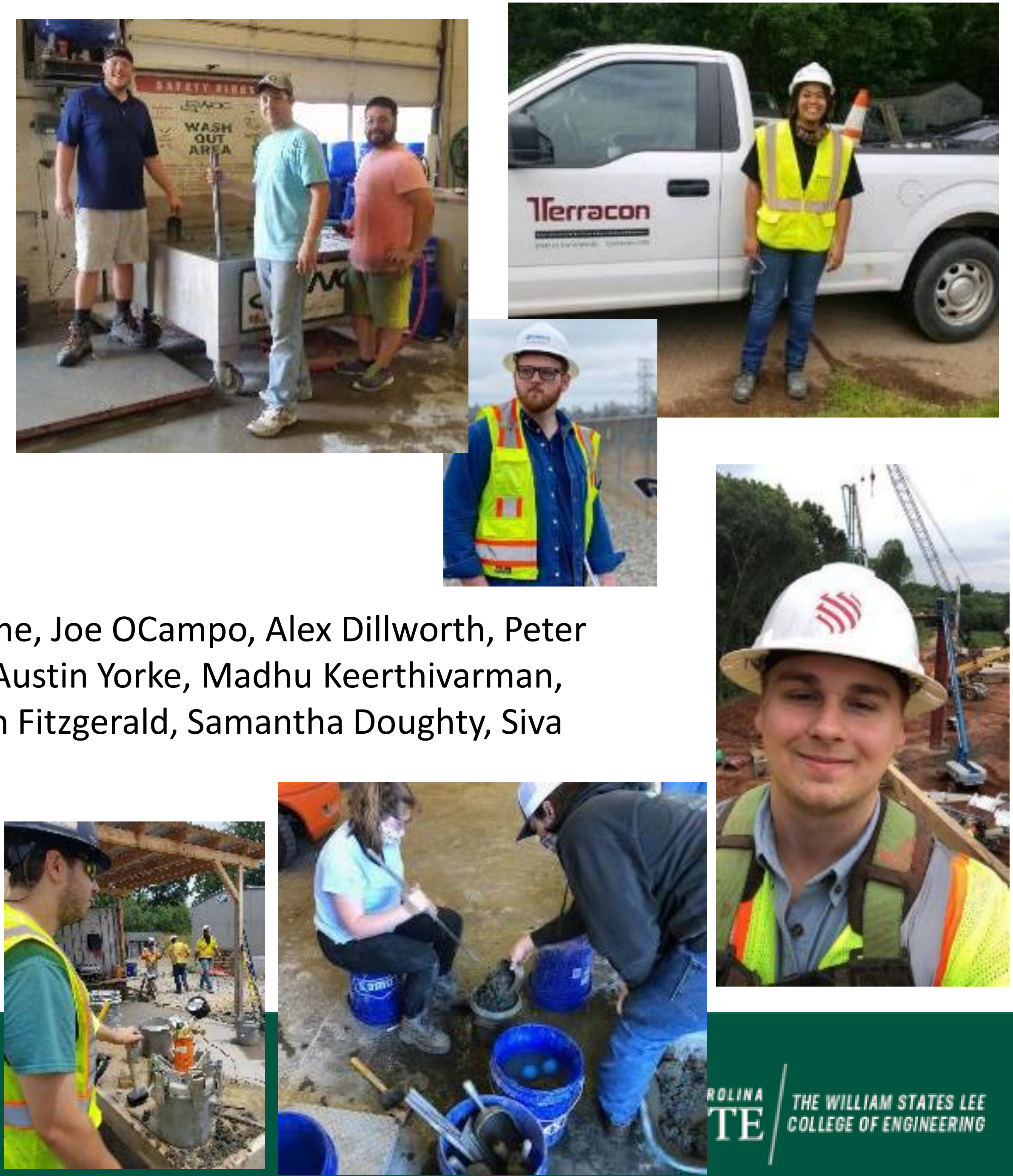


Conclusions – Fresh Properties

- Optimized aggregate gradation concrete mixtures had lower slumps than the companion non-optimized mixtures, with higher cement content mixtures requiring less WRA to achieve target slump.

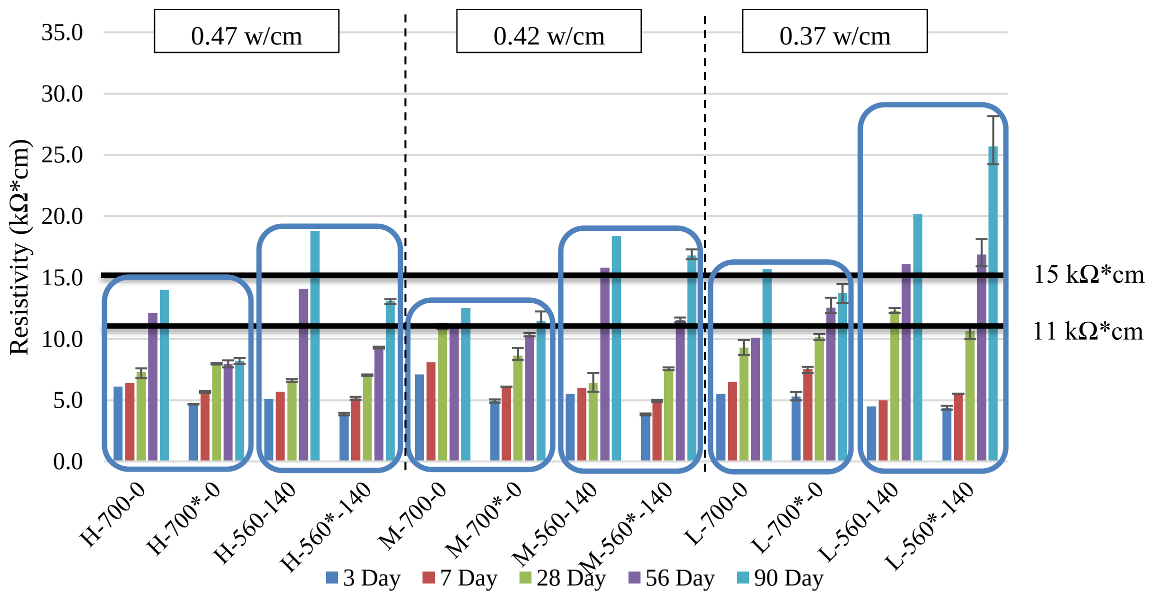
- Low (0.37) w/cm ratio and low (600* pcy) cementitious material content optimized aggregate gradation mixtures required the most AEA to achieve the target range for entrained air.

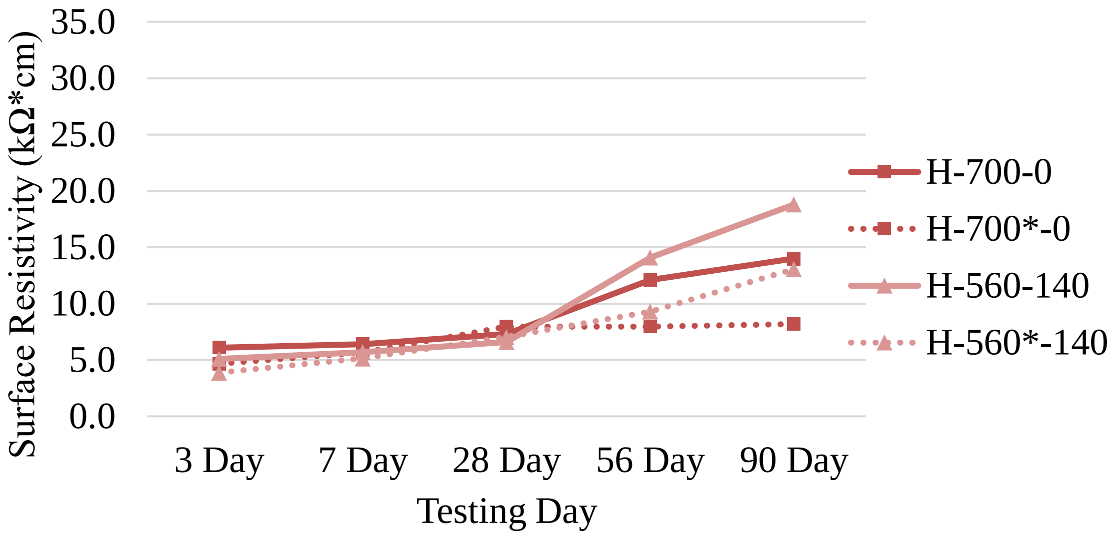
- Optimized aggregate gradation mixtures typically had a slightly higher unit weight than the companion non-optimized aggregate gradation mixtures.

Conclusions

- Mechanical properties of optimized aggregate gradation straight cement mixtures were negligibly impacted at all testing dates.
- Mechanical properties and durability performance of both non-optimized and optimized aggregate gradation mixtures improved as the w/cm ratio decreased.
- Fly ash mixtures at 30% replacement rates showed negligible impact to mechanical properties for tests past 28-days, as well as improved durability performance.
- Electrical test results for optimized aggregate gradation mixture may not be directly comparable to those for conventional mixtures. Proposed surface resistivity targets may need to be adjusted for optimized aggregate gradation mixtures.
- Benefits of reduced drying shrinkage from optimized gradation mixtures may not be evident using 28-day test results.

Surface Resistivity

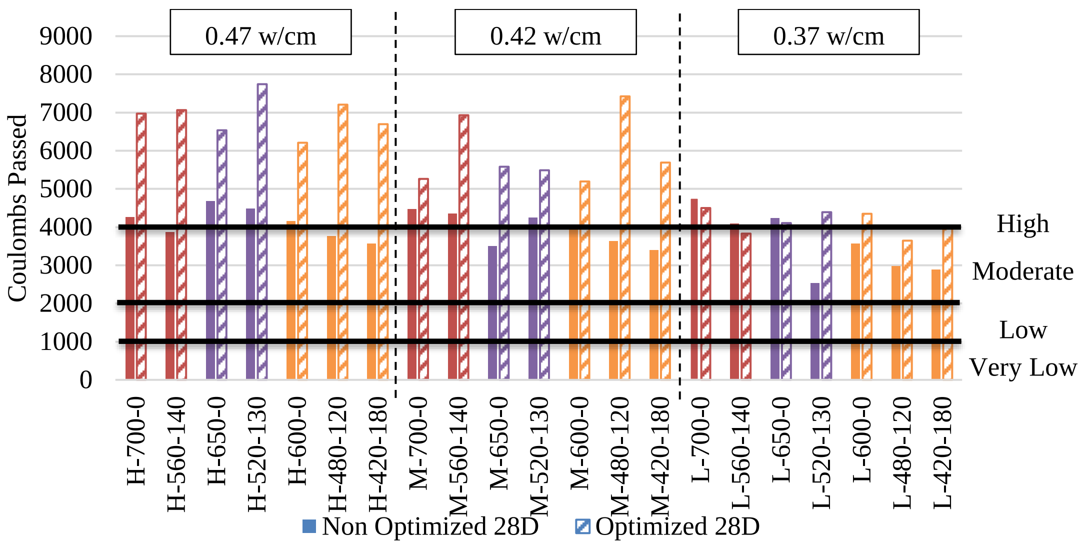


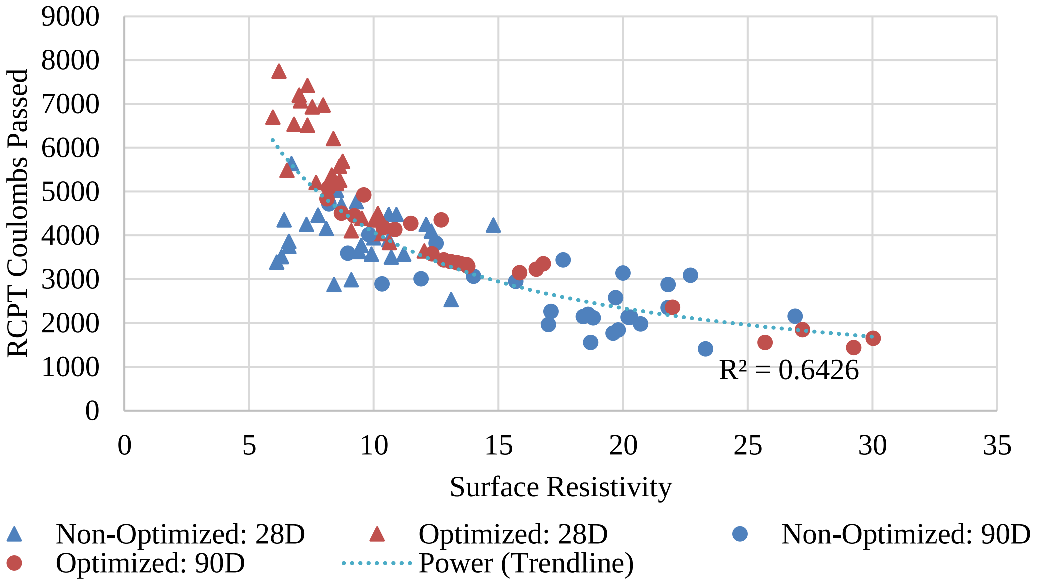


w/cm ratio	Test Day				
	3 Day	7 Day	28 Day	56 Day	90 Day
0.47	-31.4%	-11.7%	7.4%	-51.8%	-57.4%
0.42	-43.4%	-27.5%	-5.7%	-21.1%	-9.2%
0.37	-3.4%	11.5%	-3.7%	12.0%	3.5%

- Average surface resistivity test results for optimized aggregate gradation mixtures were typically lower than the companion non-optimized aggregate gradation mixtures.
    - Avg. surface resistivity of optimized and non-optimized aggregate gradation mixtures improved as the w/cm ratio decreased at later age tests. Non-optimized aggregate gradation mixtures exhibited this trend by the 28-day tests while optimized aggregate gradation mixtures exhibited this trend at all test dates.
    - Avg. surface resistivity results of optimized aggregate gradation mixtures with fly ash had similar resistivities than the companion non-optimized aggregate gradation straight cement mixtures by the 56-day tests (4.5% lower) and had higher average surface resistivities by the 90-day tests (7.2% higher).
    - These electrical test results may be influenced by the increased volume of the ITZ, the increased aggregate volume, or other factors. Additional study is recommended to better understand these results.

Rapid Chloride Permeability Test



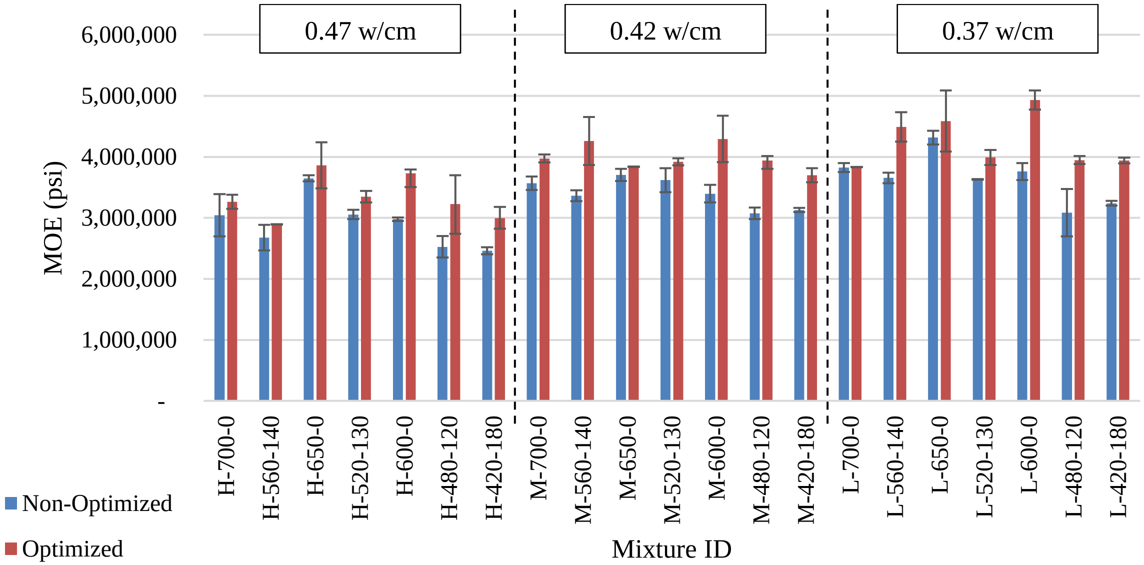


Cementitious Content (pcy)	Mixture Type	Test Day	
		28 Day (Coulombs)	90 Day (Coulombs)
700	Non-optimized	4301	2707
	Optimized	5760	3501
	Average percent difference	20.6%	16.4%
650	Non-optimized	3949	2611
	Optimized	5641	3557
	Average percent difference	28.2%	26.9%
600	Non-optimized	3544	2226
	Optimized	5605	3104
	Average percent difference	34.2%	23.3%

- RCPT results of optimized aggregate gradation mixtures were typically higher than the companion non-optimized aggregate gradation mixtures at both 28- and 90-day tests.

- These electrical test results may be influenced by the increased volume of the ITZ, the increased aggregate volume, or other factors. Additional study is recommended to better understand these results.

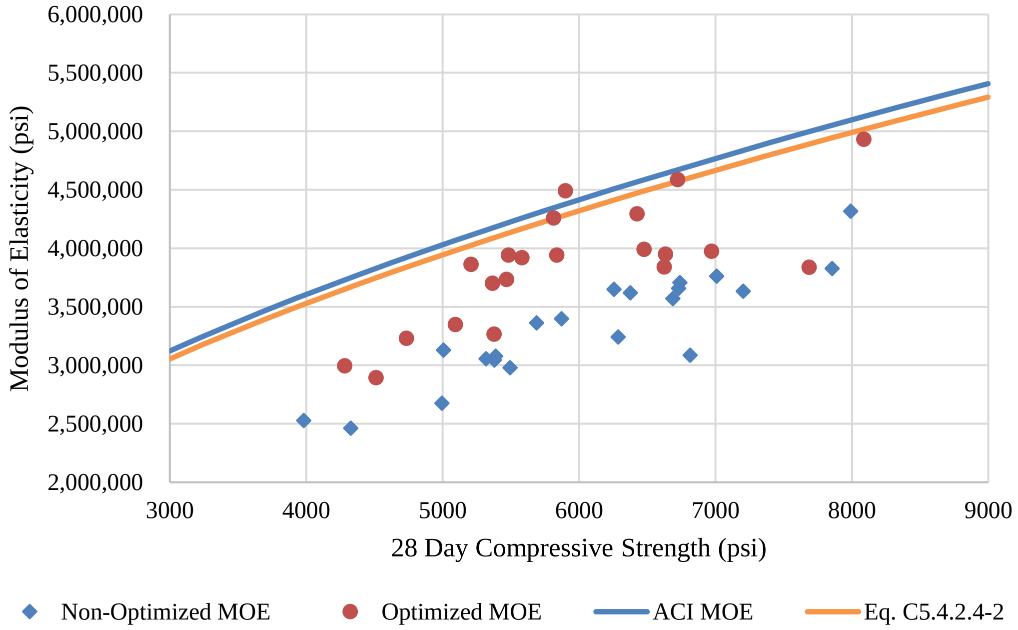
Modulus of Elasticity



Cementitious content (pcy)	Mixture characteristic	Non-optimized	Optimized
700	All mixtures	3,356,000	3,788,000
	Straight cement	3,480,000	3,693,000
	Fly Ash replacement	3,231,000	3,882,000
650	All mixtures	3,664,000	3,926,000
	Straight cement	3,891,000	4,097,000
	Fly ash replacement	3,436,000	3,754,000
600	All mixtures	3,074,000	3,857,000
	Straight cement	3,380,000	4,320,000
	Fly ash replacement	2,921,000	3,626,000

- Measured 28-day MOE values of optimized aggregate gradation mixtures were 13.6% higher than companion non-optimized aggregate gradation mixtures

- Average 28-day MOE values of optimized aggregate gradation mixtures were 14.3% lower than the MOE calculated using the ACI 318 equation; 11.9% lower than the MOE calculated with AASHTO LFRD equation C5.4.2.4-2. These differences were roughly consistent across all optimized aggregate gradation straight cement and fly ash mixtures.



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Freeze-Thaw Durability

Conclusions – Freeze-Thaw Durability

- NCDOT structural and pavement mixtures are very resistant to freeze-thaw stresses.
    - After 300 cycles of ASTM C666 testing, only 6 of the 56 mixtures exhibited a DF below 80 and only 2 falling below ASTM C666's performance threshold DF of 60.

- Spacing factor limit of 0.008 in (200 μm) likley too conservative for use in NCDOT specification.
    - Many mixtures exhibiting good to excellent freeze-thaw durability performance in the ASTM C666 test had spacing factors that exceeded this target.
    - Since most concrete mixtures included in this study exhibited DFs greater than 80, a proposed target spacing factor could not be identified.

- Findings were significantly limited by the range of air contents (5 to 6%) used in the mixtures. A more comprehensive study should be performed using a wider range of air contents (such as 2% to 10%).

- Analysis of field-produced concrete should also be paired with additional laboratory testing of to further explore the SAM number, in hopes of expanding the types of materials and mixtures used to identify the performance target. Alternatively, a target of 0.30 appears reasonable based on previous study (Ojo, 2018)

Freeze-Thaw Durability

- NCDOT mixtures historically show good freeze-thaw durability in service
- SAM device used on fresh concrete to support evaluation of air void system parameters
    - Correlates to ASTM C666 freeze-thaw test
    - Correlates to hardened air void spacing factor

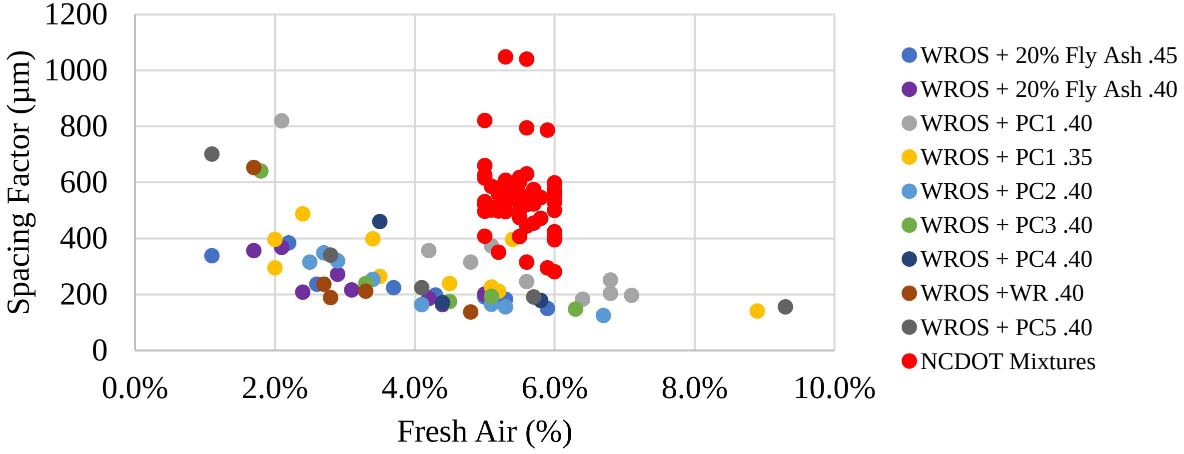
- SAM, conventional air tests, freeze-thaw test results from multiple studies compared (RP 2015-03, RP 2016-06, RP 2018-14, RP 2020-13)
- New testing performed to determine spacing factor of hardened concrete
- Results compared to identify trends, suggest target for SAM

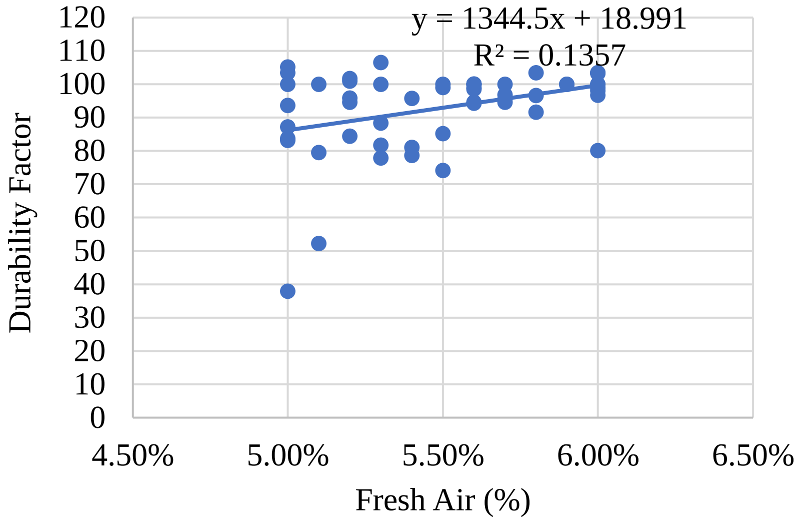
Hardened Air Void System Analysis

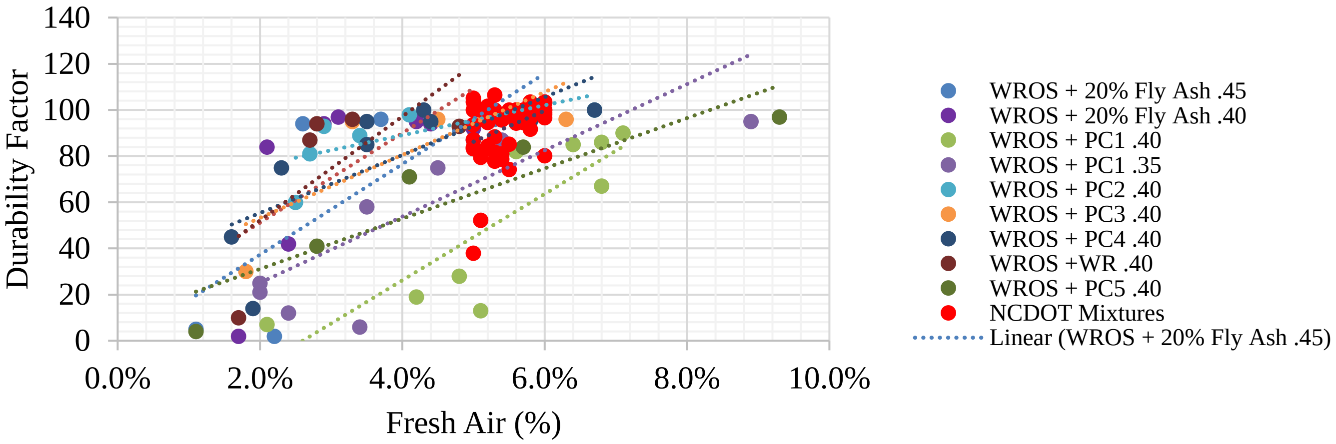
		
Figure 4.1a: Specimen cast for hardened air void analysis	Figure 4.1b: Specimen sawcut, prior to polishing	Figure 4.1c: Specimen after face is polished using progressively finer grit

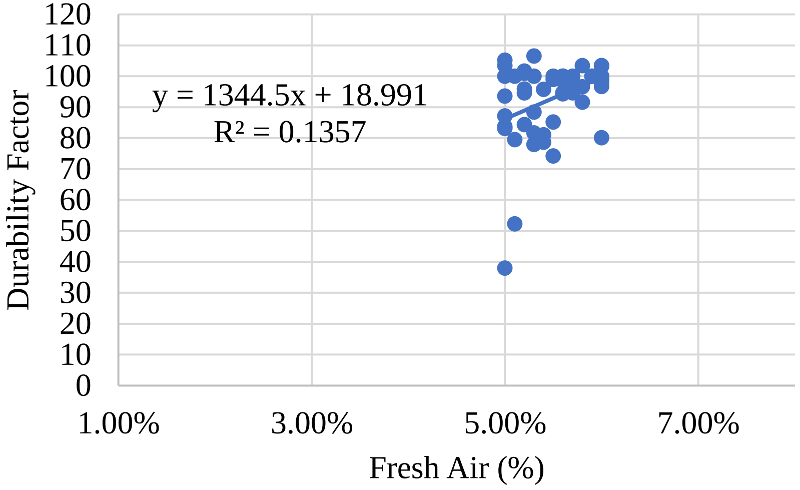
		
Figure 4.2a: Treated specimen prior to scanning. Note the limited number of white air voids visible	Figure 4.2b: Treated specimen prior to scanning. Note the presence of more air voids than in the specimen shown in Figure 4.2a	Figure 4.2c: Scanned image of sample with black and white contrast card (UNC Charlotte ID card) along with Bubble Counter system parameters

Air Void System Analysis

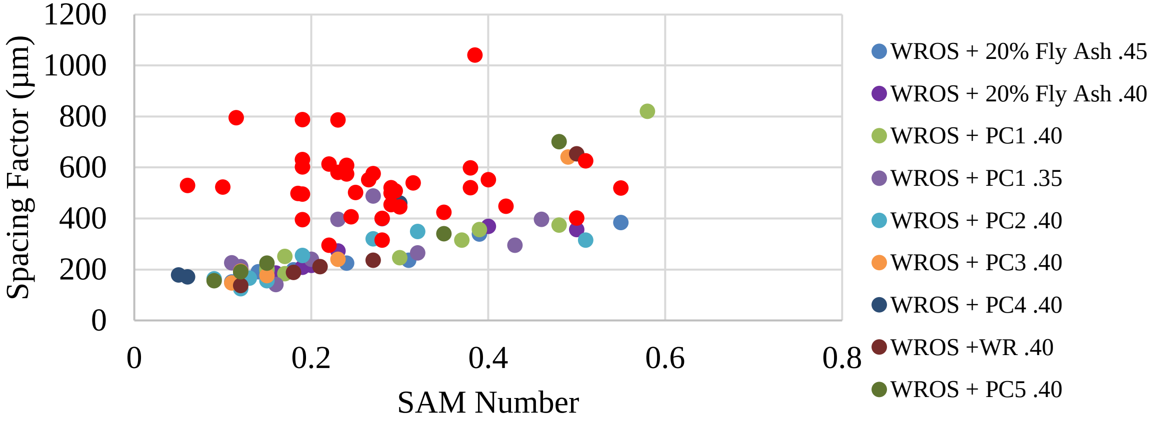


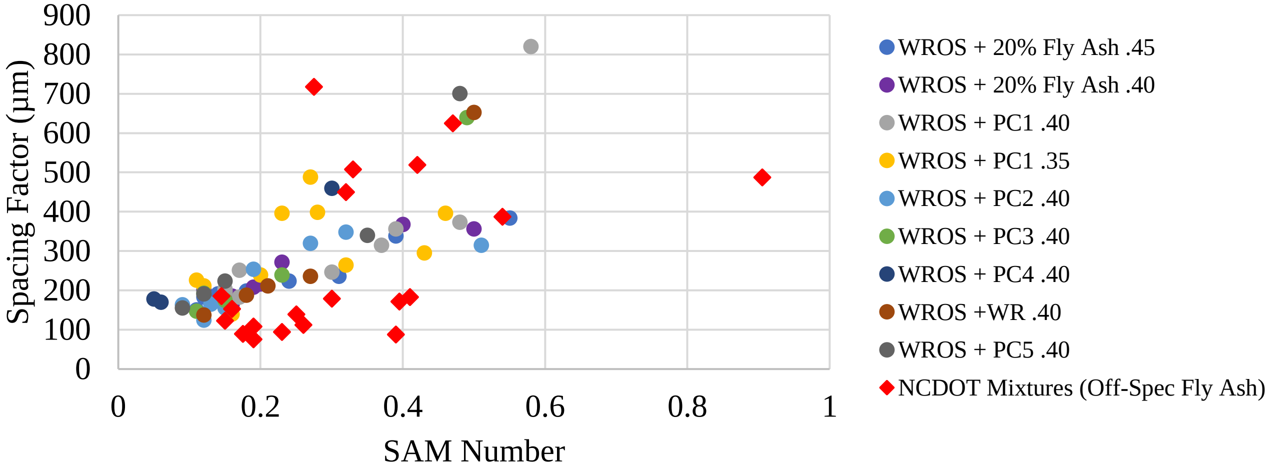






SAM test results





- SAM numbers obtained during studies of NCDOT concrete at UNC Charlotte exhibited a lesser correlation to the DF. The strong relationship between SAM number and spacing factor observed in other studies was not observed based on findings of this work.

- Variability in the SAM measurements was likely increased due to use of multiple devices, operators, and materials. Variability also exists in the spacing factor measurements, which could have affected the ability to observe meaningful correlations.