TRANSPORTATION RESEARCH
CIRCULAR

Number E-C287 February 2024

Using Performance Engineered Mixtures to Improve Pavement Performance and Sustainability

State Experiences

NATIONAL ACADEMIES *Sciences Engineering Medicine*

TRB TRANSPORTATION RESEARCH BOARD

TRANSPORTATION RESEARCH CIRCULAR E-C287

Using Performance Engineered Mixtures to Improve Pavement Performance and Sustainability

State Experiences

February 2024

Transportation Research Board
Washington, DC
www.trb.org

TRANSPORTATION RESEARCH CIRCULAR E-C287
ISSN 0097-8515

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to provide leadership in transportation improvements and innovation through trusted, timely, impartial, and evidence-based information exchange, research, and advice regarding all modes of transportation.

The **Transportation Research Board** is distributing this E-Circular to make the information contained herein available for use by individual practitioners in state and local transportation agencies, researchers in academic institutions, and other members of the transportation research community. The information in this E-Circular was taken directly from the submission of the authors. This document is not a report of the National Academies of Sciences, Engineering, and Medicine.

Contents

The TRB Standing Committee AKC50 Concrete Pavement Construction and Rehabilitation would like to acknowledge the following individuals for their contributions.

Prepared by: Gordon Smith (Gordon J. Smith Consulting, Ltd.), Leif Wathne (Concrete Pavement Tech Center), Todd Hanson (Iowa Concrete Paving Association), Maria Masten (Minnesota DOT), Signe Reichelt (Behnke Materials Engineering-Wisconsin), Ethan Bahmer (Michigan DOT), Nick Davis (International Grooving and Grinding Association-New York), Tara L. Cavalline and Brett Q. Tempest (UNC Charlotte), and Brian J. Hunter (North Carolina DOT).

Edited By: Jerod Gross (Snyder and Associates), Jagan Gudimettla and Jim Grove (ATI, Inc.), Mike Praul and Bob Conway (FHWA).

Summary

The Performance Engineered Concrete Paving Mixtures Transportation Pooled Fund (TPF-5(368)) has introduced state highway agencies to new and improved tests and technologies that measure engineering properties that are much more closely related to a pavement's long-term field performance than traditional approaches. This significant advancement in testing technologies allows for a shift away from prescriptive requirements like strength, slump, and total air content, toward performance-related criteria that are much better indicators of durability, such as transport properties, shrinkage, freeze-thaw resistance, and workability.

To encourage adoption of performance engineered mixtures (PEM) concepts, the FHWA offered various levels of incentive funding to state agencies to help offset the costs of additional shadow testing, data collection, and reporting. The intent of the shadow projects was to give state agencies exposure to PEM and new testing methods, with each state agency selecting an approach to implement PEM requirements that met their local conditions and contracting environment. Seven of the 19 pooled-fund states accepted incentive funding, and results from six of those states are presented in the subsequent sections of this circular.

In broad strokes, the majority of state agencies recognized benefits of implementing PEM concepts as part of the shadow projects, although the benefits experienced varied across states. Further, four of these six states hosted open houses to offer an opportunity to agency and industry to receive technology transfer through a brief classroom style discussion as well as exposure to PEM testing showcased by the Mobile Concrete Technology Center (MCTC). Some important highlights from six of the states' PEM pilot projects are as follows.

Iowa

PEM concepts enabled the Iowa Department of Transportation (DOT) to improve sustainability of their paving mixtures. Contractors were pleased with the PEM results and continued shadow testing on follow-on projects to maintain proficiency. PEM concepts reduced cement content (lowered cost and reduced carbon footprint) and also improved pavement smoothness.

Future implementation plans include getting more contractors involved and continuing to gather information, especially with other aggregate combinations. Iowa DOT also plans to update current concrete mixture specifications for paving (QMC) to include PEM tests (such as Super Air Meter [SAM], Box and Resistivity) and to allow for reduced cement content mixtures.

Minnesota

The implementation of PEM on these projects was an opportunity to familiarize the Minnesota Department of Transportation (MnDOT) and contractor personnel with PEM testing, especially the SAM and maturity testing. MnDOT believes that the SAM provides real-time results regarding the freeze-thaw durability of the concrete pavement. Through internal MnDOT testing and the PEM projects utilizing the SAM, MnDOT has determined that air content testing is not needed after the concrete paver and has removed the requirements from the specifications. MnDOT has also been researching the use of the Phoenix testing equipment for measuring the water content in the concrete. This device would replace the microwave oven testing equipment as MnDOT believes that controlling and measuring the water-cement (w/c) ratio of the concrete in the field during construction is a key part to achieving durable and long-lasting concrete mixtures. While the Phoenix test equipment was not utilized in this PEM research, MnDOT has used it on other paving projects with good results and will be incorporating it into a pilot project in the near future. One accomplishment not shown in test data is the level of collaboration—everyone involved worked well together in training and performing the tests and collecting the test data. Overall, the PEM testing went well on these projects. The effort helped to educate MnDOT personnel and the contractor on the use and effectiveness of PEM.

Wisconsin

Wisconsin's PEM efforts focused largely on optimized aggregate gradations. As a result of PEM testing, the Wisconsin Department of Transportation (WisDOT) has implemented optimized aggregate gradations in the 2022 specifications. WisDOT is also requiring SAM test results be included with mixture submittals to help assure a freeze-thaw resistant air-void system and required resistivity for information purposes only.

Michigan

Both the Michigan Department of Transportation (MDOT) and industry personnel found that the PEM pilot projects were successful. Optimized aggregate gradations have been readily accepted by both MDOT and the industry. Both MDOT and the industry have seen benefits from using optimized aggregates, including a decrease in permeability and an increase in strength and workability. The industry also brought to MDOT's attention that the use of optimized aggregate gradations helped create a more consistent concrete mixture.

Although some PEM concepts have already been incorporated into MDOT specifications, there was some initial hesitation about embracing PEM testing protocols like SAM and resistivity. However, as both industry and MDOT personnel increased their understanding of and familiarity with the technologies, they began to embrace them. MDOT suggests that the use of PEM concepts will not only be a best practice but a necessity moving forward.

New York State

The overall goal of the New York State Department of Transportation's (NYSDOT) PEM effort is to reduce the carbon footprint without impacting the quality and lifespan of the concrete on their projects. Optimized gradations in the performance engineered mixtures developed for the PEM pilot project enabled a significant reduction in cement use (30%). As a result of this effort NYSDOT intends to use only optimized gradations (based on the 'Tarantula Curve') moving forward. NYSDOT is continuing to work with contractors and material suppliers to advance PEM concepts in DOT specifications. NYSDOT currently has a number of ongoing PEM projects as a means to address any issues or concerns before PEM becomes the standard for all projects.

North Carolina

The North Carolina Department of Transportation (NCDOT) views PEM concepts as a means to ensure new concrete pavements and structures meet their service life goals, while also reducing the resources required for maintenance. PEM is also a part of NCDOT's efforts to meet sustainability goals, allowing the agency to focus on improving the durability of its concrete mixtures while also promoting solutions that meet economic and material supply challenges.

NCDOT is primarily interested in moving toward implementation of surface resistivity, SAM, and shrinkage, along with some use of prescriptive water/cementitious materials ratios and cement contents. Surface resistivity would potentially be used for mixture approval and for acceptance. Training has resulted in an improvement in the quality of the data collected for the SAM. The contractor found the Box Test highly useful in assessing the workability of mixtures, and the test was performed each time the mixture was adjusted. NCDOT found implementation of the resistivity meter for acceptance testing straightforward and noted that the agency can equip laboratories with this device for a low cost. The contractor noted that they could accomplish the PEM tests without additional quality control (QC) personnel, and indicated they intend to use PEM tests on future projects. NCDOT notes that PEM will help them specify and construct the infrastructure it needs for the twenty-first century, and ongoing work is being performed to develop and refine proposed shadow specifications.

From these PEM pilot projects, it is clear that each agency's experience is unique, and improvements and benefits are a function of each state's current state of practice. Most of the state agencies participating in the PEM pooled fund recognize the opportunity that PEM provides to reduce paste content in their concrete paving mixtures by using optimized aggregate gradations. The resulting reduction in cement content, lowered cost, and enhanced sustainability were clear benefits to both agency and industry. Improved freeze-thaw durability via lower permeability was also a focus of these PEM pilot projects. Some agencies noted that although initially hesitant, if not resistant, the industry quickly recognized the significant advantages offered by embracing PEM concepts, including improved consistency, better smoothness, and greater workability. The projects also afforded an opportunity for industry and agency to partner more closely and collaborate more effectively.

Every one of the agencies participating in the PEM pilot projects indicated that they are either pursuing updates to their concrete specifications with PEM concepts, planning additional pilot projects, or recognizing that PEM concepts are the future of concrete paving specification moving forward. This seems to confirm that the PEM initiative has in fact resulted in beneficial changes in the way concrete paving mixtures are designed, monitored, and accepted, resulting in more durable and economical concrete pavements, that also enhance their overall sustainability.

Introduction

Historically in the United States, concrete for pavements is field controlled around acceptance criteria that do not corelate well to durability (slump, total air content, and strength). Concrete pavement specifications need to be built upon engineering properties that relate more closely to field performance. As a result of the evolution of concrete testing technologies in the past decade or so, owners, suppliers, and contractors have new tools to test and monitor concrete characteristics. The characteristics offer the advantage of correlating better to field performance in service.

A review of current and new concrete pavement specifications found that they are still largely based on strength, slump, and total air content, which provide limited to no correlation with the mechanisms of pavement failure typically observed. The need for a change in the way we specify concrete, especially concrete for paving mixtures, is becoming increasingly apparent as mixtures become more complex through a growing use of chemical admixtures and supplementary cementitious materials. Traffic loadings continue to increase, more aggressive winter maintenance practices are being implemented, and the demand to build systems quicker and cheaper, while at the same time increase longevity, presents challenges.

Since 2017, 19 state highway agencies (SHAs), FHWA, and the concrete pavement industry supported a 5-year Transportation Pooled Fund project focused on PEM. The objective was to work with an expert team assembled by the National Concrete Pavement Technology Center (CP Tech Center) to assist concrete practitioners, explaining how concrete paving mixtures can be engineered to meet performance requirements and how to incorporate key performance parameters into a robust specification and quality control/acceptance process.

The framework for the project was the AASHTO provisional practice (designated AASHTO PP 84-17), Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures. This provisional guidance has been refined throughout the PEM initiative and was recently adopted as a full AASHTO Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures (AASHTO Designation R 101-22).

The objectives of the PEM initiative were as follows:

- Task 1: Implementing What We Know
- Task 2: Performance Monitoring and Specification Refinement
- Task 3: Measuring and Relating Early Age Concrete Properties to Performance

The focus was on the following characteristics that make a difference in today's concrete mixtures:

- Aggregate stability
- Transport properties
- Cold weather durability
- Shrinkage
- Strength
- Workability

The PEM initiative has resulted in beneficial changes in the way concrete paving mixtures are designed, monitored and accepted, resulting in more durable and economical concrete pavements that are also more sustainable. Important and positive improvements in today's concrete pavements can be made through better understanding of what matters, tests to monitor those characteristics, and increased interest in assuring design and construction of long-lasting concrete pavements.

This circular documents recent improvements to promote improved concrete durability and changes to specifications to establish new protocols that can be used for performance-based criteria. The circular shares the experiences of several SHAs illustrating growing acceptance of PEM and acknowledging the benefits. Additional information about PEM advancements can be found on the FHWA and CP Tech Center websites.

Chapter 1

Iowa's PEM Experience

Overview

The Iowa DOT owns and maintains approximately 10,000 miles of highway pavement and 4,144 bridges. The majority of newly constructed pavements in Iowa have typically been Portland cement concrete (PCC), with a few PCC overlays. Iowa DOT relies on long-term durability of PCC pavements to reduce life-cycle costs, reduce maintenance, and improve safety to the traveling public.

Concrete paving specifications have evolved from early "cookbook designs" to the quality management concrete (QMC) mixtures in the late 1990s. The contractor is more involved on QMC projects—developing well graded aggregates using the Shilstone chart, submitting a quality control plan, and performing quality control testing during construction. Ternary cementitious materials, using blended cements and fly ash, have also been used in Iowa, which has allowed use of IS and IP cements since 1995. Over 1,000 lane miles of paving with IS cements have been constructed and over 250 lane miles of pavements with IP cements. Although Iowa has fairly advanced concrete specifications relative to many SHAs, PEM design and testing has allowed the DOT to further improve concrete pavement sustainability.

The Iowa DOT applied for funds through the Transportation Pooled Fund (TPF-5(368)) Performance Engineered Concrete Paving Mixtures to collect data and demonstrate the new tests. In 2018, the funds were used on a US 20 Woodbury County project that was being paved by Cedar Valley Corporation, LLC. The FHWA MCTC Laboratory was on the site to demonstrate the PEM test procedures. The contractor performed quality control testing, PEM shadow testing, and developed a reduced cement mix design, validated with the PEM testing. Fortunately for the Iowa DOT, the vice president of field operations at Cedar Valley Corporation became interested in the PEM program and has continued to perform shadow testing on several paving projects the past few years.

Demonstration Project

The project location was on US 20 in Woodbury County between Correctionville and Holstein. Ames Construction Inc. was awarded the $62.9 million contract for this stretch of US 20, which is divided into six construction segments. Cedar Valley Corporation, LLC is the paving subcontractor responsible for the US 20 paving.

PEM implementation funds were used for the following:

- Incorporation of the SAM, Box Test, VKelly, unit weight, bucket test, resistivity, and calcium oxychloride potential testing into the mixture design and approval process.
- Coordination between the Iowa DOT and CP Tech Center to obtain project materials and develop a mixture design for the contractor's Class A mixture used on the shoulder. Once the lab mixture parameters were established, the contractor did a field trial batch to include SAM testing and Box Test to validate the lab mixture. While the FHWA trailer was on the project, the Class A PEM modified mixture was used to compare with the contractor designed mix (QMC) they were currently using. The contractor performed SAM testing, Box Test, and resistivity testing (formation factor).
- The contractor provided an extra technician to perform additional sampling and testing for the remainder of QMC paving and 1 week of Modified PEM A mixture. These tests were performed as shadow tests only:
  - Plastic air and SAM test to support side-by-side comparison of QC air tests.
  - Plastic air and SAM test behind paver twice per week.
  - Temperature and unit weight twice per day.
  - One Box Test per day.
  - Cast one cylinder per day. The air content, SAM number, unit weight and temperature were recorded on the cylinder mold after casting. After initial testing by the contractor, cylinders were sent to the Central Laboratory for resistivity testing and for hardened air analysis. Since Iowa DOT's RapidAir457 equipment needed repairs, the hardened air analysis was performed by Oklahoma State University and Tyler Ley.
  - Resistivity testing was performed on concrete cylinders per AASHTO T 358 at ages of 7, 14, 28, 56, and 90 days. One set of cylinders was tested for calculation of the ionic penetration (formation factor) per Appendix X2 of AASHTO PP 84-17.
  - Calcium oxychloride potential was performed by the CP Tech Center. At time of this report, the LT-DSC was being repaired, so results were not available.
  - VKelly testing was performed by the CP Tech Center.
- The contractor performed QC testing using each of these methods and submitted these results to Iowa DOT. The contractor updated the US 20 quality control plan to include SAM meter testing, the Box Test, and the formation factor, with corrective action also added to the QC plan. In addition, the contractor included QC procedures for percent-within-limits (PWL) plastic air content (shadow testing only).

- Iowa DOT already requires control charts to plot aggregate combined gradations, air content before and after paver, unit weight, moistures, and w/c ratio. Iowa DOT added requirements for control charts for the SAM air test, SAM number, Box Test, and resistivity testing for this segment of the US 20 project. The contractor also monitored PWL for plastic air specification compliance (shadow testing only).

Mixture Design Characteristics

The contractor's mixture design was used for the PEM testing. The Iowa DOT QMC mixture design requires a well graded mixture in Zone II of the Shilstone coarseness and workability chart. The mixture is designed for 6% air content, a basic w/c ratio of 0.40 and MOR-TPL of 640 psi at 28 days. Contractors are required to perform quality control testing of QMC mixtures also. Table 1 summarizes the mixture design proportions for segment 4 of the US 20. For all mixtures, the air-entraining agent was Brett Admixture Eucon AEA92 and the water reducer was Brett Admixture Eucon WR 91.

Using the mixture proportions from the mixture design, the volume of paste was calculated. The paste volume for this mixture was 24.4%. To limit shrinkage and take advantage of other benefits such as lower cement/cementitious contents, and lower cost, it is recommended by AASHTO PP 84 to have a paste volume of less than 25%.

Table 1 Mixture Design Proportions

Material	Description/Source	Weight
Cement Type I/II	GCC, Pueblo PC2902	449 lb
Fly Ash	HW Class C, Nebraska City	112 lb
Coarse Aggregate	1" x #4 – A18528LG Everist Crocker	1382 lb
Intermediate Aggregate	3/8" – A47504 LG Everist Larrabee	378 lb
Fine Aggregate	Sand – A18514 LG Everist - Washta	1361 lb
Water	Municipal	224 lb

Figure 1 shows the combined aggregate grading on the Shilstone coarseness and workability factor graph. The workability and coarseness factor graph of the combined aggregate gradation fell in the optimal or well graded region. Figure 2 shows Cedar Valley Paving on US 20.

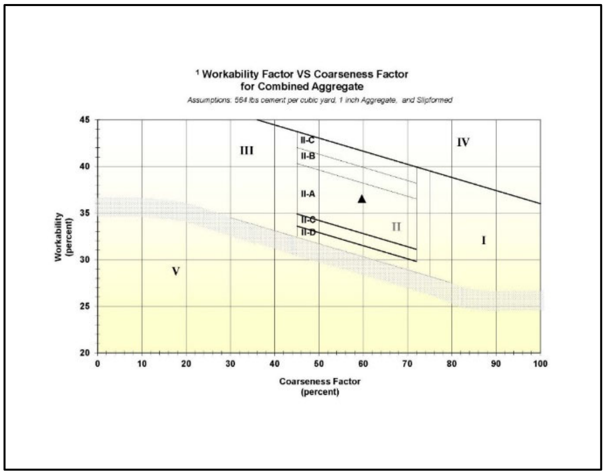

Figure 1 Coarseness factor chart.

Figure 2 Cedar Valley Paving on US 20.

PEM Mixture

A reduced cement content mixture was utilized on the shoulders. The CP Tech Center used the contractor's aggregate proportions and developed a cement content based on dry rodded unit weight for the combined grading. The original Class A shoulder mixture was 550 pounds per cubic yard with a coarse and fine aggregate. The modified PEM mixture was 515 pounds per cubic yard with coarse, intermediate, and fine aggregates. Table 2 shows the comparisons between the Class A and PEM mixture designs.

Table 2 Mixture Design Comparisons

A Mix	Abs. Vol.	lbs/CY
CEMENT:	0.083	440
FLY ASH:	0.025	110
WATER: w/c=0.474	0.155	261
FINE AGGREGATE (45%):	0.305	1357
COARSE AGGREGATE (55%):	0.372	1680
INTERMEDIATE AGG.:	0	0
AIR:	0.06	0
Paste Content, %	26.3	

PEM Mix	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	

The contractor expressed concerns with lowering the cement content, noting the Class A mix sometimes is lean. They utilized the PEM mixture on the shoulders with the caveat that if they had issues with workability, they would add 10 pounds of cement per cubic yard until they achieved the workability they desired.

Prior to paving, the contractor performed a trial batch of the PEM mixture. The Box Test indicated the mixture would be workable. The contractor went ahead with the PEM mix trial placement on the shoulders and was pleasantly surprised how well the PEM mixture placed (Figure 3). The contractor also desired to try the mixture on mainline, if they had any left to place.

Figure 3 Box Test PEM shoulder mix and paving.

Test Results

SAM Testing

SAM number testing was performed once per day. As recommended by the developer Tyler Ley, action limits were placed on the control charting with 0.20 or lower within limits, 0.25 as a warning limit, and 0.30 as a rejection limit. Of the 36 tests performed, all SAM number test results were at or below the rejection limit of 0.30 (Figure 4).

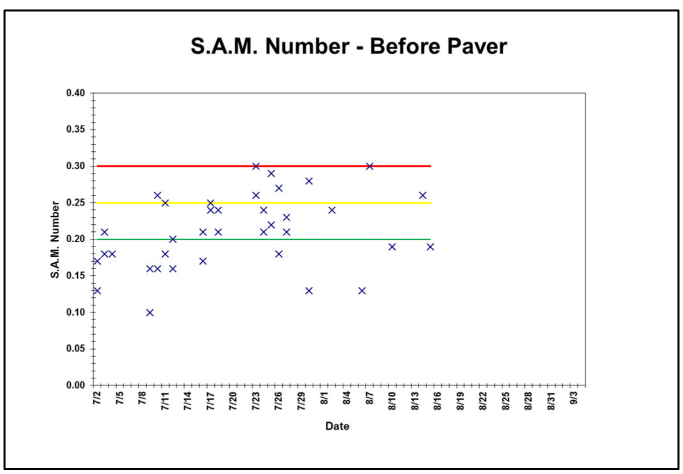

Figure 4 SAM Test data.

Box Test

The Box Test was tested once per day during production. All but three tests were either a 1 or 2 (Figure 5). Although, the three tests were at a 3 rating, there were no issues with workability. Since the test requires judgment comparing against images, these results may have been between a 2 or 3 rating.

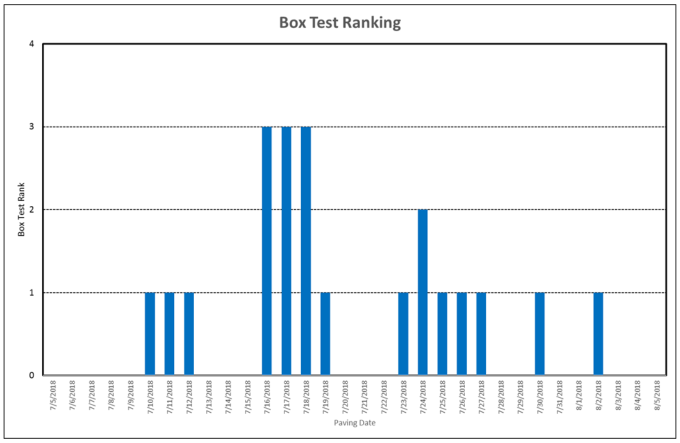

Figure 5 Box Test results.

Resistivity and Formation Factor

Cylinders were cast every day and placed in a 5-gallon bucket with a well-sealed lid, with 3.5 gallons of water and 102.6g NaOH, 143.90g KOH and 27g $Ca(OH)_2$. Resistivity testing was performed by the contractor at 3 and 7 days. The buckets were delivered to the Central Laboratory, placed in the moist room, and resistivity was performed at 14, 28, 56, and 91 days. Results are shown in Figure 6.

One set of two cylinders was tested following the protocol found in the appendix for the formation factor (FF). The resistivity after 91 days was 21.1 and 19.9 k-ohm cm respectively, which correlates with formation factors of 2111 and 1999. These values are classified as low to very low. Since test methods were being finalized during this project, temperature correction was not included in the resistivity results.

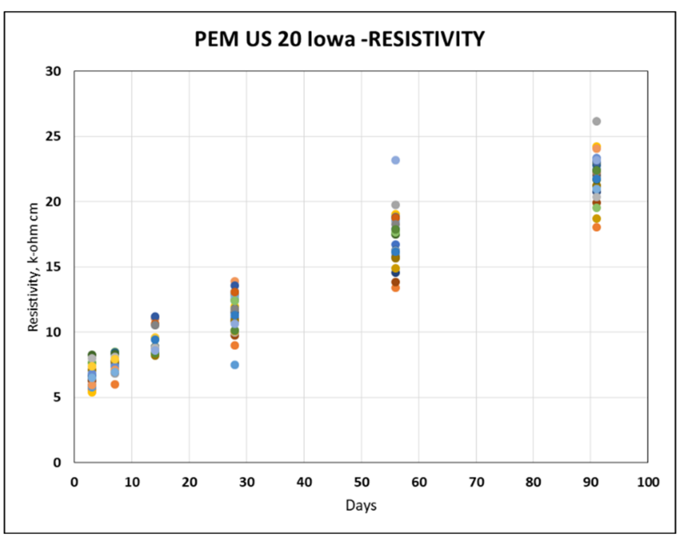

Figure 6 Resistivity Test results.

Combined Grading

On QMC paving projects, the Iowa DOT requires well graded aggregate combinations in Zone II using the Shilstone chart. The coarseness and workability factor weekly averages are shown in Figure 7.

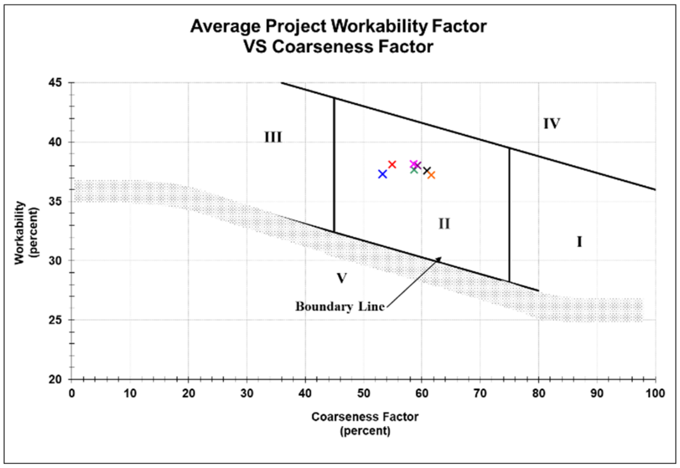

Figure 7 Weekly averages Shilstone coarseness and workability factors.

The combined grading was also plotted on the Tarantula Curve to see how closely it would fit within the curve boundaries. Although the proportions were developed with Shilstone principles, the combined grading also fit the Tarantula Curve as shown in Figure 8.

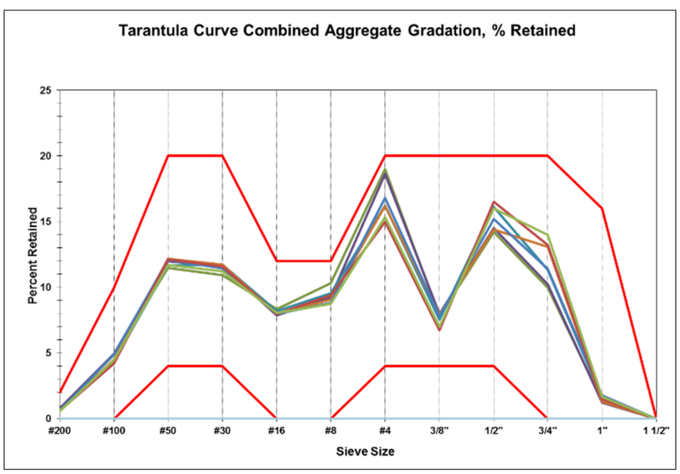

Figure 8 Weekly averages Tarantula Curve combined grading.

Additional Projects

Based on the success of the shadow testing project, the contractor elected to continue shadow testing the PEM test methods in order maintain proficiency and learn more about them. The average results for the project are included in Table 3.

Table 3 Average Data from Shadow Projects 2019

	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

Harrison County I-29 Project

Based on the success of the PEM shoulder placement on US 20 in Woodbury County in 2018, Cedar Valley Corporation requested to perform a similar trial on the I-29 Harrison County project. In 2019, the mainline and inside 6-foot shoulder was placed with the traditional QMC mixture design. The first 4.07 miles of the outside shoulder was placed with an A-6-C20 mixture. The remaining 2.83 miles of the outside shoulder was placed with a mixture with reduced cement content of 484 lb/yd^3.

After the successful outside shoulder placement, utilizing the reduced cement mixture in the fall of 2019, it was decided to investigate the use of a similar mixture on the mainline placement in 2020.

The project is located on the southbound lanes of I-29 in Harrison County, Iowa. During construction, the contractor elected to place the inside 6-foot shoulder with the 24-foot mainline. The outside 10-foot shoulder was placed in a separate operation.

Materials and Mixture Design

The materials used in the mixture for 2019 and 2020 remained the same, with the exception of the coarse aggregate. Cementitious materials include Ash Grove Type IP cement containing a 25% replacement with Class F fly ash and Nebraska City Class C fly ash at a 20% weight replacement of the cement. The fine/intermediate aggregate source was from North Valley. North Valley is a Class V gravel with material retained on the ½ inch sieve to the #100 sieve.

The only difference between each year was the coarse aggregate source. In 2019, the coarse aggregate was from Weeping Water Mine. In 2020, the coarse aggregate came from the Ft. Calhoun Mine. The fine/intermediate aggregate source was from North Valley. North Valley is a Class V gravel with material retained on the ½ inch sieve to the #100 sieve. A closeup view of the aggregates can be found in Figure 9.

The location of the various mixture designs used can be found in Table 4. The batch weights for each mixture used are shown in Tables 5 through 8. The average coarseness and workability chart for the mainline is provided in Figure 10. The average combined grading on the Tarantula Curve may be found on Figure 11.

Figure 9 Ft. Calhoun coarse aggregate and North Valley sand-gravel aggregate (2020).

Table 4 Mixture Type and Location

Mix Design	Begin Station	End Station	Date
QMC	1834+00	1470+00	8/13/19 to 9/27/19
A-6-C20	1834+00	1619+30	8/22/19 to 10/3/19
PEM Shoulder	1619_30	1470+00	10/3/19 to 10/8/19
QMPEM	1470+30	1133+00	8/18/20 to 9/1/20
QMPEM (Shoulders)	1470+30	1133+00	9/15/20 to 9/22/20

Table 5 QMC Mixture Design 2019

Material	Source	Weight (lb/yd^3)
Cement	Ash Grove Type IP(25)	426
Fly Ash (20%)	Nebraska City, Class C	107
Coarse Aggregate (45%)	Weeping Water	1427
Fine Aggregate (55%)	North Valley – Cl. V	1708
Water (basic w/c=0.40) 0,42 max	Willow Creek near Modale	213

Table 6 A-6-C20 Shoulder Mixture Design 2019

Material	Source	Weight (lb/yd^3)
Cement	Ash Grove Type IP(25)	463
Fly Ash (20%)	Nebraska City, Class C	116
Coarse Aggregate (40%)	Weeping Water	1188
Fine Aggregate (60%)	North Valley – Cl. V	1744
Water basic w/c = 0.474, 0.532 max	Willow Creek near Modale	274

Table 7 PEM Shoulder Mixture 2019

Material	Source	Weight (lb/yd^3)
Cement	Ash Grove Type IP(25)	387
Fly Ash (20%)	Nebraska City, Class C	97
Coarse Aggregate (45%)	Weeping Water	1476
Fine Aggregate (55%)	North Valley – Cl. V	1761
Water basic w/c 0.40, max 0.42	Willow Creek near Modale	194

Table 8 PEM Mixture Mainline and 10 Ft. Outside Shoulders 2020

Material	Source	Weight (lb/yd^3)
Cement	Ash Grove Type IP(25)	399
Fly Ash (20%)	Nebraska City, Class C	100
Coarse Aggregate (45%)	Ft. Calhoun	1441
Fine Aggregate (55%)	North Valley – Cl. V	1752
Water basic w/c 0.40, 0.42 max	Willow Creek near Modale	200

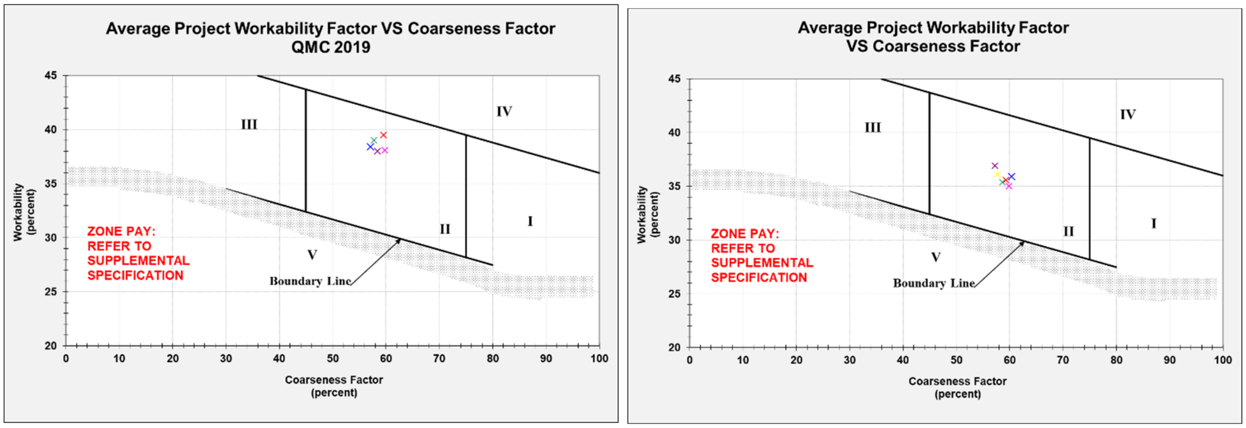

Figure 10 Coarseness workability chart—QMC 2019 vs. PEM 2020.

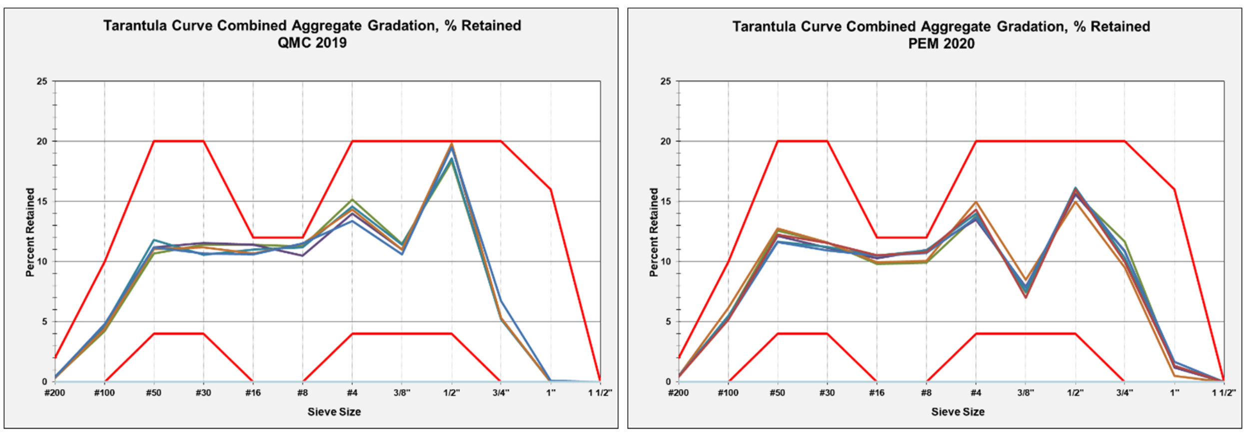

Figure 11 Tarantula Curve combined gradation—QMC 2019 vs. PEM 2020.

Project Data

The standard mixture for shoulders was A-6-C20, and the average w/c ratio during production was 0.393. The PEM shoulder mixture had a reduced cement content of 484 pounds per cubic yard, with an average w/c ratio was 0.413.

The w/c ratio is determined from batch weight at the plant. The average w/c ratio for the QMC mix in 2019 was 0.396. The average w/c ratio for the PEM mix in 2020 was ratio 0.390. Based on the control charts, it appears that the daily results for the w/c ratio for the PEM mix were lower than that of the QMC mix. The w/c ratio control chart for each year can be found on Figure 12.

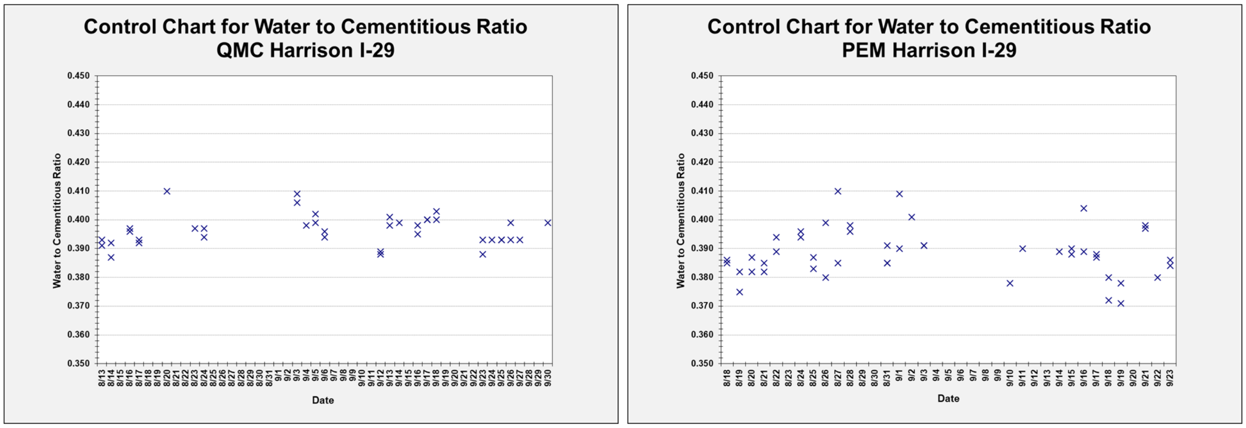

Figure 12 Water to cementitious ratio control chart—QMC 2019 vs. PEM 2020.

SAM Air Testing

On the 2019 portion of the project utilizing the QMC mix, SAM number and SAM air content was tested at the plant. On the 2020 portion, utilizing the PEM mix, the SAM number and SAM air content was tested at the plant and the same truck was tested on the grade. Two SAM air meters were used to accomplish testing at the plant and grade.

Based on the control charts, it appears the SAM number for the PEM mixture was lower overall, with more results less than 0.20, than the QMC mixture. Control charts for the SAM number are shown in Figure 13. The SAM air content at the plant average was 9.5%, with a standard deviation of 0.76, while the SAM air content on the grade average was 8.9%, with a standard deviation of 0.86. The SAM number at the plant average was 0.13, with a standard deviation of 0.050, while the SAM number on the grade average was 0.18, with a standard deviation of 0.063. The plant versus grade results of the SAM air content and SAM number can be found on Figure 14.

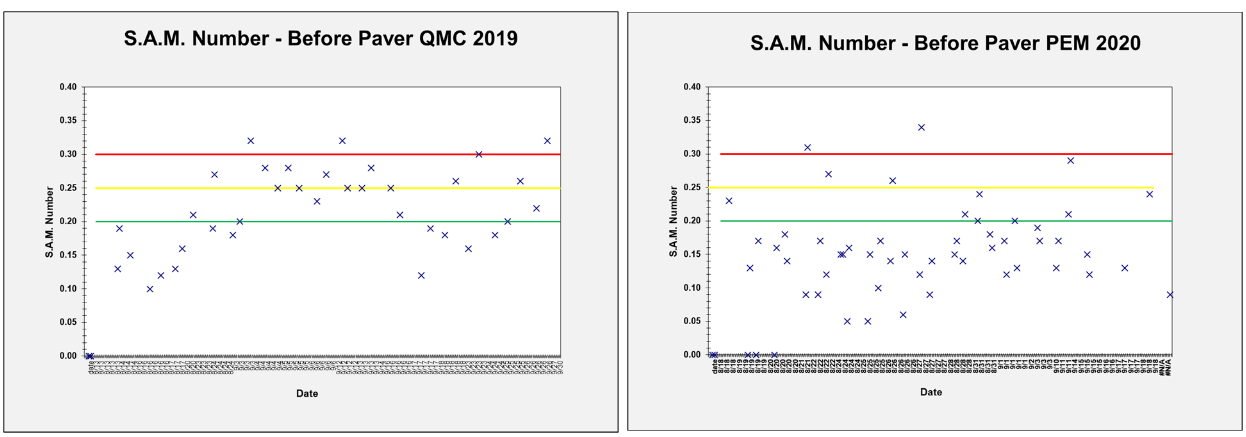

Figure 13 SAM number before paver—QMC 2019 vs. PEM 2020.

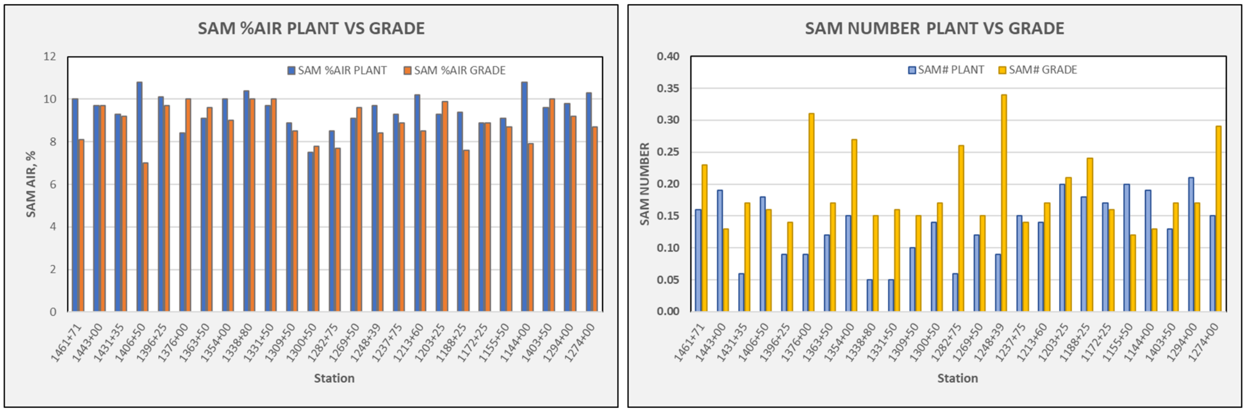

Figure 14 SAM air (%) and SAM number—plant vs. grade (PEM 2020).

Workability—Box Test

The Box Test was performed once per day during normal production. In 2019, the Box Test was performed at the plant. In 2020, the Box Test was performed on the grade. All Box Test ratings were a "1" with the exception of one test result with a "2" rating in 2019. Results are provided in Figure 15.

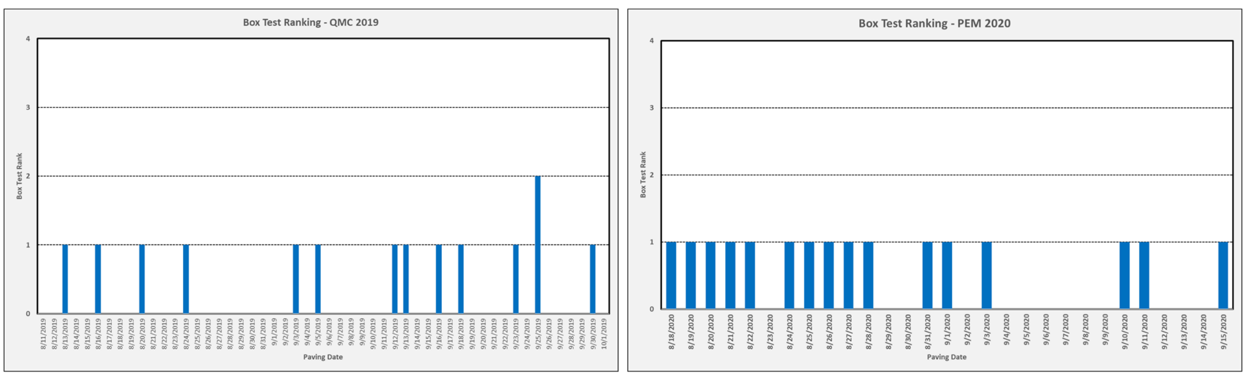

Figure 15 Box Test workability ranking—QMC 2019 vs. PEM 2020.

Resistivity

Cylinders were cast every day and placed in a 5-gallon bucket with a well-sealed lid, with 3.5 gallons of water and 102.6g NaOH, 143.90g KOH and 27g Ca(OH)2 into. Resistivity testing was performed by the contractor on the project at 3 and 7 days. The buckets were delivered to Iowa State University laboratory for testing at 28 and 56 days. Overall, the resistivity for the PEM mixture is higher at 56 days than the QMC mix. Results for the QMC mixture in 2019 and results for the PEM mixture in 2020 are shown in Figure 16.

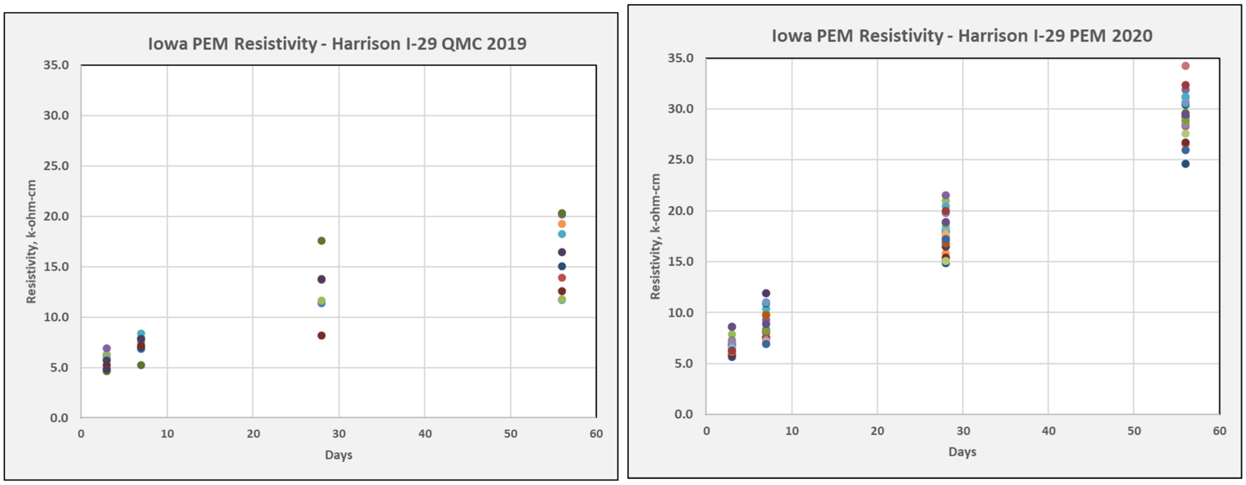

Figure 16 Resistivity test results—QMC 2019 vs. PEM 2020.

Pavement Smoothness

Pavement smoothness testing was performed by the contractor using zero blanking band, with verification performed by the Iowa DOT. In 2019, the average profile index was 24.87 inches per mile for the 6.69 miles of mainline paving. In 2020, the average profile index was 19.36 inches per mile for the 5.98 miles of mainline paving. 2019 QMC paving 142 segments achieved 58.45% of the maximum incentive. 2020 PEM paving 144 segments achieved 72.66% of the maximum incentive. Overall, the PEM mixture with reduced cement content achieved better smoothness compared to the QMC mixture.

The mixture placement had no issues with workability and finishing. The pavement edge of the extruded slab was sharp and clean. See Figure 17.

Figure 17 Overall view pavement slab behind paver—Harrison I-29 (2020).

PEM Implementation

The PEM program has allowed Iowa DOT to further improve concrete pavement sustainability. Iowa is considering updating its current QMC specifications for paving to include PEM testing. The state is also planning to allow for reduced cement content in mixtures validated with PEM testing. Tests would include the SAM, Box Test, and resistivity. The state is also considering PEM mixture design and testing for large bridge structures.

Chapter 2

Minnesota's PEM Experience

The Minnesota Department of Transportation (MnDOT), as a participant in the FHWA Transportation Pooled Fund TPF-5(368) Performance Engineered Concrete Paving Mixtures, specified the use of PEM designs for two paving projects constructed in Minnesota: Trunk Highway TH-60 in Watonwan County (MnDOT S.P. 8309-52) and I-35W in Hennepin County near Lake Street in the City of Minneapolis (MnDOT S.P. 2782-327).

The first project, located on I-35W in Hennepin County, was comprised of approximately 4.929 miles of mainline interstate pavement, with concrete pavements ranging from 8 to 12 inches in depth. SAM testing, aggregate gradation monitoring, flexural strength testing, strength monitoring through maturity, and concrete surface resistivity testing, among other testing, were carried out through the construction period.

In summary, the following observations on the PEM implementation can be made. First, use of maturity testing was challenging since the materials for the mixtures in the field were not the same as the trial mixtures. However, in general terms, it was a useful tool and will continue to be used.

While MnDOT has not established if formation factor (FF) will be incorporated into the specifications, if FF is incorporated, it is likely to be used only for mixture qualification, not for quality control and assurance.

Finally, the use of SAM also presented some difficulties as about half of the tests performed in the field were deemed as "not run properly." Additional training and experience should help reduce the number of "not run properly" tests that occur. Future pilot projects using the SAM will help MnDOT determine how best to use the SAM in the future.

The following are excerpts from the reports of the findings for these two projects.

Super Air Meter

MnDOT required the contractor to perform the SAM testing for the I-35 project. The contractor was trained to use the SAM. Based on the results obtained in the field, the following observations can be made:

- A total of 36 SAM tests were performed, with over half of these tests considered run correctly.
- The SAM average for the correctly run tests was 0.19, with about 85% of the SAM below 0.25 (i.e., considered freeze-thaw resistant by MnDOT).

- The measured air content after the paver decreased 0.4% to 1.1% from the values measured before the paver. The SAM average measured after the paver was 0.21 in comparison to an average of 0.20 measured before the paver.
- A total of nine cylinders were tested on the correctly run SAM tests to determine the hardened air-void systems according to ASTM C457/C457M [9]. All of the cylinders presented good air-void systems, with spacing factors between 0.002 and 0.004 in. and specific surfaces above 920 in.^{2}/in^3. In one of the nine cylinders, the SAM number was greater than 0.25.

MnDOT required the contractor to perform the SAM testing on the TH-60 Watonwan County project. The contractor was trained to use the SAM by American Engineering Testing (AET) at their facility and at the project site.

- The percent air measured using SAM did not correlate well with ASTM measurements of air on several of the early tests. It was determined that the SAM was likely leaking. MnDOT asked the contractor to perform leak tests on the SAM daily. After implementing this leak test better agreement between SAM and the ASTM standard for air was observed.
- SAM test results that were run correctly indicated that we had freeze-thaw durable concrete (SAM numbers of 0.25 or less).
- Hardened air tests have not been conducted to date on the SAM samples. They will be sent to Oklahoma State University (OSU) for testing.

Maturity and Strength

The maturity-strength curve is a powerful tool to estimate in-place strength. The contractor's experience using maturity on these two projects was limited so there were some growing pains.

The maturity curves were first developed in the lab prior to the start of construction. Due to issues with the fly ash supply, new maturity curves had to be developed, creating an unexpected extra step to the process. New maturity curves were developed in the field at the batch plant. Once the new curves were established, maturity testing provided a good real-time estimate of strength for opening to traffic.

Resistivity Tests and Formation Factor

Results were reported for surface resistivity, as per AASHTO T 358 [10] or as "effective" surface resistivity (a geometry factor was applied to the T 358 results). In addition, for particular ages, bulk resistivity was also determined for the field cylinders. Surface resistivity (reported as per AASHTO T 358 [10]) are about double of the "effective" surface resistivity, for 4-by-8 in. cylinders (as observed with the field cylinders), and about 40 % higher, for 6-by-12 in. cylinders (as observed with the trial batches).

In addition, the importance of cylinder conditioning was also presented. For the trial batches, two different conditionings were used: calcium hydroxide saturated, simulated pore solution (Option A of AASHTO TP 119 [14]) and sealed curing (Option B of AASHTO TP 119 [14]). The ratio of the resistivity of cylinders conditioned in calcium hydroxide saturated, simulated pore solution and the resistivity of the sealed cylinders varied, depending on the mixture microstructure, from 0.46 to 0.60.

In the field, two cylinders were cast, and conditioned in calcium hydroxide saturated, simulated pore solution (Option A of AASHTO TP 119 [14]). An anomaly was observed on the surface resistivity results between the ages of 56 and 91 days, because the surface resistivity decreased with time. However, bulk resistivity confirmed the expected trend of resistivity increase with time. Bulk resistivity values are expected to be comparable to those of the "effective" surface resistivity. At age 56 days, bulk resistivity and effective surface resistivity were comparable. However, since an anomaly was observed with the 91 days surface resistivity results, the 91 days resistivities were not comparable.

Formation factor was calculated from the "effective" surface resistivity and bulk resistivity results. AASHTO PP 84 [16] presents a requirement of a minimum formation factor of 1,000 for concretes exposed to freezing-thawing. The formation factor at 91 days calculated from the bulk resistivity results was in compliance with this requirement.

From the I-35 project, field test samples for resistivity tests were made by MnDOT personnel and delivered the next day to a consulting company (AET) for testing in the laboratory. MnDOT elected to use laboratory tests to avoid field training personnel on preparing the soaking solution. The calculated formation factor indicated good resistance to freezing and thawing.

Phoenix Test

The Phoenix test was supposed to be conducted on the I-35 project but after equipment issues it was removed from the scope of work. MnDOT has since been using this device on several other paving projects with good results, and MnDOT has been sharing their experiences with OSU as they further refine the test apparatus and procedure.

Box Test

The Box Test was only conducted during the lab testing and not in the field. MnDOT did not require the Box Test during the paving process.

Conclusions and Discussion

The implementation of PEM on these projects was an opportunity to familiarize MnDOT and contractor personnel with PEM testing, especially the SAM and maturity testing. MnDOT believes that the SAM provides real-time results regarding the freeze-thaw durability of the concrete pavement. Through internal MnDOT testing and the PEM projects utilizing the SAM, MnDOT has determined that air content testing is not needed after the concrete paver and has removed the requirements from the specifications. One accomplishment not shown in test data is the level of collaboration. Everyone involved worked well together in training and performing the tests and collecting the test data. Overall, the PEM testing went well on these projects. The effort helped to educate MnDOT personnel and the contractor on the use and effectiveness of PEM.

Chapter 3

Wisconsin's PEM Experience

Overview

WisDOT, in conjunction with the Wisconsin Highway Research Program (WHRP), funded PEM research over a 5-year period, from 2017 to 2022 (WHRP 0092-17-07). This research was in two phases, where the second phase focused on areas of interest identified during the first phase. The breadth of research included optimized aggregate gradation, SAM, hardened air system characteristics, resistivity, Vibrating Kelly Ball, Box Test, coefficient of thermal expansion and compressive and flexural strengths. Tests were performed in the lab, and field projects were visited as well. This section will focus on the major findings that WisDOT has already or is considering implementing into their PEM program. The following sections are separated by the PEM test, highlighting the findings in Phase I and Phase II of the WHRP research.

Optimized Gradation

For this research, the following optimized aggregate gradation curve was used to evaluate mixtures. Any mixture within the curve would be expected to have good workability with enough cementitious and water contents. The coarse and fine sand limits were chosen to help designers produce concrete mixtures with good workability. The warning band was used to encourage producers to make their aggregate gradations far enough away from the limits so they would not violate the boundary under typical variations in the gradation (Figure 18).

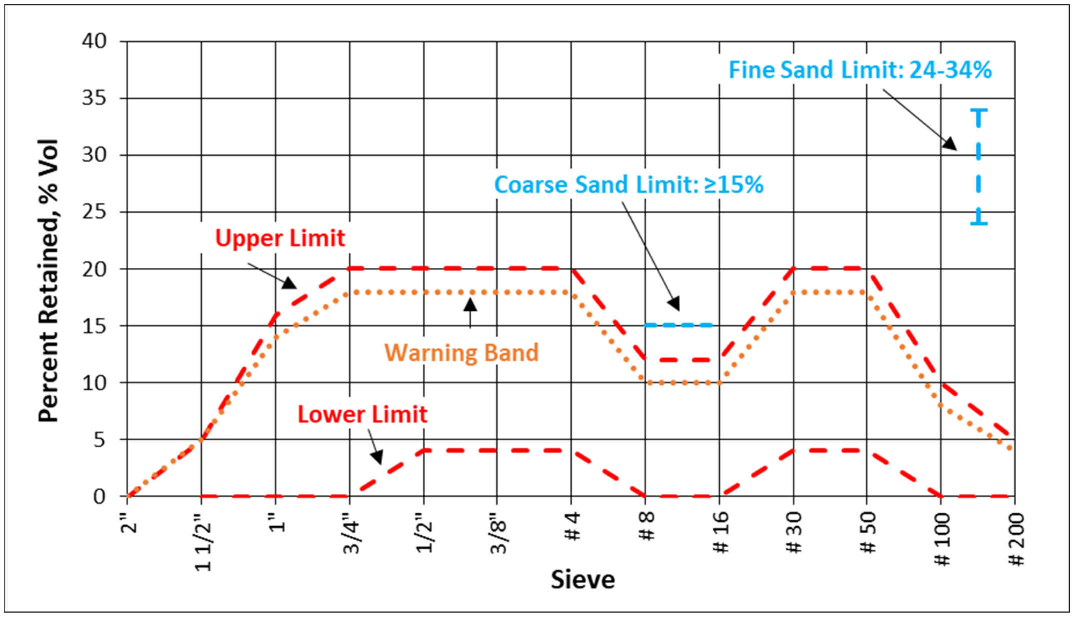

Figure 18 Optimized aggregate gradation guidelines for workable mixtures.

During Phase I of the WHRP research, eight projects were visited in the field and tested for various PEM properties. These mixtures were produced with varying aggregate sources such as limestone, gravel, dolomite, and quartzite. The research team did not modify any of the mixtures produced, but rather documented the mixtures and compared PEM properties. In Phase I, three out of the eight mixtures did not meet the optimized aggregate gradation. Additionally, five out of the eight mixtures exceeded the warning band. During Phase II, five more projects were visited in 2021 and tested for various PEM properties. These aggregate sources included carbonate, gravel, igneous gravel, and limestone. It is important to note that all Phase II mixtures met the optimized aggregate gradation and were within the warning band.

During Phase I, the researchers questioned whether the allowed 1 ½-inch stone influenced workability and PEM properties. Therefore, Phase II included a laboratory research study to specifically look at the presence of 1 ½-inch stone in concrete mixtures and how (or if) PEM properties were affected. Mixtures were created using varying percentages of aggregates and varying source of aggregates, to result in blends that were within the optimized aggregate gradation, and others that were not.

Findings—Optimized Aggregate Gradation: Field Projects

The PEM testing of the field projects resulted in some interesting findings. Figure 19 shows how the SAM number improved from Phase I to Phase II, which the researchers contribute to the increased use of the optimized aggregate gradation mixtures between 2017 and 2022.

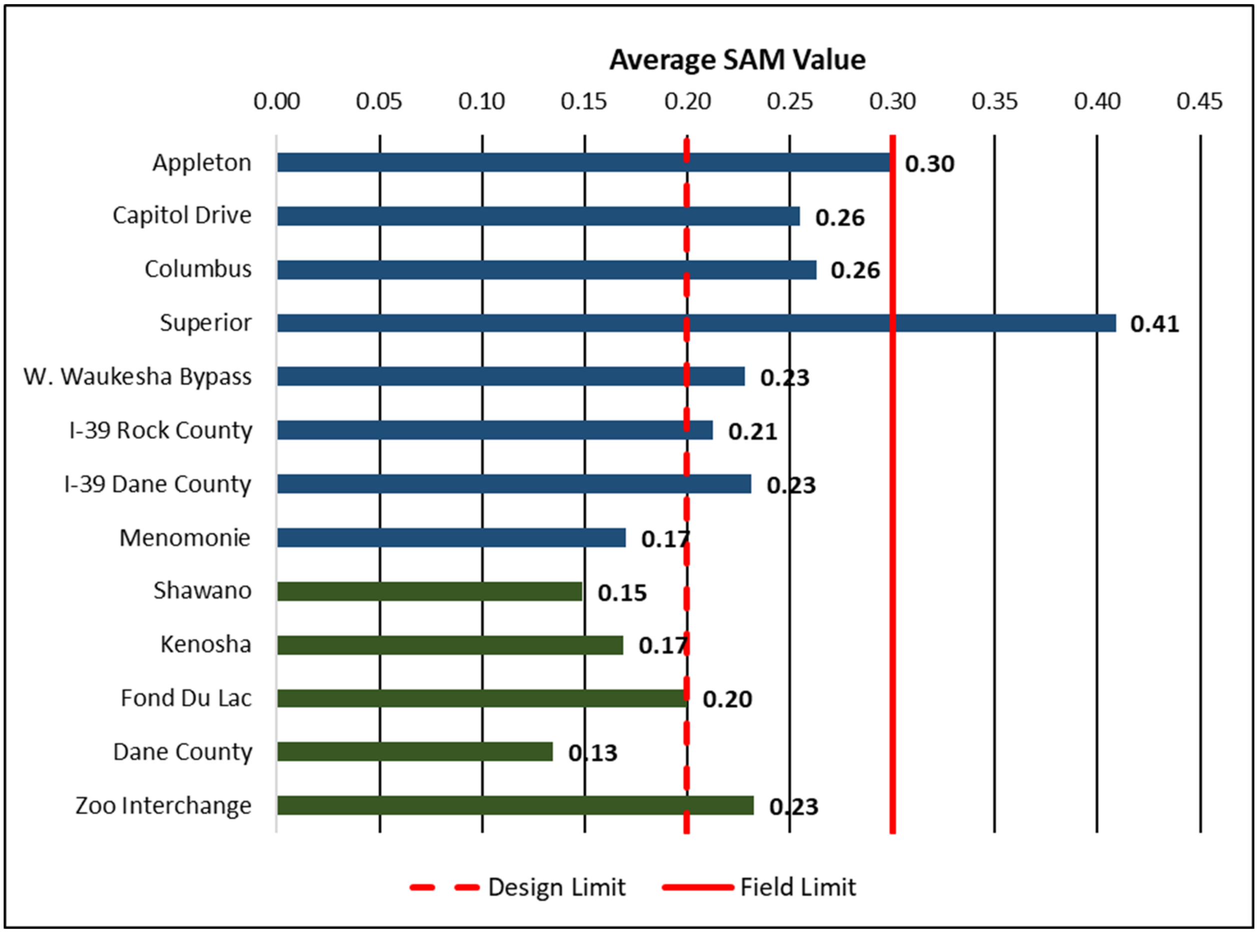

Figure 19 Comparison of average SAM values from Phase I using rodding and battery vibration consolidation to Phase II projects using MinT consolidation. Phase I projects are shown with blue bars and Phase II projects are shown with green bars.

Figure 19 shows the recommended Design and Field limits for the SAM test. The SAM section below provides more details regarding this recommendation.

Findings—Optimized Aggregate Gradation: Laboratory Study

All of the blends created in the laboratory were tested for Box Test, slump, compressive strength, electrical surface resistivity, mass change from drying, and shrinkage strain. Figure 20 shows varying blends from one aggregate source, where the dashed lines (Haas 1 & Haas 6) indicate a failing Box Test. Additionally, this laboratory study found that significant changes in the aggregate gradation did not change the compressive strength, electrical surface resistivity, mass change during drying, or the shrinkage of the concrete mixture.

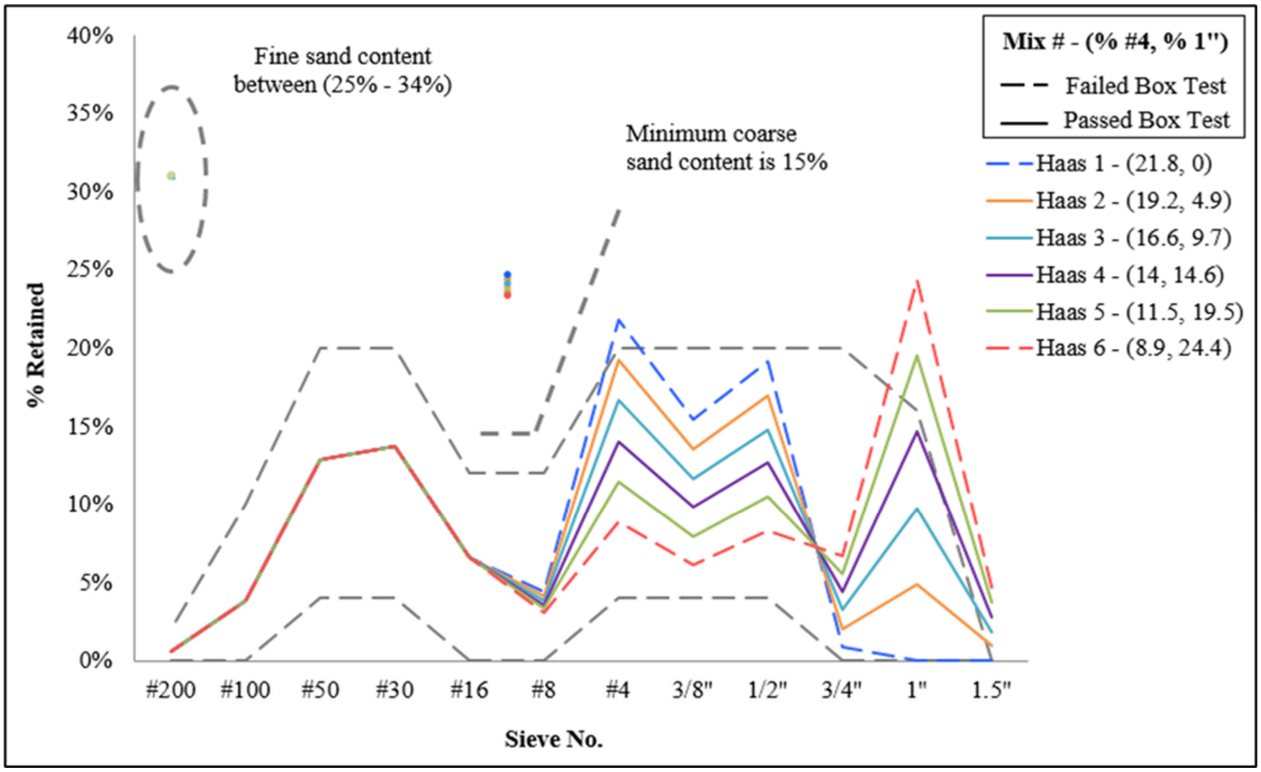

Figure 20 All mixtures plotted on the optimized aggregate gradation curve.

From this laboratory study, it is recommended that the boundaries of the optimized aggregate gradation curve include 1 ½-inch diameter stone.

Air Content, Super Air Meter, and Hardened Air-Void System Characteristics

During the Phase I and Phase II field visits, samples were collected for determination of hardened air-void system characteristics, and the SAM was tested at various locations (plant, before and after paver) using multiple gauges and technicians (for repeatability) and various consolidation methods (rod, vibe and MinT). Figure 21 shows how the air content changes throughout production and placement from the plant, to before and after the paver. Similarly, Figure 22 shows how the SAM value changes throughout production. Finally, Figure 23 shows the hardened air test results throughout production.

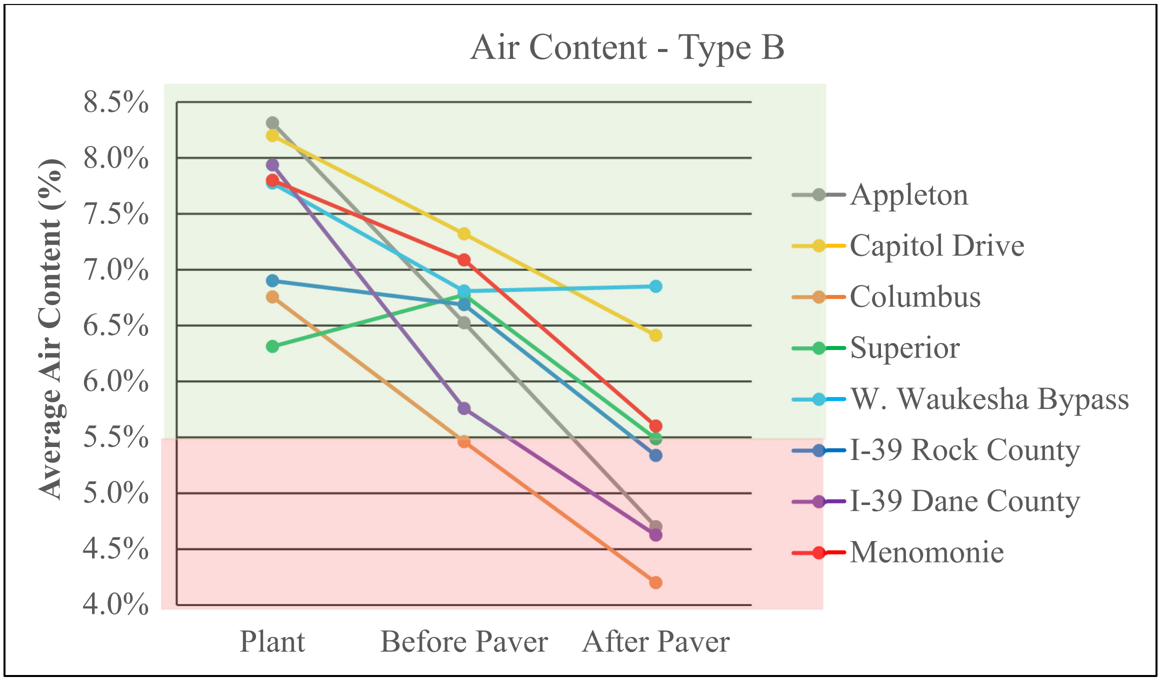

Figure 21 Phase I—air content (Type B) throughout production.

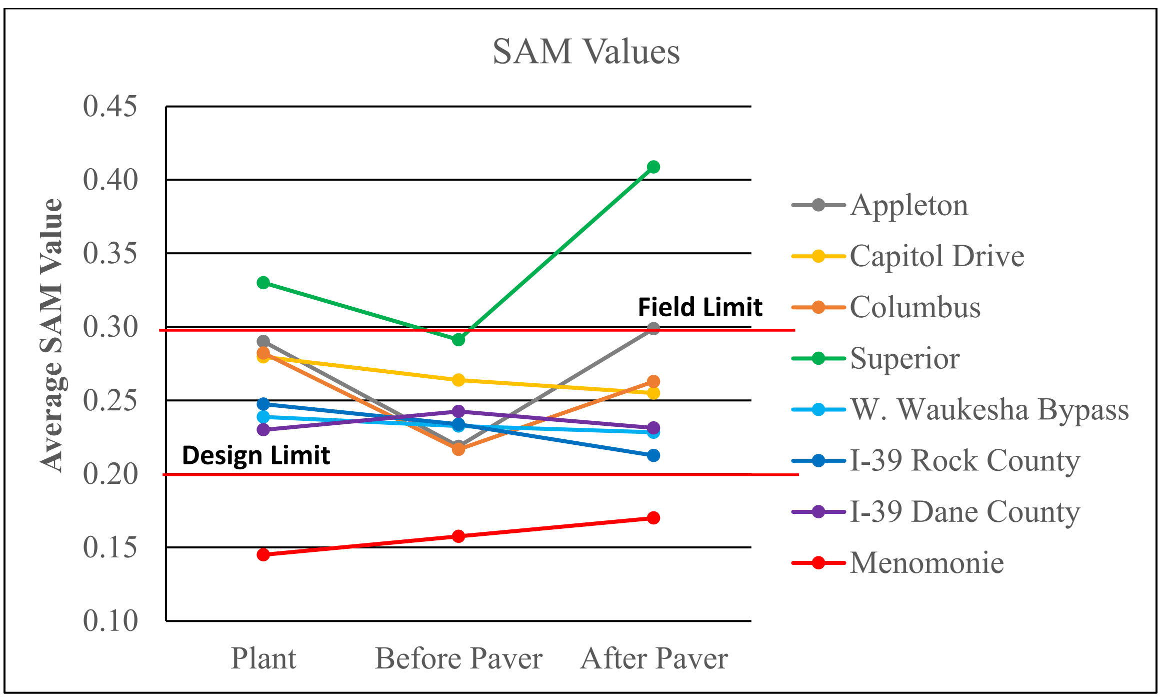

Figure 22 Phase I—SAM value throughout production.

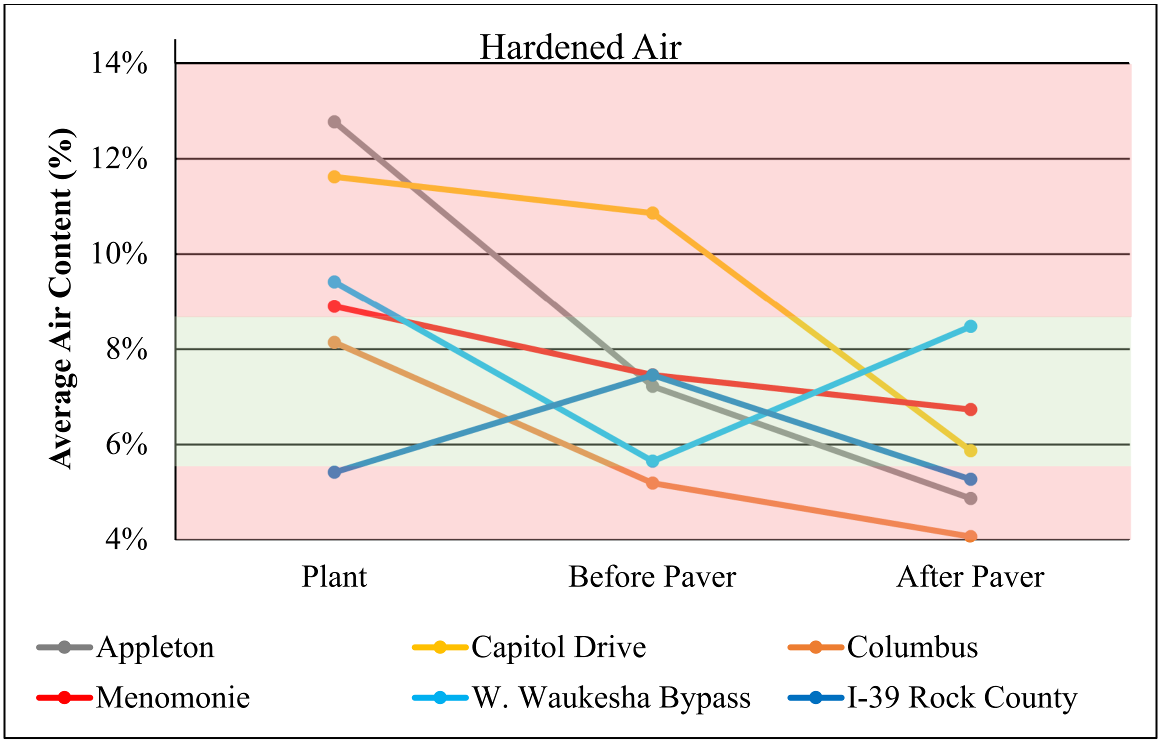

Figure 23 Phase I hardened air throughout production.

In Phase I, the research team also looked at various methods to consolidate during SAM testing using rodding and a vibrator. From the findings of Phase I, Phase II additionally focused on the use of the MinT vibrating unit shown in Figure 24. All methods were evaluated using multiple SAM units (for redundancy) and the same technicians performing the tests (for consistency).

Figure 24 MinT consolidation unit for SAM testing.

Findings—Air Content

An important finding from this Phase I work is that the air that is lost from the plant to the job site seems to be largely coarse "entrapped" bubbles. This is shown because the air volume is decreasing but the SAM number is not changing. During Phase I, the research team had initially recommended that a SAM number < 0.20 and air content > 4% be used for the mixture design and evaluated in the lab; and a SAM number < 0.30 and air content > 4% in the field. When comparing Phase I to Phase II SAM numbers (Figure 19), which represent material sampled after the paver, these observations prove that a field limit of 0.30 is achievable with an optimized gradation mix design.

Findings—SAM Consolidation

The analysis of rodding vs. vibe in Phase I concluded that rodding was the more consistent method to use during SAM testing. In Phase II, rodding was compared to the MinT. During the field visits, the research team encountered other obstacles that seem to have affected the mixtures, such as inconsistent production and cold weather. The research team acknowledges that these outside factors may have had an effect on the variability of the SAM values, however the recommendation is to use the MinT for consolidation as it is a mechanical method that should reduce human error, which will be a benefit for new technicians running this test.

Resistivity

In Phase I, resistivity was tested on samples from all the field projects. The samples were cured in cure room for 90 days and tested at various intervals. Figure 25 shows the results of the various mixtures tested compared to the ranges listed in AASHTO T 358.

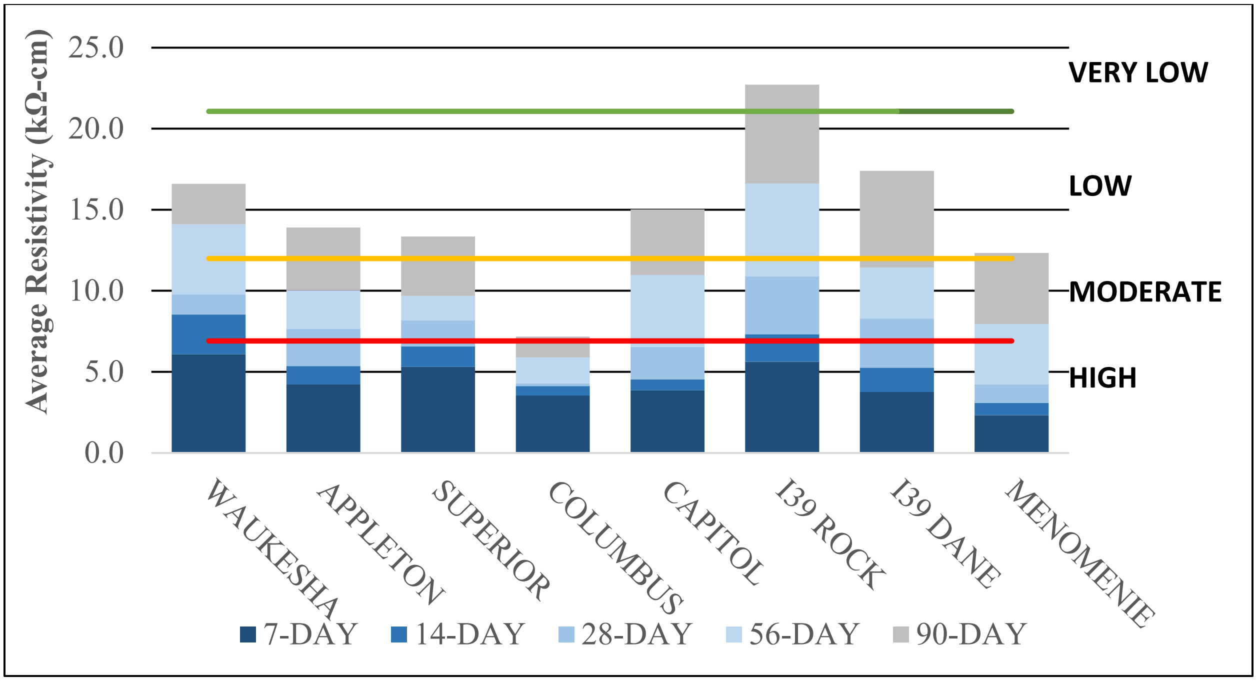

Figure 25 Phase I field project resistivity.

Initially, Phase II looked at two curing methods for resistivity—limewater curing (AASHTO R39-21 Section 8.3) and bucket curing (AASHTO TP119-21 Section 10.2). However, after the first field visit, accelerated curing (AASHTO T358-21 Section 8.1.1), and sealed sample curing (AASHTO TP119-21 Section 10.3) were added to the list of curing methods. All resistivity[1] values reported were corrected for geometry and conditioning. Figure 26 shows the comparison of curing methods.

---

[1] Resistivity - In this document, the term resistivity is used to describe the electrical resistivity of a material. Electrical resistivity is a fundamental property of a material that measures how strongly it resists electric current. The term bulk or uniaxial resistivity refers to the electrical resistance of a material that is measured from end to end of a sample corrected for geometry. Surface resistance is measured using a 4-probe configuration. The surface resistance needs to be corrected to account for the shape of the electrical field and the confined geometry of a cylinder. If the confined cylinder geometry is not used the term 'apparent surface resistivity' is used by convention in the concrete community. When the test is properly performed, the sample is properly conditioned, and the geometry is properly accounted for; the resistivity measured using the bulk/uniaxial geometry (TP119) and the surface resistivity geometry (TP 358) are generally interchangeable.

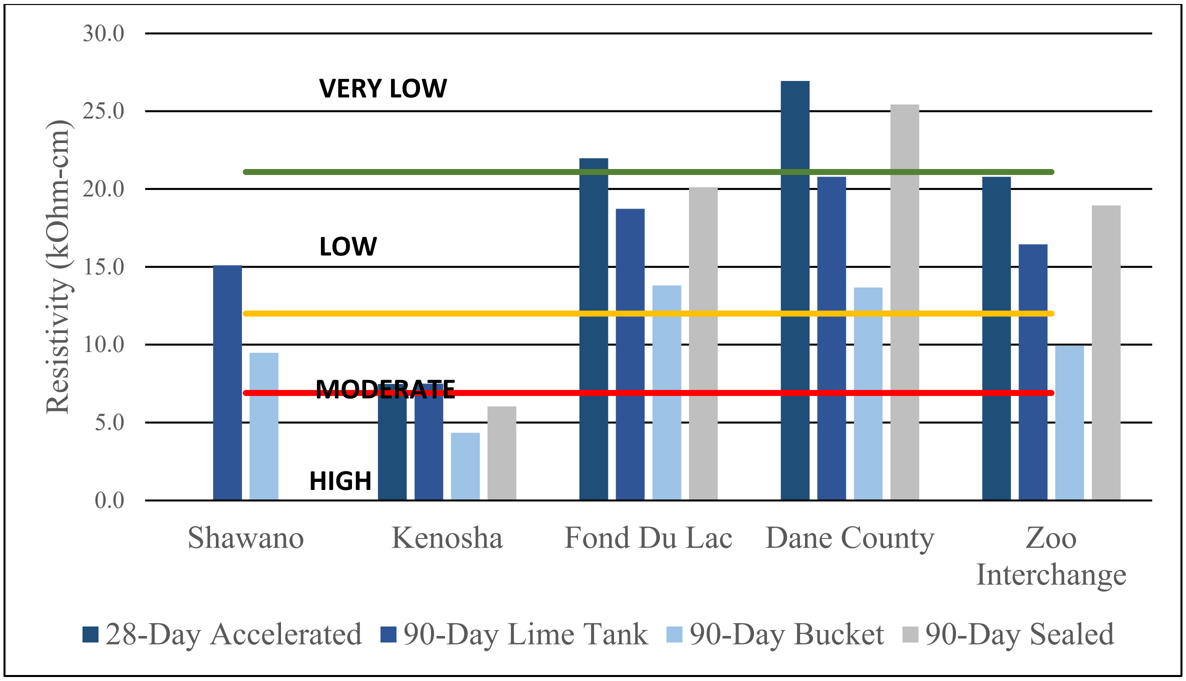

Figure 26 Resistivity 28-day accelerated vs. multiple 90-day curing methods.

Findings—Resistivity

As expected, with increasing curing time, all concrete specimens exhibited increased surface resistivity (Figure 25).Figures 25 and 26 both show that all the projects reached the low permeability values except for Columbus, Shawano (for bucket conditioning only) and Kenosha. Kenosha's mixture contained 0% SCMs and Shawano's mixture contained only 15% fly ash. It is unclear why the mixture used in Columbus did not reach the low surface resistivity in the same way as the other specimens.

When comparing the conditioning methods, the 28-day accelerated curing was higher than the 90-day lime testing. From a testing and laboratory standpoint, each method has pros and cons regarding test duration, additional equipment, or supplies (chemicals or bags). The one benefit that outweighs the others is to receive test results 62 days sooner when using the accelerated conditioning method. However, the data showed that the accelerated conditioning method resulted in the highest resistivity values. This needs to be considered when determining an appropriate minimum (design or field) requirement for resistivity.

Implementation of Results

WisDOT has implemented the optimized aggregate gradation in the 2022 Standard Specification Section 501.2.7.4.2.1, which was updated in 2022. WisDOT is requiring the SAM value be included as part of the mixture design submittal (Standard 715.2.1(5)), and requires SAM testing for information only, once per lot for certain bid items (Standard 715.3.1.1(4)). WisDOT is requiring resistivity to be performed for information only, once per lot for certain bid items (Standard 715.3.1.1(3)).

Chapter 4

Michigan’s PEM Experience

Overview

In Michigan there are over 120,000 miles of paved roads. In addition, there are over 10,750 bridges which carry vehicular traffic in Michigan. MDOT is responsible for maintaining over 9,600 miles of these paved roads and over 4,400 of the bridges. Many of the bridges are aging and approaching the end of their service life.

Michigan’s weather creates further difficulties when maintaining the system. The weather creates shorter windows for construction seasons. Also, due to the wet climate and the effects of the Great Lakes, Michigan goes through an extraordinary number of freeze-thaw cycles from late fall through early spring. Michigan also has a “Clear Road Policy,” so large amounts of deicing agents are used. Due to the age of Michigan’s system and exposure to a harsh environment, a lot of the roads and bridges are showing signs of distress. These circumstances prompted Michigan’s Legislature in 2015 introduce a bill, Public Act 175, to pilot a 30- and 50-year pavement design. The goal of this bill was to create long-life pavements with reduced maintenance costs and have an overall service life cost lower then what MDOT was currently doing. From this bill, two pilot projects (discussed below) were constructed in 2017 and 2018.

In the 1990s MDOT’s specifications were still quite prescriptive. Most of MDOT’s concrete mixture designs were still being determined and created internally. However, with the increasing demand on the pavements and bridges from environment factors and increased traffic conditions (volume, velocity, and weight), MDOT understood there was a need for change. The introduction of optimized gradations, supplementary cementitious materials (SCMs), and other PEM ideas and designs starting in the late 1990s provided MDOT with the means to begin transitioning from the “cookbook mixtures” toward PEM designs.

MDOT started by introducing and allowing the use of an optimized aggregate gradation in 1996. Since the early 2000s, MDOT has been mandating the use of optimized aggregate gradations for mainline pavements. Due to the success of optimized aggregate gradation in pavements, they were introduced to structures approximately 5 years ago. MDOT has created its own optimized aggregate gradation analysis methods. These methods are based off the Shilstone aggregate system (Modified Haystack). Currently MDOT requires the use of optimized aggregate gradations in all the high-performance concrete mixtures for both pavements and structures.

With the introduction of optimized aggregate gradations, the total paste content could be reduced without sacrificing strength. MDOT acknowledged this and used it as an opportunity to reduce the maximum permitted Portland cement content in concrete mixtures using SCMs.

Although SCMs have been present in the concrete industry for decades, MDOT did not fully incorporate the use of them until 2010. Prior to 2010 they were optional to be used at the request of the contractor. However, MDOT witnessed that pavement sections and structural elements which had SCMs incorporated were not showing the same level of distress as those with just straight Portland cement. This prompted MDOT to begin requiring SCMs in all critical items of work. Currently MDOT requires a 25% to 40% replacement of Portland cement with SCMs in all critical concrete items. The two main types of SCMs that are currently being incorporated into MDOT projects are slag cement and fly ash. Contractors have also noted improvements with the workability and consistency of the mixes with the inclusion of the SCMs and optimized aggregate gradations.

MDOT's methods of concrete mixture design approval also began to change in the 1990s. MDOT began to transition from the standard "cookbook" mixtures to allowing unique mixtures to be proposed and used by contractors. As these concrete mixtures showed promise and performed well, MDOT continued to allow more opportunities for contractor-engineered mixture designs. These changes were incorporated into the 2012 Standard Specifications of Construction. This has worked well for Michigan but there was still room for improvement. Currently MDOT is still working on transitioning from prescriptive concrete mixture designs toward performance-based designs.

In 2020 the requirements for SCMs, the contractor-provided mixtures and optimized aggregate gradations were incorporated from Special Provisions (SP) into the MDOT's 2020 Standard Specifications of Construction.

Along with all the concrete mixture improvements in materials and designs, MDOT understood the need for updating the methods in which concrete mixtures are evaluated for durability. MDOT was not the only one to recognize this need; other state DOTs and the FHWA recognized as well. Because of this need, the PEM group and State Transportation Innovation Council (STIC) Incentive programs were created and MDOT is an active member in both. MDOT is also a member of the National Concrete Consortium since its birth. Both groups and programs have provided MDOT with the opportunity to be involved with the development of various durability tests and PEM ideas. Recently MDOT has taken a particular interest in the SAM, Surface and Bulk Resistivity, Box Test, Vkelly and other tests that were developed and proposed through AASHTO PP 84.

Using PEMs, MDOT hopes to achieve its goal of economically sustainable concrete. MDOT hopes PEMs will allow more opportunities for contractors to innovate and meet the challenges of our ever-changing world. By moving toward performance-based specifications, MDOT hopes that the concrete industry will be more prepared for material shortage issues and provide the contractor with the ability to make material adjustments as needed. Through mixture design flexibility the contractor would also be able to economize the mixtures through savings on materials and pass those savings onto MDOT.

MODT's overall objectives from PEM initiatives are:

1. Create more durable concrete mixtures
    a. Using optimized aggregate gradations
    b. Using SCMs
    c. Limiting the w/c ratio
    d. Limiting total cementitious content
    e. Creating a hybrid between prescriptive and performance-based specs
2. Establish preliminary internal evaluation of PEM methods and testing
    a. Surface and Bulk Resistivity
    b. Formation Factor (Bucket test)
    c. SAM
    d. w/c ratio testing (Phoenix test)
    e. Shrinkage
    f. Other test methods included in AASHTO PP 84
3. Technology transfer to division and regional personnel and industry stakeholders
    a. Introduce to internal personnel by statewide personnel (just so they can see it)
    b. Create opportunity for training (partnering with Industry)
    c. Pilot Projects
        i. Create initial specifications (shadow SPs)
        ii. Collect and evaluate data
        iii. Allow personnel to get field experience
4. Inclusion into Standard Specifications

MDOT has worked with the National Concrete Consortium and the FHWA on a multitude of research studies over the years. These studies have all been published either on the CP Tech Center's website or in FHWA's research database. MDOT has also performed internal research involving PEMs. MDOT publishes all research reports on the MDOT Research Reports web page (https://www.michigan.gov/mdot/programs/research). The information and conclusions provided in these research reports have been used to guide MDOT's current specifications and practices.

As mentioned previously, MDOT was directed to select and created two long-lasting pavement projects. These two projects incorporated MDOT's best practices and materials to create a 30- and 50-year design service life concrete pavement. Each project used a different contractor and was in a separate region. Creating them in two different regions provided the opportunity to build both projects within a year of each other. When selecting the locations, MDOT had to make sure that the traffic volumes were appropriate for the intended designs. MDOT also wanted to use sections of road that required full reconstructions. With all this in mind, MDOT selected a section of US 131 just north of Grand Rapids and a section of I-69 through Flint. Overall, these two pilot projects were largely successful. Both MDOT and industry personnel found that the projects went well. So far, MDOT has not had any issues with the pavements. However, only time will tell whether MDOT will achieve its goal of 30- and 50- year pavement design lives. Additional details on these projects are provided in later Implementation and Status sections.

Due to the long-life pavement projects and MDOT's interest in PEMs, a SAM shadow SP was created. It was used on the two long-life pavement projects and two additional pilot projects. The last pilot project was constructed in 2020 and the data is being evaluated by MDOT personnel with the help of the University of Michigan.

Throughout the development and creation of specifications for both long-life concrete pavement projects and SAM testing, MDOT's region personnel and industry partners have been involved. They have provided input when MDOT created new specifications and have helped with data collection for evaluating the viability of the new testing methods and procedures.

There are plans to continue to include the SAM shadow SP in multiple projects in the next few years. MDOT is also currently collecting bulk resistivity data and plans to continue. MDOT and industry are continuing to talk and work together to evaluate PEM designs, methods, and innovative testing.

Tests and Testing

Reduction in Cement Content

MDOT limits the maximum amount of total cementitious content permitted in a mix. A high-performance concrete pavement/structural mix (3500HP) has a permitted maximum cementitious content of 564 lb/yd^3 (6 sack) and a minimum cementitious content of 470 lb/yd^3 (5 sack). The two main differences between high-performance structural concrete mixes and high-performance concrete pavement mixes are the slump requirements and the nominal maximum size of an aggregate for optimized aggregates gradations. The structural mix requires a higher slump then a pavement mix. The higher slump is obtained through using a water-reducing liquid chemical admixture. A typical concrete bridge deck mix (4500HP) has a permitted maximum cementitious content of 658 lb/yd^3 (7 sack). These maximum permitted cementitious contents have remained the same for MDOT since the 1990s. MDOT's current concrete mixture requirements are summarized in Table 9.

Table 9 MDOT Concrete Mixture Requirements

Table 1004-1:
Concrete Mixtures

		Concrete Grade								
		3000	**3500**	**3500HP(a),(b)**	**4000**	**4000HP(a),(b)**	**4500**	**4500HP(a),(b)**	**M**	**X**
Compressive strength (psi)	7 day	2200	2600	2600	3000	3000	3200	3200	Commercial-grade concrete containing 517 lb/cyd. Portland cement may be replaced with an SCM.	Unless otherwise specified, Grade X concrete contains 282 lb/cyd of cement.
	28 day	3000	3500	3500	4000	4000	4500	4500		
	70%	2100	2450	2450	2800	2800	3150	3150		
Flexural strength (psi)	7 day	500	550	550	600	600	625	625		
	28 day	600	650	650	700	700	750	750		
	70%	420	455	455	490	490	525	525		
Slump (inch)		(c)–(f)	(c)–(k)	(c)–(k)	(l)–(n)	(l)–(n)	(d)–(f)	(e)–(f)		
Cementitious material content (lb/cyd)		489–517	517–611(o)	470–564(o)	517–611	517–611	517–658	517–658		
Class of coarse aggregate		(p)–(r)								
Maximum w/cm ratio		0.45								
Air content range		5.5 – 8.5%								

Although the maximum permitted cementitious contents have remained the same, the total permitted amount of Portland cement has been reduced since 2010. The allowable amount of Portland cement was reduced by requiring a 25% to 40% replacement with SCMs. Prior to 2010 MDOT piloted the use of SCMs starting in 2005 but did not require the replacement. When optimized aggregate gradations were mandated in 2005, it provided contractors with the opportunity to decrease the total cementitious content. Contractors were able to do this because optimized aggregate gradations provided a boost to compressive strength.

Currently it is common to see contractor-provided mixture designs submitted below the maximum allowable cementitious content. Contractors have done this to improve the mixture and reduce material costs. Even with some contractors choosing to reduce the total cementitious content on their own, MDOT does not currently have any plans of reducing the maximum total cementitious content. One major benefit MDOT has witnessed from reducing the total cementitious content has been decreased permeability. This is important for long-life pavements and structures in Michigan because limiting the intrusion of deicing agents is key to sustainable concrete.

Optimized Gradation

MDOT started researching optimized aggregates in 1996. The first attempt involved a 60/40 blend of 6AA and 29A (MDOT coarse aggregate gradations) and a 2NS sand (MDOT fine aggregate gradation). The 6AA was used as the coarse aggregate with a nominal maximum sieve size of 1 inch and the 29A was used as the intermediate with a nominal maximum sieve size of 3/8 of an inch. Details on the gradations are in section

902 of MDOT's 2020 Standard Specifications for Construction. The proportions of the coarse and intermediate aggregates were based on the maximum unit weight from laboratory trials. These laboratory trials were run at the following proportions: 60/40, 50/50 and 40/60.

In 2005, MDOT adopted the Shilstone and Modified Haystack methods for optimized aggregate gradations for concrete mixtures. MDOT selected to only allow gradations which would fall into Zone III of the Shilstone coarseness vs. workability graph. MDOT calls this the Operating Zone, as displayed in Figure 27. Any gradations which plot outside this zone are considered unacceptable. Initially a problem that kept occurring was that the aggregate gradations were plotting inside but near the operating zone for job mix formula reviews but when actual production occurred, the gradation would fall outside the boundary. This led MDOT to create the Job Mix Formula Zone which provided a buffer from the operating zone boundary (little box in Figure 27). MDOT also noticed significant differences in the workability of the mix while still staying in Zone III of the Shilstone graph. Therefore, MDOT requires the contractor to create an action limit boundary. The dotted line in Figure 27 is an example of an action limit boundary which is used as a quality control function and to maintain consistency. When this boundary is breached, the contractor is required to adjust the gradation to bring it back within the boundaries. However, the material is not rejected during this process. The only time the material is rejected is when it falls outside the operating zone boundary.

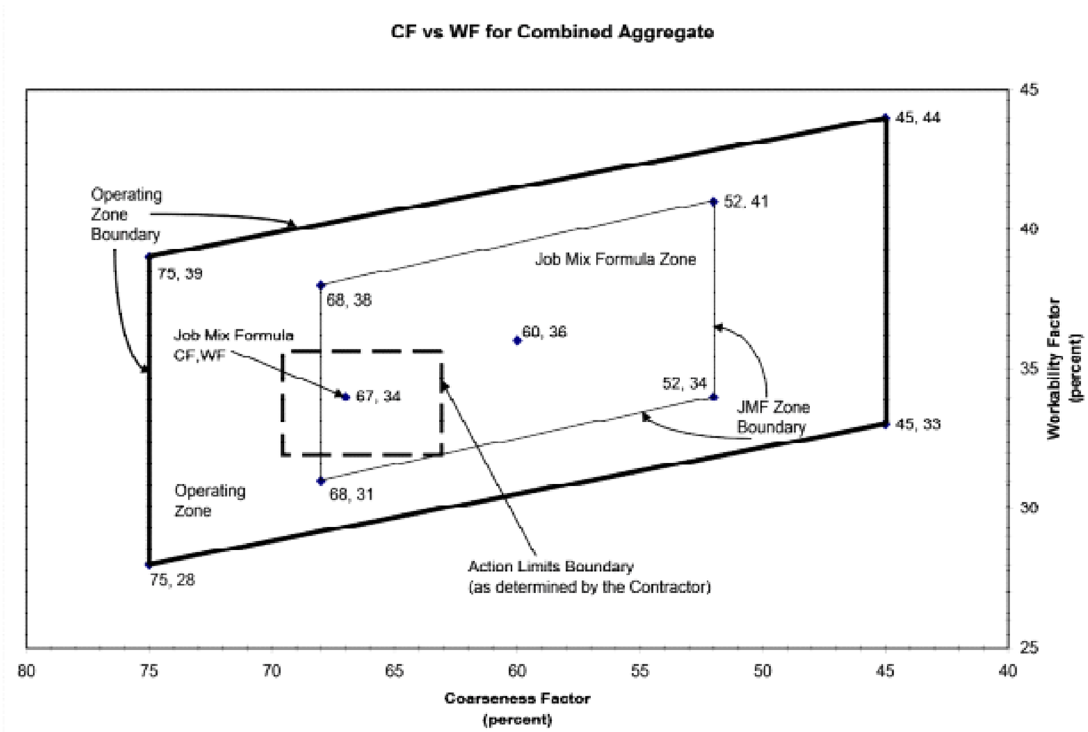

Figure 27 Coarseness vs. workability graph.

With the success MDOT has had with optimized aggregate gradations in pavements, it was decided to introduce the usage into structures and pavement overlays. This required MDOT to making slight modifications to the Shilstone aggregate system. One modification was to reduce the maximum sieve seize for structural applications and pavement sections 6 inches and under from 2 inches to 1 and ½ inches. This was done for clear space in structures and to ensure that aggregates would be less than ⅓ the thickness of the pavement.

When optimized aggregate gradations were introduced for structural applications the concrete was no longer being supplied only by on-site batch plants; commercial batch plants (ready-mix suppliers) started supplying as well. This created an issue with the method MDOT was sampling. MDOT had to create two different sampling methods. One for on-site plants and the other for read-mix suppliers. The on-site plants must perform one optimized aggregate gradation analysis per day and the ready-mix suppliers must do this at least once per week. Quality assurance (QA) sampling is based off a tonnage requirement determined by if the aggregate source is prequalified.

A few years ago, MDOT required the use of optimized aggregate gradations in all the high-performance concrete mixtures for both pavements and structures. High-performance mixtures are required for all mainline systems. This introduced optimized aggregate to some of MDOT's smaller rural commercial batch plants which have a limited number of aggregate bins, making it difficult and in some cases impossible for a three aggregate blend to be used. Some of Michigan's commercial batch plants approached MDOT. The only way they could meet MDOT specifications was to preblend the coarse and intermediate aggregates. This blending occurred for a small amount of time. Then they presented data to MDOT showing that with a slight tweak to some of the individual sieve requirements they could meet the optimized aggregate requirements with the use of just two of MDOT's standard aggregate gradations.

During this discussion, OSU released research on the Tarantula Curve. The Tarantula Curve research supported this request and MDOT incorporated the modifications. Currently MDOT does not use the Tarantula Curve for optimized aggregate gradations. However, a multitude of aggregate gradations supplied to MDOT have been compared to the Tarantula Curve and they have all met the requirements. MDOT has also compared its specifications to the Tarantula Curve, and it was determined that if a blend meets MDOT's requirements it also meets the Tarantula Curve. For more details on MDOT's optimized aggregate specification, see section 3.09 (page 72) of the MDOT Materials Quality Assurance Procedures Manual (MQAP).

To help with the evaluation of optimized aggregate gradations, MDOT created an analysis tool through Microsoft Excel. This tool checks an aggregate gradation against all MDOT's optimized aggregate requirements. It also plots the workability versus coarseness factors and plots the combined sieve gradation. This optimized aggregate spreadsheet tool is available at MDOT's web site.

Overall optimized aggregate gradations have been accepted by both MDOT and the industry. Both have seen many benefits from using optimized aggregates. The biggest benefits have been a decrease in permeability and an increase in strength and workability. There was an initial concern from the industry about the cost associated with optimized aggregate gradations. However, the total paste content could be reduced without sacrificing strength. MDOT acknowledged this and used it as an opportunity to reduce the amount of Portland cement allowed in a high-performance concrete mixture, by requiring the use of SCMs. By doing this, the durability of the concrete improved. The industry realized that the total cementitious content could be reduced while still maintaining strength. This also provided the industry with a means to balance increased cost associated with optimized aggregates with the savings from not incorporating as much cement. The industry also brought to MDOT's attention that optimized aggregate gradations helped create a more consistent mix. Both MDOT and the industry appreciated this side benefit, especially because MDOT adopted percent-within-limits for quality assurance on mainline pavements.

Water-Cement Ratio and Water Content

MDOT specifies a maximum water-cement (w/c) ratio of 0.45 for all concrete except precast and prestressed. This is the maximum recommended w/c ratio for outdoor concrete exposed to freezing per ACI 318. However, MDOT does not have a lower specification limit for a w/c ratio. There are many contractors that have seen a benefit in their concrete mixtures when they keep their w/c ratio low. Some of the benefits include increased strengths, faster opening to traffic times, decreased permeability, and a reduction in freeze-thaw damage. Therefore, it is not uncommon to see mixture designs around 0.40 for pavements and structures. Contractors are still able to obtain the flowability/slump they are looking for, without the extra water. They are obtaining this by using liquid chemical admixtures (ASTM C494) which have water-reducing properties. To help with this reliance MDOT has a robust liquid chemical admixture qualified products program. This program is laid out in section 5.15 of the MDOT's Materials Quality Assurance Procedures Manual. To meet this need, the industry requested that MDOT create a midrange water-reducing admixture (MR) category which was to fill the gap between a Type A and F per ATM 494. MDOT agreed and created this unique category. Concrete paving mixtures typically use either a Type A or MR, with MR being the most popular. Structural concrete mixtures typically use either a MR or Type F.

Batch Tickets

MDOT requires all material weights to be displayed on the batch tickets. Theoretically the water-to-cement ratio could be calculated off the batch tickets. This works well when dealing with a central batch plant and just haul units. This occurs mainly on large paving operations. However, MDOT has run into difficulties at times with knowing the exact amount of water which is incorporated into a mix when a ready-mix truck is used. The amount of water which is displayed on the batch ticket is the amount of water the plant places into the truck. If there is excessive washout water in the truck or the driver adds water and the inspector is not informed, then the calculations can be off. MDOT does require the truck driver to inform MDOT personnel if and how much water was added. This is then recorded on the batch ticket.

MDOT currently still relies heavily on paper batch tickets. However, MDOT has been involved with many electronic and paperless batch ticket studies. MDOT has done a few electronic ticketing pilot projects and is transitioning toward requiring electronic ticketing on all projects in the future.

Microwave Phoenix

MDOT is aware of the water-to-cement ratio test (Phoenix) but currently is not pursuing the use of the microwave/Phoenix test for water content verification. MDOT is waiting to see if the testing equipment will become more compact and portable to allow for easier use in field applications.

Super Air Meter

MDOT has been actively involved with the SAM since 2014. MDOT, along with 17 other state DOTs, came together in a pooled-fund project, Improving Specifications to Resist Frost Damage in Modern Concrete Mixtures, TPF-5 (297). This study was focused on the development of the SAM. Then in 2017 MDOT joined another pooled-fund project, with 12 other states and FHWA, called Performance Concrete Engineered Paving Mixtures, TP-5 (368). This study's purpose is to focus on developing the next generation's performance-based specifications for concrete pavements. MDOT was also awarded STICs funds which were used to purchase SAMs and implement training. Currently MDOT owns 19 SAM meters.

MDOT first introduced the SAM meter by having statewide personnel take it out to jobsites and test concrete for informational purposes only. This provided statewide personnel the opportunity to begin evaluating the potential of the device and allowed construction personnel to get to know the device. This occurred for about 3 years. In 2017 MDOT had OSU personnel provide a training class on how to run the SAM meter. In attendance were MDOT personnel, a local agency rep, contractors, and concrete suppliers. After the training MDOT offered a SAM meter to each region for informational testing. The Metro Region took a SAM meter and tested on the I-75 Rouge River project. This testing was done by region staff.

With the upcoming 30- and 50-year pavement design life projects starting in 2018, MDOT mandated that SAM data be collected informational purposes only. The SAM testing was going to be performed by both MDOT construction staff and contractor personnel. Since MDOT was going to require field staff and the contractor to do the SAM testing, an SP would need to be created to maintain consistency.

Seeing the need to have an SP, the SAM shadow special provision was created, Pilot Field Testing for Determining the Air Content of Fresh Concrete Using the Sequential Air Metric Apparatus 12CF601. This special provision required SAM testing for each sublot (5 sublots are in a typical day's production) and to follow the testing procedures in AASHTO Provisional Test Method Designation TP 118-17, Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method. The SP required testing be performed on mainline pavement, barrier, and structural concrete. This SP also required SAM testing certification. This was done to ensure that every SAM meter operator has a solid understanding of how to run the device and that everyone is running the test in the same way.

With the help of OSU and the Michigan Concrete Association, a certification class was created. To date, OSU has performed two training classes for MDOT, and the Michigan Concrete Association has completed three certification classes.

In 2019 the SAM shadow SP was used again; it was used on the I-75 reconstruction near Monroe, Michigan. Along with the SAM shadow SP, OSU's SAM Predicted Response Tool was used on the project. This tool was designed to estimate whether the SAM meter was run correctly. Initially the results for running the test correctly were dismal, it indicated a large number of tests were run incorrectly. However, as the testers gained experience with the device the number of tests ran incorrectly decreased. For pavements, just over half of the tests were most likely run correctly, but for structures it was over 90%. Details on the results of this testing are below.

In 2020 the SAM shadow SP was again used. It was used on the I-496 reconstruction in Lansing, Michigan. The testing data from this project is currently being compared to hardened air results obtained from companion cylinders made on the project through Michigan's Centers of Excellence Program. The University of Michigan is performing the hardened air analysis of the companion cylinders.

On every project where the SAM meter was used, initially there was hesitation and concern. The biggest concern was the amount of time it takes to run the test. However, as the testers gained experience with running the device, the amount of time it took them to run it decrease greatly. By the end of each project this concern was gone. The other concern was that the SAM meter is complex and difficult to run, but after testers ran the device a few times, they realized it is not difficult.

Currently, MDOT is still evaluating the SAM meter. MDOT is working on trying to determine what will be an appropriate SAM number for a freeze-thaw durable concrete with Michigan's concrete mixtures. There are plans to continue to include the SAM shadow SP on projects in the future. Here are some valuable tips MDOT has learned while running the test:

1. Introduce the SAM meter in stages (allow people to get used to it)
2. Do not store wet SAM meters in the Pelican cases (mold will grow in the case and the SAM meter will have corrosion issues)
3. Ensure the SAM meter is at the same temperature as the ambient air temperature before running the test (may take longer than expected)
4. Always have spare batteries
5. Have a backup SAM meter for the project
6. Use the Shotgun (makes running the test easier)
7. Don't overthink the test (follow the gauge's directions)

Resistivity

Surface Resistivity

MDOT was performing surface resistivity testing but in the last year and a half, it has transitioned to using only the bulk resistivity method. MDOT performed surface resistivity testing on two long-life pavement projects for information only, as discussed in detail in the Implementation and Status section. MDOT also was performing surface resistivity on 40 freeze-thaw samples in the State Concrete Lab. Each material used in the concrete mixtures was then sampled, bagged, and shipped to an Oregon State University researcher along with the test data. The data from these two projects and what MDOT lab personnel witnessed while testing showed that there can be a high level of variability in the test. The US 131 project's variance of an individual sample (cylinder) was greater than one over 50% of the time. However, lessons MDOT learned that helped reduce the variability are as follows:

1. Ensure the tester holds the apparatus perpendicular to the surface (any skew seems to affect the results)
2. Avoid placing probes near or in surface voids
3. Avoid placing probes on large aggregates that are exposed
4. Ensure the water reservoirs on the device are always filled (between each cylinder always check that the reservoirs were filled)
5. Limit cylinder time out of curing environment (keep the cylinder surface at the same moisture level)

6. Ensure the battery isn't low on charge (notice the device will still give a reading but it will be inaccurate)

Bulk Resistivity

MDOT has been performing bulk resistivity testing for the last year and a half. Currently MDOT is still collecting data and evaluating the test method. However, MDOT has already seen a vast improvement in the repeatability of the test method when compared to surface resistivity testing. Another benefit of bulk resistivity is the reduction in testing when compared to surface resistivity. MDOT has been collecting bulk resistivity information through the freeze-thaw program and has used it on a few research projects. As of summer 2023, MDOT has neither created a shadow specification for a field project nor required its use in the field. Lessons MDOT has learned while running bulk resistivity are as follows:

1. Ensure the sponges used between the cylinder and the conductive plates are clean, not broken down, and still absorbent.
2. Soak the sponges for 10 minutes before starting testing (helps avoid dry spots in the sponges).
3. If testing on a metal surface place a non-conductive barrier between the testing apparatus and the table (even though there are little rubber pads on the conductive plates if the table is wet enough the table can affect the measurements).
4. Ensure the probe and alligator clamps are not touching a conductive surface.
5. Resoak sponges for a few seconds between each cylinder.
6. When replacing sponges ensure the sponge is large enough to completely cover the end of the cylinder.
7. Ensure the battery isn't low on charge (notice the device will still give a reading but it will be inaccurate).

Formation Factor

Currently MDOT is not performing the formation factor internally or requiring it to be performed on any projects. MDOT has reservations with the current curing practices (bucket curing). Some of MDOT's and the industry's labs have limited space for storage and cannot accommodate the number of buckets that would be required to perform this test on all projects. Both MDOT's and the industry's labs also vary in their current curing methods. Some use cure rooms while others use a limewater bath. Therefore, MDOT is going to wait until the formation factor's methods and procedures are finalized before deciding whether to pursue and require changes to both MDOT's and the industry's lab facilities.

Shrinkage

MDOT is currently not pursing shrinkage testing on a statewide project basis. There are some mass pours, unique placements, and research projects where MDOT has required the use of shrinkage testing. When MDOT does require shrinkage testing, the restrained ring test (ASTM C1581) has been used. MDOT has also used a sealed beam shrinkage test (University of Michigan test method) for research purposes. This test method can show the potential of autogenous shrinkage which can affect curling and warping of concrete pavements. Overall MDOT does not see shrinkage related distresses in pavements. This is mainly due to MDOT's concrete pavements being jointed plain concrete pavements with a joint spacing of 12 to 16 feet. Also, cracking of bridge decks is not a major concern. MDOT Design standards include cracking in their calculations. Therefore, if the cracks do not open or become "working cracks," they are not a concern. With the use of SCMs and optimized aggregates, MDOT obtains a non-permeable mixture, so chloride intrusion is minimal (confined to the crack surfaces). MDOT also places enough steel reinforcement in bridge decks to keep the cracks tight and has vigorous bridge deck curing practices. MDOT also has a robust concrete curing process which consists of a two-phase, 7-day, wet-cure. For bridge deck curing practices, see section 706 of MDOT's 2020 Standard Specifications for Construction.

Workability

MDOT currently is not pursing the use of the Box Test or the Vkelly test. MDOT views these as good quality control tests for the contractor to perform. By performing these tests, the contractor can ensure they are obtaining the correct amount of workability prior to placement. However, MDOT is not witnessing enough issues with workability to request the contractor to perform these tests. MDOT visually inspects all its critical concrete placements along with QA testing and feels that any possible issues with workability will be caught in the field.

Oxychloride Testing

MDOT is currently not pursing oxychloride testing.

Implementation and Status

I-75 Rouge River Bridge Rehabilitation

In 2017 I-75 from Goddard Road to the Rouge River and at various locations along I-75 in the cities of Allen Park, Southgate, Lincoln Park, Detroit, Melvindale, and Wayne County were repaired and partially reconstructed. This total project length was 4.41 miles. The project consisted of concrete pavement repair, bridge rehabilitation on six structures, removal of two structures, and construction of four structures, and reconstruction of 0.63 mi of roadway. MDOT’s standard and HP concrete mixtures per Table 1004-1 (Table 9) were used. The SAM meter was used to sample bridge deck concrete for informational purposes. The concrete met the requirements of a grade 4500HP concrete. A total of 18 samples were collected, all of which were below a SAM number of 0.3 with approximately 72% of them below 0.25. Overall, the SAM indicated that the concrete being used for bridge decks on this project was freeze-thaw resilient. More information on the SAM testing is in Table 10.

Table 10 Rouge River SAM #

Rouge River SAM # Comparision			
SAM #	# >0.3	0	0.0%
	0.3≥ # >0.25	5	27.8%
	0.25≥ # >0.2	9	50.0%
	# ≤0.2	4	22.2%

MDOT was also interested in how the SAM number compared to the total plastic air content. There was no direct correlation that MDOT could draw between the SAM number and total plastic air content as displayed in Figure 28. All the samples were within MDOT’s total plastic air content rejection limits (5% to 9%) and the SAM numbers were below 0.3. Thus, this concrete should be durable against freeze-thaw.

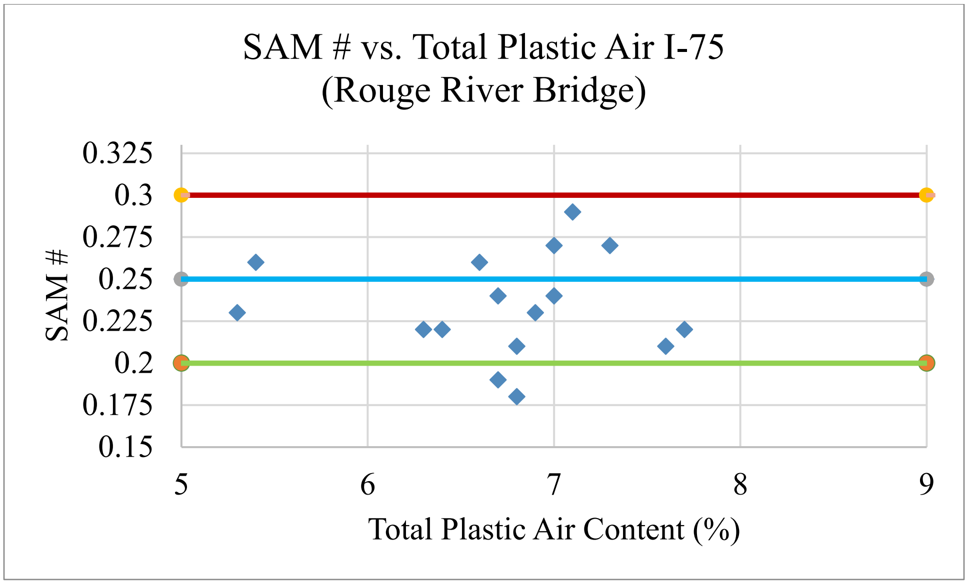

Figure 28 Rouge River SAM # vs. plastic air content.

US 131 Reconstruction North of Grand Rapids, Michigan (50-year pavement design life)

In 2018 the US 131 pavement from 10 Mile Road M-57 (14 Mile Road) in Kent County was fully reconstructed. This total project length was 4.35 miles. Two lanes with shoulders were reconstructed for both northbound and southbound. The northbound section was constructed using MDOT's normal methods for the time. The southbound section was constructed using the selected PEM methods. One area of focus was on creating a stabilized base and subbase. The base was a cement-treated permeable base. The subbase was treated with a few different materials and products. The dowel bars for bridging the load at the joints were also an area of focus for the 50-year design. These dowel bars were required to be coated with a highly durable epoxy coating (purple bar coating). Proper curing was another focus which led MDOT to create a SP specific for concrete pavement curing.

There were no special requirements for the concrete mixture. Therefore, a concrete mixture meeting the requirements of grade 3500HP (formally called a P1M) per Table 1004-1 (Table 9) was required. This concrete mix had a 30% slag cement replacement and had a total cementitious content of 490 lb/cy. The concrete mixture also incorporated an optimized aggregate gradation consisting of a course, intermediate, and fine aggregate. The optimized aggregate gradation had to meet the requirements of the MDOT optimized aggregate gradations, currently in section 3.09 of the MQAP. The water-cement ratio for this mixture was a 0.42, which was 0.03 below the maximum allowable. Both an air-entraining liquid chemical admixture and a water-reducing liquid chemical admixture were used. The exact proportions of the concrete mixture (per cubic yard) are provided in Table 11.

Table 11 Batch Weights for US 131 Concrete

Material Type		Manufacture/Supplier	Weights (lbs.)
Aggregates	Coarse (Limestone)	Carmeuse-Port Inland	1090 (SSD)
	Intermediate (Limestone)	Cameuse-Port Inland	820 (SSD)
	Fine	Grand Rapids Gravel-Boulder Creek	1334 (SSD)
Cementitious Materials	Portland Cement (Type 1)	Lafarge-Alpena	343
	Slag Cement (Grade 100)	Lafarge-South Chicago	147
Admixtures	Air Entrainer	ConAir 260 Premiere Admixtures	NA
	Water-Reducer	OptiFlo 500 Premiere Admixtures	NA
Water		Well Water	206

The SAM meter was used to sample the concrete pavement mixture for informational purposes. A total of 50 samples were collected. 90% of these samples were below a SAM number of 0.3 with approximately 84% of them being below 0.25 and 62% of the samples falling below 0.2. Overall, the SAM indicated that the concrete being used for the pavement on this project was freeze-thaw resilient. SAM testing results are in Table 12.

Table 12 SAM # for US 131

50 Year Design Life (US-131)			
SAM #	# >0.3	5	10.0%
	0.3≥ # >0.25	3	6.0%
	0.25≥ # >0.2	11	22.0%
	# ≤0.2	31	62.0%

MDOT also recorded and compared the SAM number to the total plastic air content. There was no direct correlation that MDOT could draw between the SAM number and total plastic air content as displayed in Figure 29. The only conclusion that could be drawn was that almost all the samples that were within MDOT’s total plastic air content rejection limits (5% to 9%) also had SAM numbers that were below 0.25. This indicated that this concrete should be durable against freeze-thaw.

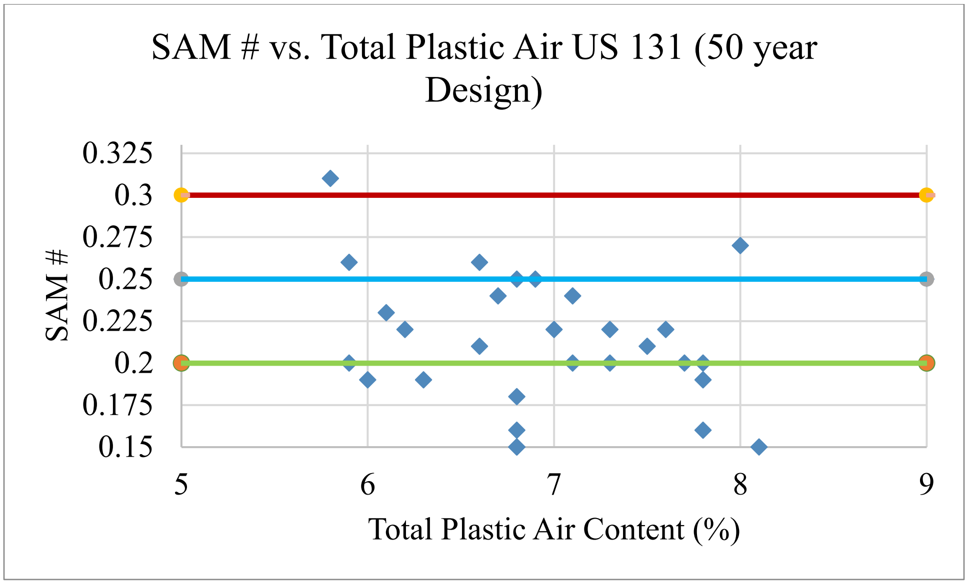

Figure 29 SAM # vs. plastic air US 131.

Another test that MDOT performed for informational purposes only on this project was surface resistivity. A total of 376 tests were performed. None of these tests indicated that the concrete was going to have high permeability. Most of the samples indicated that the concrete was going to have low permeability, with approximately 93% of the tests falling in this category. Therefore, surface resistivity pointed toward the concrete mixture being dense and indicated it will resist/limit chloride and water penetration. The surface resistivity testing results are in Table 13 and Figures 30 and 31.

Table 13 Surface Resistivity for US 131

Surface Resistivity (US-131)			
Permeability	High (9.5> #)	0	0.0%
	Moderate (16.5≥ # >9.5)	16	4.3%
	Low (29≥ # >29)	351	93.3%
	Very Low (# >29)	9	2.4%
	Average kΩ-cm:		21.5

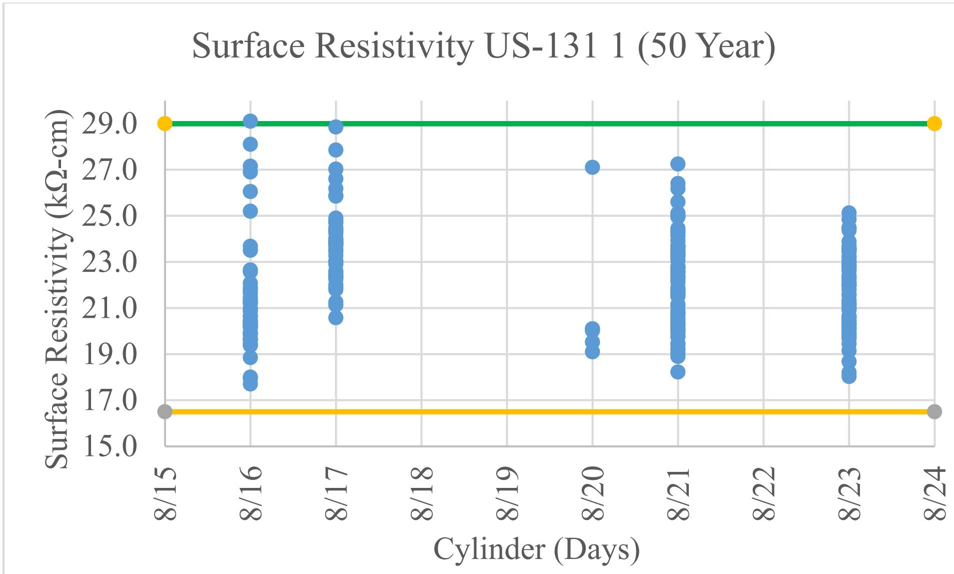

Figure 30 Surface resistivity for US 131 Part 1.

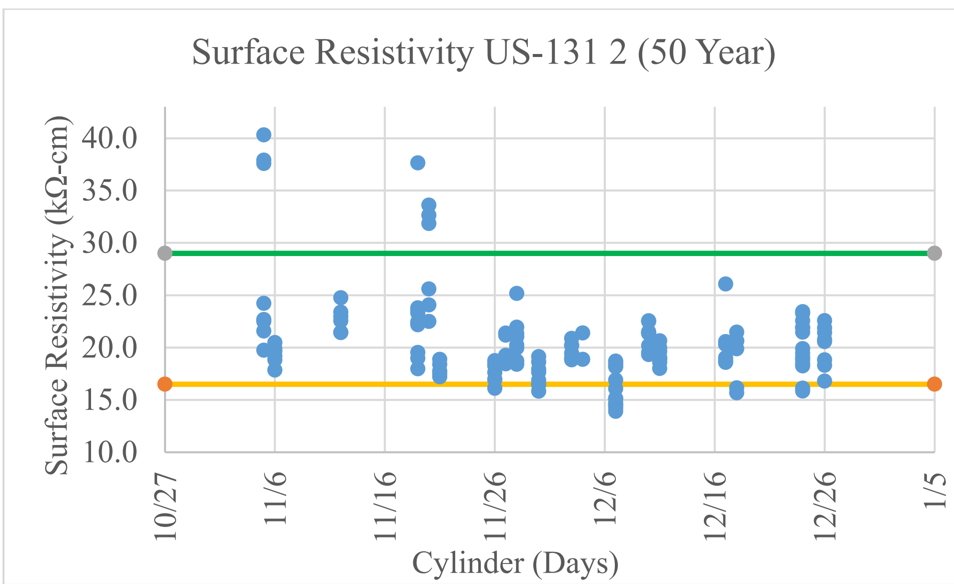

Figure 31 Surface resistivity for US 131 Part 2.

MDOT found a lot of fluctuation between each surface resistivity check on the same cylinder. Even when the same location on the cylinder was retested a different result was sometimes provided. To find out the variability in the test, MDOT took the results of each surface check on an individual cylinder (total of 8 for a cylinder) and calculated the variance of each cylinder. The results were that the average variance for the project was 4.0 and more than half of the cylinders had a variance greater than 1. This created concern about the repeatability of this test method. This became one of the leading reasons for MDOT to transition to bulk resistivity testing. Information on the variance of a cylinder when running surface resistivity is in Table 14 and Figure 32.

Table 14 Surface resistivity variance for US 131

Surface Resistivity (US-131)		
Variance per Cylinder	>1	192
	<1	184
	Average:	4.0
	<1	48.9%

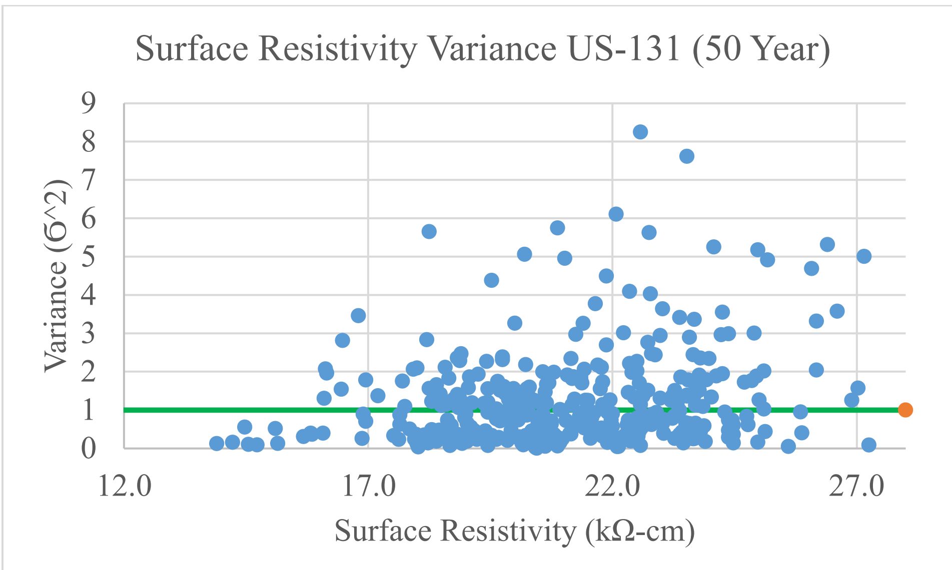

Figure 32 Surface resistivity variance for US 131.

I-69 Reconstruct Through Flint, Michigan (30-year pavement design life)

In 2018 the I-69 pavement through the city of Flint, Michigan was fully reconstructed. This totaled to a project length of 2 miles. Multiple lanes with shoulders were reconstructed for both east and west bound. The eastbound section was constructed using MDOT’s normal methods for the time. The westbound section was constructed using MDOT selected PEM methods. One area of focus was on creating a stabilized base; a cement-treated permeable base was used. Just the standard epoxy coated dowel bars (green bars) were required for this project. Proper curing was another focus and led MDOT to create a SP specific for concrete pavement curing.

There were no special requirements for the concrete mixture. Therefore, a concrete mixture meeting the requirements of grade 3500HP (formally called a P1M) per Table 1004-1 (Table 9) was required. This concrete mix had a 25% fly ash replacement and had a total cementitious content of 500 lb/cy. The concrete mixture also incorporated an optimized aggregate gradation consisting of a coarse, intermediate, and fine aggregate. The optimized aggregate gradation had to meet the requirements of the MDOT optimized aggregate gradations, currently residing in section 3.09 of the MQAP. The water-cement ratio for this mixture was 0.44, which was 0.01 below the maximum allowable. Both an air-entraining liquid chemical admixture and water-reducing liquid chemical admixtures were used. The exact proportions of the concrete mixture (per cubic yard) are provided in Table 15.

Table 15 Concrete Mixture Design for I-69

Material Type		Manufacture/Supplier	Weights (lbs.)
Aggregates	Coarse (Limestone)	Presque Isle	919 (Dry)
	Intermediate (Limestone)	Presque Isle	874 (Dry)
	Fine	Holly Plant	1287 (Dry)
Cementitious Materials	Portland Cement (Type 1)	Lafarge-Alpena	375
	Fly Ash (Type F)	Boal/Monroe	125
Admixtures	Air Entrainer	ConAir Premiere Admixtures	NA
	Water-Reducer	OptiFlo 500 Premiere Admixtures	NA
	Water-Reducer	OptiFlo Plus Premiere Admixtures	NA
Water		Municipality	220

The SAM meter was used to sample the concrete pavement mixture for informational purposes. A total of 21 samples were collected. 95% of these samples were below a SAM number of 0.3 with approximately 71.5% below 0.25, and 28.6% of the samples below 0.2. Overall, the SAM indicated that the concrete being used for the pavement on this project was freeze-thaw resilient. More information on the SAM testing results is in Table 16.

Table 16 SAM # for I-69

30 Year Design Life (I-69)			
SAM #	# >0.3	1	4.8%
	0.3≥ # >0.25	5	23.8%
	0.25≥ # >0.2	9	42.9%
	# ≤0.2	6	28.6%

MDOT also recorded and compared the SAM number to the total plastic air content. There was no direct correlation that MDOT could draw between the SAM number and total plastic air content as displayed in Figure 33. The only conclusion that could be drawn was that almost all the samples that were within MDOT's total plastic air content rejection limits (5% to 9%) also had SAM numbers that were below 0.25. This indicated that this concrete should be durable against freeze-thaw.

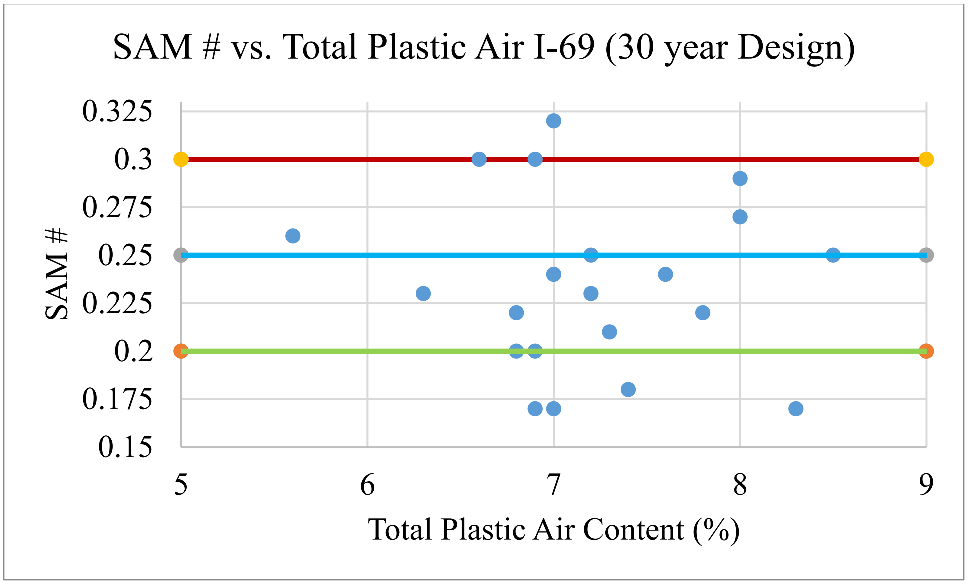

Figure 33 SAM # vs. plastic air I-69.

MDOT had hardened air analysis by the linear traverse method performed on nine samples. The hardened air analysis showed that all the samples were within MDOT's rejection limits for air content (5% to 9%). Also, there was a general trend that was found, as shown in Figure 34. The trend was that as the hardened air went up, the SAM number went down. There was one outlier to this general trend. The hardened air and SAM number both indicated that the concrete will be freeze-thaw durable.

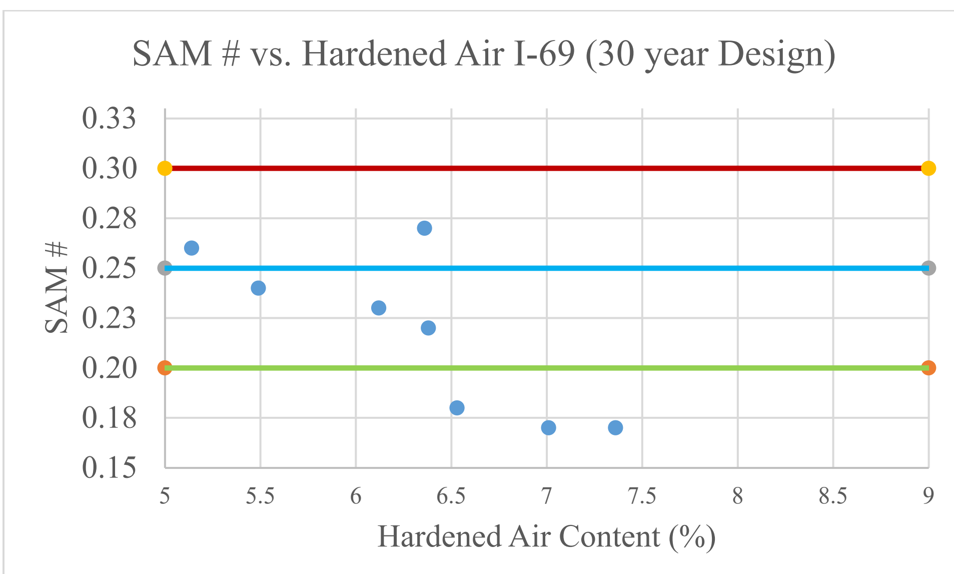

Figure 34 SAM # vs. hardened air I-69.

While the hardened air analysis was being performed, the spacing factor was calculated for each sample. There was no real trend between the SAM number and the spacing factor, as shown in Figure 35 below. And only about 67% of the samples had a spacing factor less than 0.008 inches.

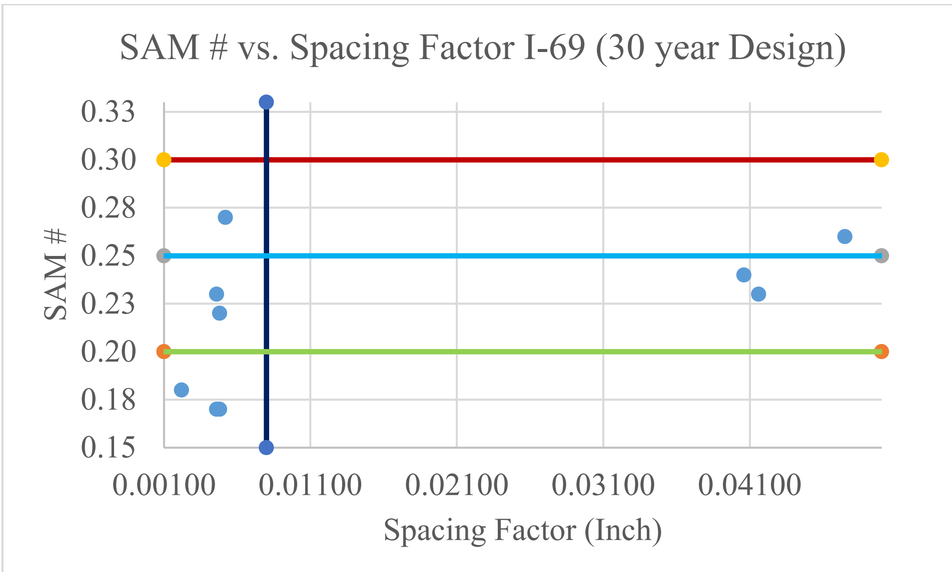

Figure 35 SAM # vs. Spacing Factor I-69.

Surface resistivity was also tested on this project for informational purposes only. A total of 186 tests were performed. None of these tests indicated that the concrete was going to have high permeability. Most of the samples indicated that the concrete was going to have moderate permeability, with approximately 65.6% of the tests falling in this category. Therefore, surface resistivity pointed toward the concrete mixture being somewhat dense and limiting or slowing chloride and water penetration. More information on the surface resistivity testing results is in Table 17 and Figure 36.

Table 17 Surface Resistivity I-69

Surface Resistivity (I-69)			
Permeability	High (9.5> #)	0	0.0%
	Moderate (16.5≥ # >9.5)	122	65.6%
	Low (29≥ # >29)	64	34.4%
	Very Low (# >29)	0	0.0%
	Average kΩ-cm:		15.9

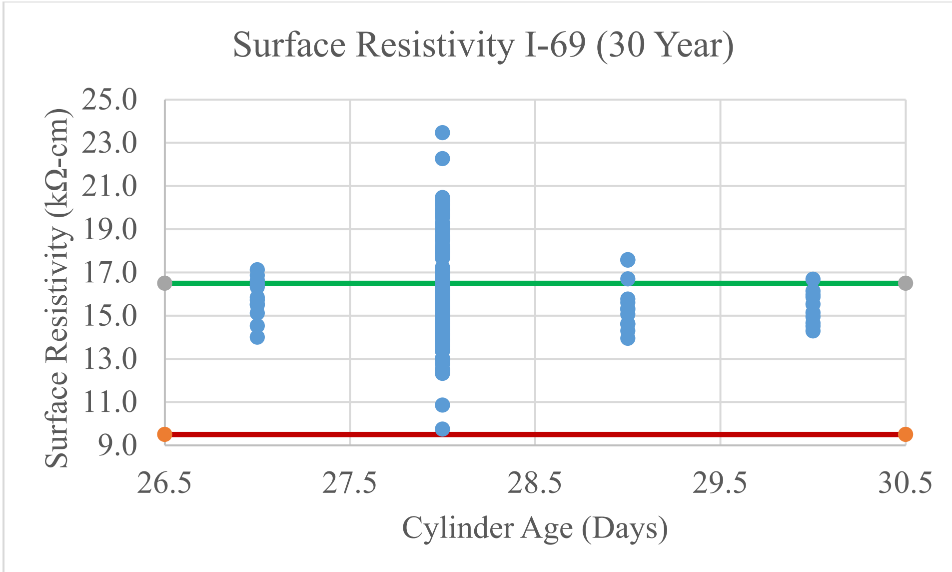

Figure 36 Surface resistivity I-69.

Just like in the US 131 project, DOT staff noticed a lot of fluctuation between each surface resistivity check on the same cylinder. MDOT staff again took the results of each surface check on an individual cylinder (total of 8 for a cylinder) and calculated the variance of each cylinder. They discovered that the average variance for the project was 1.2 but almost 68% of the cylinders had a variance less than 1. Even though the variance was better for this project there were still a lot of cylinder tests that had a significant amount of variability. Therefore, this did not alleviate concern about the repeatability, but rather confirmed MDOT's decision to transition to bulk resistivity testing. More information on the variance of a cylinder when running surface resistivity is in Table 18 and Figure 37.

Table 18 Surface Resistivity Variance I-69

Surface Resistivity (I-69)			
Variance per Cylinder	>1	60	
	<1	126	
	Average	1.2	34.4%
	<1	67.7%	

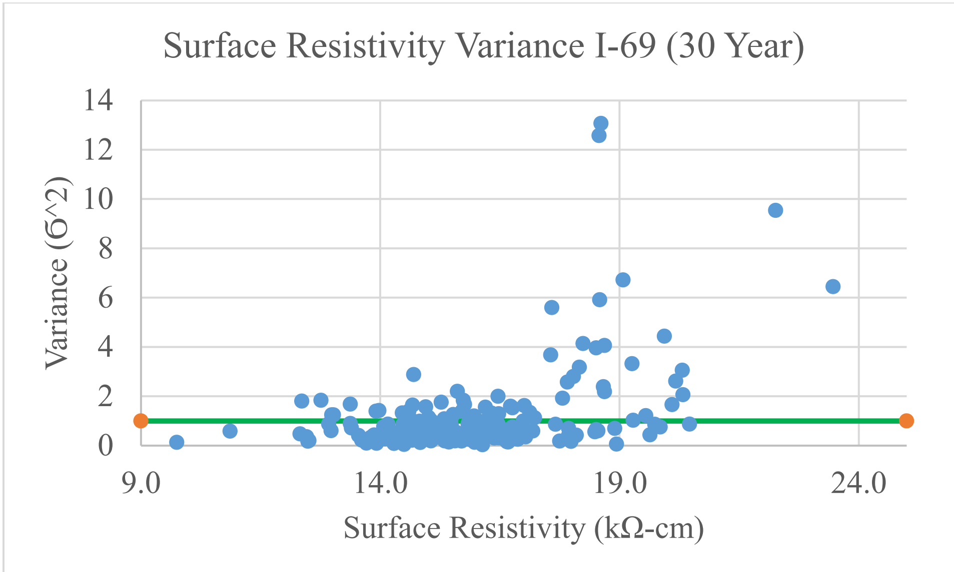

Figure 37 Surface resistivity variance I-69.

I-75 Reconstruct near Monroe, Michigan

In 2019, a project with a length of 5.06 miles on I-75 from the Michigan-Ohio state line to Erie Road in Monroe County was reconstructed. The project consisted of pavement reconstruction using concrete, bridge rehabilitation on two structures, and reconstruction of nine structures. MDOT's standard and HP concrete mixtures per Table 1004-1 (Table 9) were used. The SAM meter was used to sample HP concrete for bridge deck and pavements. The concrete met the requirements of a grade 4500HP concrete for the bridge decks and 3500HP for the pavement.

A total of 208 samples were collected during concrete paving. From these samples, 77.4% were below a SAM number of 0.3. Approximately 68.8% of the samples were below a SAM number of 0.20. Overall, the SAM indicated that most of the concrete being used for the pavement was freeze-thaw resilient with the possibility of some being questionable. More information on the SAM testing is in Table 19.

Table 19 SAM # Paving All Tests I-75

Paving Application (All Tests)			
SAM #	# >0.3	47	22.6%
	0.3≥ # >0.25	18	8.7%
	0.25≥ # >0.2	0	0.0%
	# ≤0.2	143	68.8%

Some of the SAM numbers were outliers, and the SAM must have been run incorrectly. As seen in Figure 38 some of the SAM readings were above a value of 1, indicating something was wrong.

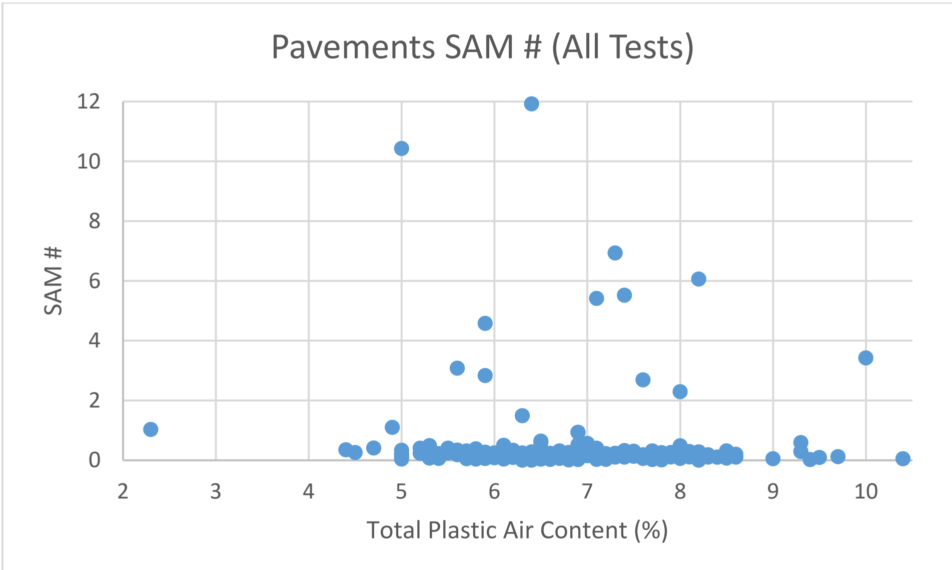

Figure 38 SAM # paving all tests I-75.

OSU had released a tool to determine if the SAM meter was run correctly. When the data was run through this tool, only about 54% of the tests on the paving concrete were likely to be correct, as shown in Table 20.

Table 20 SAM # Likely Correct I-75

Paving Application				Structural Applications	
Consultant 1		Consultant 2		Consultant 2	
Likely Correct	Ran Incorrectly	Likely Correct	Ran Incorrectly	Likely Correct	Ran Incorrectly
128	110	6	2	89	9
% Likely Correct	53.8	% Likely Correct	75.0	% Likely Correct	90.8

After using OSU's check tool, MDOT hoped for improved results. The tool removed outliers that had high SAM numbers and determined that a large portion of the low SAM numbers were likely to have been run incorrectly. After removing all the incorrect tests, a total of 128 samples remained. From these samples, 83.6% were below a SAM number of 0.3. The percentage of the samples below 0.3 improved. However, the percent of cylinders below a SAM number of 0.20 dropped to 51.6%. Thus, by running the OSU tool, the SAM's prediction of durable concrete improved. There was also no direct correlation that MDOT could draw between the SAM number and total plastic air content. Overall, the SAM indicated that most of the concrete being used for the pavement was freeze-thaw resistant with the possibility of some being questionable. More information on the SAM testing is in Table 21 and Figure 39 below.

Table 21 SAM # Paving Likely Correct I-75

Paving Application (Likely Correct Tests)			
SAM #	# >0.3	21	16.4%
	0.3≥ # >0.25	17	13.3%
	0.25≥ # >0.2	24	18.8%
	# ≤0.2	66	51.6%

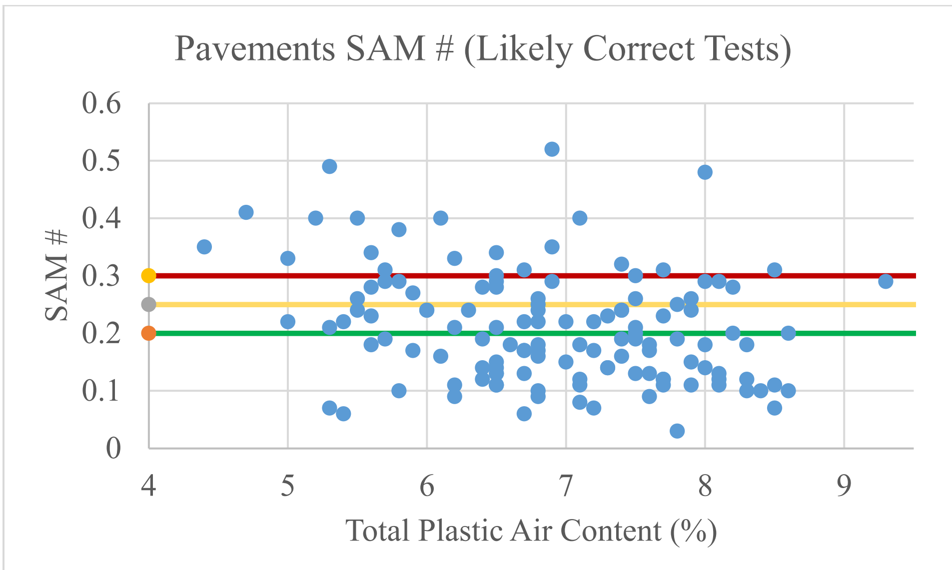

Figure 39 SAM # paving all likely correct I-75.

A total of 98 samples were collected during bridge deck pours, of which 98% were below a SAM number of 0.3. Approximately 89.8% of the samples were below a SAM number of 0.20. Overall, the SAM indicated that the concrete being used for the bridge decks was freeze-thaw resilient. More information on the SAM testing is in Table 22.

Table 22 SAM # Structural All Tests I-75

Structural Application (All Tests)			
SAM #	# >0.3	2	2.0%
	0.3≥ # >0.25	2	2.0%
	0.25≥ # >0.2	6	6.1%
	# ≤0.2	88	89.8%

However, some of the SAM numbers were high and these could be outliers as well. As seen in Figure 40, some of the SAM readings were above a value of 0.5, indicating that possibly the SAM meter was run incorrectly.

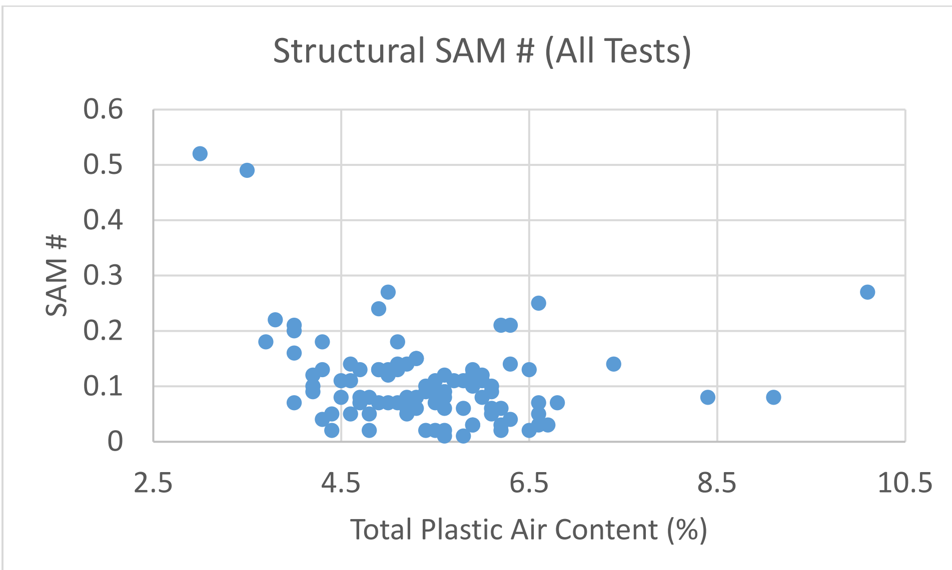

Figure 40 SAM # structural all tests I-75.

Again, the OSU tool was used to determine if the SAM meter was run correctly. It produced a result that about 91% of the tests that were run on the bridge deck concrete were likely to be correct (Table 20). After removing all the incorrect tests, a total of 89 samples remained. From these samples, 97.8% were now below a SAM of 0.3 and 89.9% were below a SAM of 0.20. Therefore, there was no significant change in the SAM number's overall prediction of the concrete. There was also no direct correlation that MDOT could draw between the SAM number and total plastic air content. Overall, the SAM still indicated that most of the concrete being used for bridge decks was freeze-thaw resilient. For more information on the SAM testing, see Table 23 and Figure 41.

Table 23 SAM # Structural Likely Correct I-75

Structural Application (Likely Correct Tests)			
SAM #	# >0.3	2	2.2%
	0.3≥ # >0.25	1	1.1%
	0.25≥ # >0.2	6	6.7%
	# ≤0.2	80	89.9%

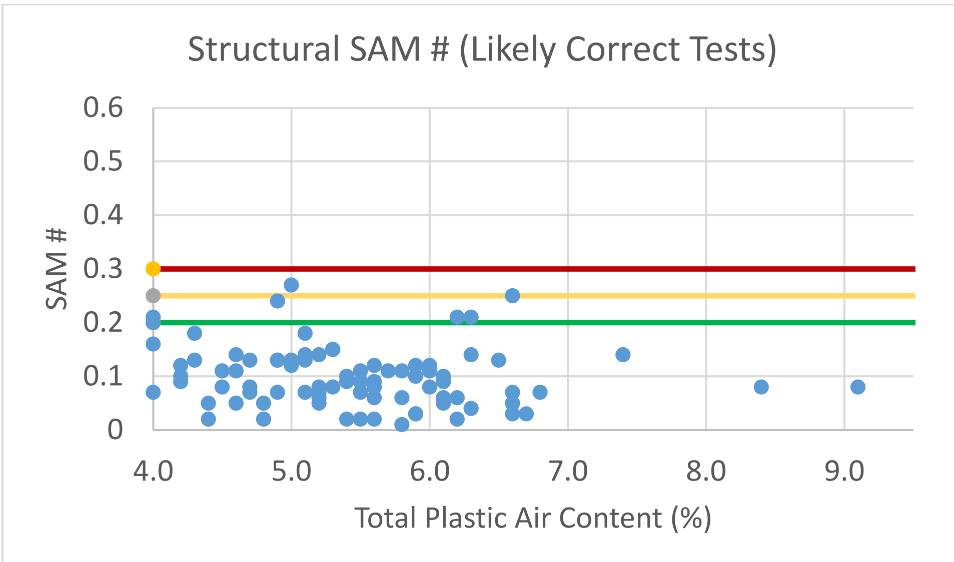

Figure 41 SAM # structural likely correct I-75.

Conclusions

MDOT has been incorporating and using aspects of PEMs for decades and will continue to pursue new methods to increase concrete durability. However, like with all new ideas and technology, it takes time to implement and to overcome the proverbial learning curve. This is also true with PEMs and AASHTO PP 84. At first there was a dislike for them and resistance to embrace them. However, as industry and MDOT personnel learned about PEM approaches and tests and gained experience, they began to embrace them. Michigan is still in the learning curve phase for AASHTO PP 84 test methods. Therefore, MDOT continues to engage and work with industry partners and regional personnel through presentations, meetings, and pilot projects. At this time, MDOT is unsure what PEMs and AASHTO PP 84 methods or tests will be implemented or how they will be used.

However, MDOT is aware that with changing service demands, supply chain issues, and the aging of Michigan's infrastructure, the use of PEMs will be a best practice and a necessity. Working with and partnering with industry counterparts will provide the means to maintain the state's current infrastructure and prepare for the future. This will no doubt require the continued use of SCMs, optimized aggregate gradations, PEMs, and new innovative methods for determining the durability of concrete mixtures to ensure the life span of the system is not only met but exceeded. Therefore, MDOT has no plans to remove the requirement to use SCMs/optimized aggregate gradations in concrete or PEM practices that it has already adopted.

Chapter 5

New York State's PEM Experience

Summary

Over the past several years, NYSDOT has been working on developing a PEM specification. The goal of the specification is to reduce the carbon footprint of a typical NYSDOT construction project without impacting the quality and lifespan of the concrete on NYSDOT's projects. At the start of the 2020 construction season, a project using NYSDOT's structural PEM specification broke ground. The project was the replacement of the bridge carrying Route 29 over the Batten Kill in Saratoga Country. The use of optimized gradations and reduced cement paste in the performance engineered mix developed for this project created a significant reduction in cement when compared to the traditional NYSDOT prescriptive concrete mixture. An estimated 38,850 pounds of cement were saved.

Based on the lessons learned from NYSDOT's initial experience, some changes have been made to the specification. First, expectations for a QA/QC plan from the producer have been moved to the beginning of the specification to highlight their importance. Also, a meeting with the contractor, concrete producer, and NYSDOT is required early in the project to discuss the specification and answer questions. Moving forward, NYSDOT will only be using the Tarantula Curve and has called out the specific sieves to be used in an aggregate sieve analysis to remove confusion regarding the optimized gradation. A sieve analysis is now required to be included with the mixture design. Another change increases the paste content from 25% to 27%. The 25% paste content originated in the pavement PEM specification and the increase addresses workability concerns for finishing. The option to use a 6-inch by 12-inch cylinder as a resistivity sample option was removed to avoid confusion and conversion factors as NYSDOT moves to all 4-inch by 8-inch cylinders. Also, submission deadlines were increased from 30 days to 45 days to allow more time for communication and mix adjustments. NYSDOT is also continuing to monitor the data collected during QA/QC operations and will continue to evaluate and update the pay factor section of the specification prior to implementation.

The optimized gradations and reduced cement paste in the performance engineered mixture developed for this project created a significant reduction in cement when compared to the traditional NYSDOT prescriptive concrete mix that would have typically been used. An estimated 38,850 pounds of cement were saved. The two PEM projects NYSDOT has completed have provided lessons for improvement while still producing a successful project. NYSDOT is continuing to work with its contractors and material

suppliers to advance these specifications and has two PEM projects and an additional six projects planned across the state for 2022.

Background

Over the past several years, NYSDOT has been working on developing a PEM specification. The goal of the specification is to reduce the carbon footprint of a typical NYSDOT construction project without impacting the quality and lifespan of the concrete on its projects. Following the guidance of AASHTO PP 84, Standard Practice for Developing Performance Engineered Concrete Pavements, a specification was drafted and NYSDOT's first PEM project was for highway pavements on NY Route 7, north of the city of Albany. Approximately 1,300 cubic yards of standard paving concrete was placed in various 9-inch-thick, 12-feet-wide, full-depth pavement slab repair areas ranging in length from 10 feet to 120 feet. Concrete placement on the project began on May 01, 2019, and was completed on May 31, 2019. Overall, the project went well. There were some issues with surface resistivity readings requiring extra time to meet specified values, but the mixture developed higher compression strengths, flexural strengths, and surface resistivities than are expected from the standard NYSDOT pavement mix. A full report on this project can be found in: TPF-5(368) Performance Engineered Concrete Paving Mixtures, Performance Engineered Concrete Pavement Mixture Pilot Project: Contract # D263826: NY Route 7.

An expanded structural concrete version of the highway concrete PEM specification was developed and at the start of the 2020 construction season, a project (Contract D264040) using the NYSDOT's structural PEM specification broke ground. The project was the complete replacement of the bridge carrying Route 29 over the Batten Kill (BIN 1020720, Figure 42) in Saratoga Country. The structure had a 215-foot 6-inch span with an AADT of 9,146 vehicles a day, of which 8.4% were trucks. To maintain traffic flow, the construction was split into two stages which left a single lane open to traffic during construction.

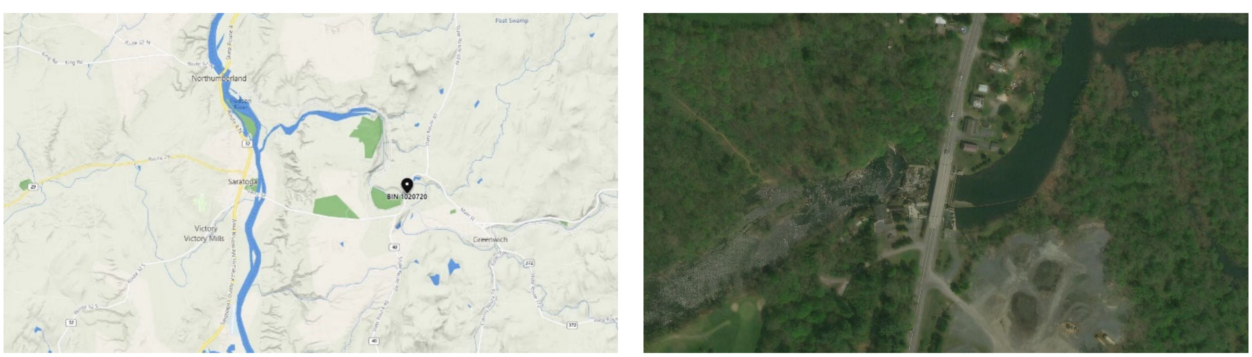

Figure 42 Location map of the structure.

Pilot Program

The structural PEM pilot specification was used solely as a shadow specification to gather information, check protocols, and look for improvements or clarifications in the specification wording. The specification does include pay factor language for concrete materials not meeting certain criteria such as compression strength or target resistivity levels, however, in this initial shadow effort, none of the pay factors was in effect.

The specification called for a 25% paste content in the mixture design (as originally specified in the Highway PEM), a SAM reading of 0.20 or less with an air content of 5% to 9%, a minimum compression strength of 4000 psi, and a minimum resistivity requirement that can vary based on the element being poured. The 25% paste content is aimed at reducing the amount of cement in the mix which reduces the concrete's carbon footprint. A low SAM reading during design allows for some fluctuations during full load batching and transport, and the test result is a predictive measurement of the mix's freeze-thaw durability. Statistically, a SAM reading under 0.30 will have good freeze-thaw resistance. The surface resistivity reading quantifies a concrete's resistance to chloride ion penetration. For structural concrete above a footing, a surface resistivity greater than 30 kΩ-cm is required at 28 days.

The contractor was having some issues with the mixture's workability during the substructure placements and was concerned about how a bridge deck would finish. Additionally, supply issues dictated a sand source change. NYSDOT worked with the concrete supplier to adjust the mixture up to a 27% paste content. In the end, there were three iterations of the mixture: the original with a 25% paste, an intermediate mixture with the new sand source that was never placed on-site, and the final mixture with the increased paste content and new sand source. The three designs are shown in Table 24, and the original mix design's Tarantula Curve is shown in Figure 43.

Table 24 Mixture Designs

	Original Mix	Intermediate Mix (not used)	Final Mix
Cement	425 lb	425 lb	425 lb
Flyash	115 lb	115 lb	135 lb
Microsilica	35 lb	35 lb	35 lb
Fine Aggregate	1110 lb	1110 lb	1053 lb
Coarse Aggregate 1	282 lb	282 lb	275 lb
Coarse Aggregate 2	740 lb	1711 lb	1667 lb
Water Reducer	17.25 oz	23.00 oz	12.00 oz
Super Plasticizer	24.40 oz	24.00 oz	16.00 oz
Water	26.40 gal	26.40 gal	30.50 gal
Entrained Air	5" – 9%	5" – 9%	5% - 9%
Water/Cement Ratio	0.38	0.38	0.43
Slump	3" – 5"	3" – 5"	3" -5"

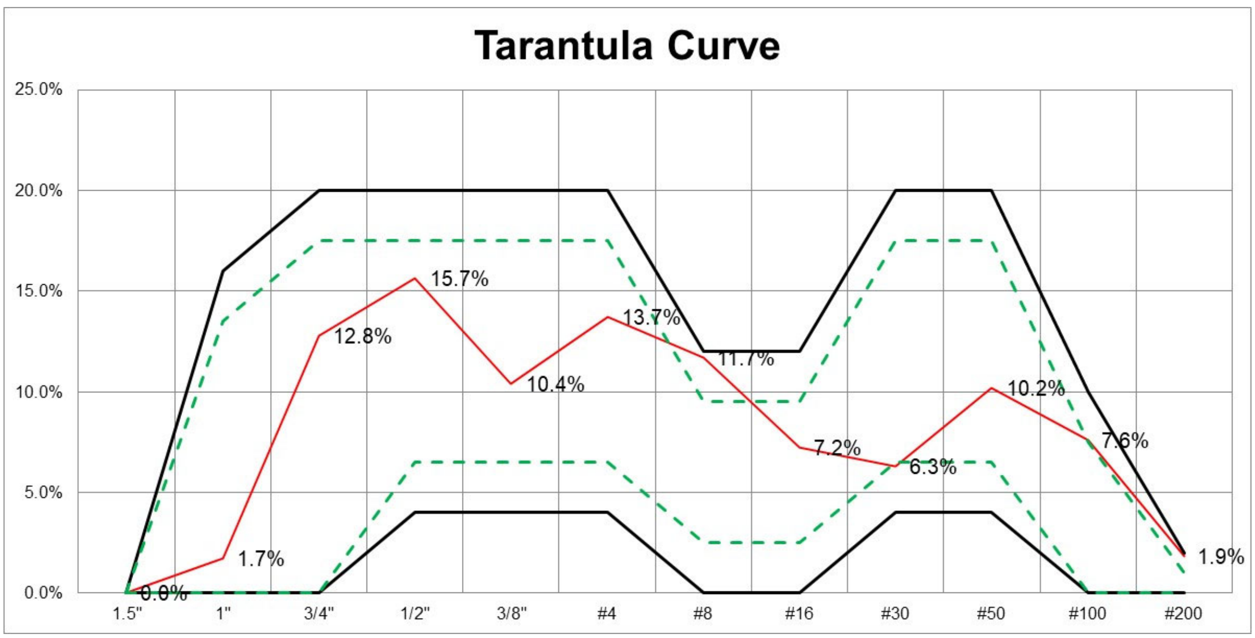

Figure 43 Tarantula Curve for the original mix.

Due to site considerations and traffic, the concrete was placed by a crane or excavator with a concrete bucket as well as a concrete pump truck (Figure 44). No separation of the mixture was observed when using either method. When discussing the mixture, the pump truck operator said the mix wasn't a perfect pumping mix and there were some minor pressure spikes, but overall, pumping the mix was not a problem.

Figure 44 Typical concrete placements on-site.

Material Testing

NYSDOT personnel were on-site during the concrete pours to take SAM readings. All the SAM readings taken in the field are shown in Tables 25 and 26, divided by project stage. During the design trial, the SAM reading in the lab was 0.18. While there were a few errors or lost readings, only three of the SAM readings were above 0.30 and each of these high SAM readings was accompanied by acceptable SAM numbers as testing continued during the pour. The contractor rejected one truck for having low air, but other than these few exceptions, the field testing of the concrete went well.

Table 25 Field Measurements Taken in the Field During Stage 1

Date	Truck #	Slump (in)	Concrete Temp (°F)	Air Temp (°F)	Air % (Pot)	Air % (SAM)	SAM#	Element Poured
6/3/2020	1	4.25	75	70	5.1	5.2	0.46	Footing
	2	5.00	75	70	6	5.9	0.13	
6/9/2020	1	4.25	73	66	7.2	7.4	0.22	Footing
	2	5.00	74	66	6.8	6.8	0.22	
6/12/2020	1	3.50	78	79	5.6	5.9	0.17	Stem
	rejected	5.00	79	78	3.9	4.1	0.22	Wing Wall
	3	3.00	80	75	6.2	6.4	0.15	
	4	4.00	79	74	5.2	5.0	0.18	
6/17/2020	1	5.25	82	83	12.0	11.9	0.18	Wing wall
	2	3.00	86	85	8.5	8.5	error	
	3	5.25	85	84	8.5	8.0	error	Stem
6/23/2020	1	5.00	90	82	5.8	5.9	0.23	Back Wall
	2	3.25	90	83	6.0	9.2	0.14	
		4.00	90	84	6.0	5.4	0.27	
6/29/2020	1	3.00	82	79	6.5	6.2	0.26	Pedestals
7/30/2020	1	3.50	82		5.5	5.5	0.24	Deck
	2	6.50	82	69	8.9	8.8	0.17	
	7	4.00	82		8.9	8.2	0.13	
	11	6+	85	82	4.5	4.6	0.19	
7/31/2020	1	6.00	76	62	6.0	-	-	Wing Wall
8/4/2020	1	6.00	80	70	7.0	6.5	0.21	Sleeper
8/6/2020	1	-	-	-		-		Crane Pad

Table 26 Field Measurements Taken in the Field During Stage 2

Date	Truck #	Slump (in)	Concrete Temp. (°F)	Air Temp (°F)	Air % (Pot)	Air % (SAM)	SAM#	Element Poured
9/16/2020	1	5.00	72	65	6.5	-	-	Footing
9/21/2020	1	5.00	68	65	5.8	5.4	0.22	Stem
	2	5.00	68	65	5.8	6.0	0.09	
9/23/2020	1	6.00	72	77	7.0	-	-	Footing
9/25/2020	1	3.50	68		7.6	7.5	0.17	Wing Wall
	2	3.00	72	57	9.0	8.7	0.11	
9/29/2020	1	5.00	74	74	8.0	8.1	0.08	Back Wall
	2	4.50	75	-	8.0	7.6	0.07	
10/1/2020	1	4.75	70	-	7.0	6.7	0.19	Wing Wall
	2	6.25	71	-	8.5	8.4	error	
	4	5.00	74	70	7.5	7.2	0.16	
	5	NA	NA	-	7.5	7.8	0.37	
10/5/2020	1	4.00	70	-	8.0	8.3	0.17	Back Wall
	2	3.50	69	65	9.0	9.6	0.09	
11/4/2020	1	5.00	59	-	9.5	8.6	0.27	Deck
	2	4.50	60	56	8.0	7.5	0.12	
	6	5.00	61	-	5.5	5	0.22	
	11	4.25	63	59	7.0	7.2	0.25	
	16	5.00	59	-	6.5	6.7	0.10	
11/7/2020	1	4.25	63	47	5.3	5.2	0.17	Sleeper
11/12/2020	1	4.50	65		4.5	4.7	0.37	Closure
	1+H_2O	4.50	65		5.5	5.5	0.29	Pour
	2	4.25	69	47	5.0	4.9	0.24	

Cylinders were made in the field to test resistivity and compression strength. The results from those tests are shown in Table 27. All samples met the resistivity requirements of the pilot specification. Two compression strength sets were below the 4000 psi requirement. In this shadow effort, no corrective actions were taken. While the results were below the PEM requirement, they were above the 3000 psi used in the structural design process.

Table 27 Resistivity and Compression Test Results

Date Cast	28 Day Average (k-ohms)	56 Day Average (k-ohms)	28 day Compression Strength (psi)
6/3/2020	51.8	70.1	6,240
6/9/2020	48.7	-	4,850
6/12/2020	44.9	50.0	4,770
6/12/2020	36.7	40.7	4,780
6/17/2020	56.3	63.0	5,160
6/17/2020	61.7	64.2	6,300
6/23/2020	52.7	63.8	5,980
6/29/2020	36.0	53.8	4,170
7/30/2020	59.9	36.6	5,310
7/30/2020	62.7	58.1	3,660
7/30/2020	33.3	62.8	-
7/31/2020	61.8	59.1	5,140
8/4/2020	58.1	58.9	7,180
8/6/2020	48.5	52.8	5,390
9/16/2020	32.9	40.3	5,090
9/21/2020	31.1	33.2	6,630
9/23/2020	33.9	35.5	6,110
9/25/2020	41.4	47.9	3,520
9/29/2020	35.6	47.0	4,100
10/1/2020	43.7	48.2	4,530
10/5/2020	38.7	47.8	4,830
11/4/2020	41.3	53.3	7,550
11/4/2020	43.5	56.1	8,010
11/7/2020	45.9	52.5	6,480
11/12/2020	40.3	53.1	6,290

Conclusion

The bridge was fully opened in spring 2021 and the completed project is shown in Figure 45. The optimized gradations and reduced cement paste in the performance engineered mixture developed for this project created a significant reduction in cement when compared to the traditional NYSDOT prescriptive concrete mixture that would have typically been used. An estimated 38,850 pounds of cement were saved.

Based on the lessons learned from NYSDOT's initial experience, some changes have been made to the specification. First, expectations for a QA/QC plan from the producer have been moved to the beginning of the specification to highlight their importance. Also, a meeting with the contractor, concrete producer, and NYSDOT is required early in the project to discuss the specification and answer questions. Moving forward, NYSDOT will only be using the Tarantula Curve and have called out the specific sieves to be used in an aggregate sieve analysis to remove some confusion regarding the optimized gradation. The sieve analysis results are now required to be included with the mixture design submission. With this data, NYSDOT will be able to assist the producer if adjustments are needed to optimize the aggregate gradation. NYSDOT is considering adding additional language to ensure the optimized mixture falls within the Tarantula Curve envelope and is not too close to the curve's boundaries. If the gradation falls on the boundaries, minor variations in source materials could move the optimized mix outside the Tarantula Curve envelope. A potential 2% buffer of the boundary limits is shown as the green, dashed lines in Figure 43.

Another change increases the paste content from 25% to 27%. The 25% paste content originated in the pavement PEM specification and the increase addresses workability concerns for finishing. The option to use 6-inch by12-inch cylinder as a resistivity sample option was removed to avoid confusion and conversion factors as NYSDOT moves to only 4-inch by 8-inch cylinders. Also, the submission deadlines were increased from 30 days to 45 days to allow more time for communication and mixture adjustments. NYSDOT is also continuing to monitor the data collected during QA/QC operations and will continue to evaluate and update the pay factor section of the specification prior to implementation.

The two PEM projects NYSDOT has completed have provided lessons for improvement while still producing a successful project. As a department, NYSDOT is continuing to work with its contractors and material suppliers to advance these specifications. NYSDOT currently has two ongoing PEM projects and an additional six planned across the state for 2022. It is trying to get as many NYSDOT personnel, contractors and concrete suppliers involved with its pilot program to address issues and concerns prior to making PEM the standard for all projects.

Figure 45 Completed structure.

Chapter 6

North Carolina's PEM Experience

Overview

NCDOT owns and maintains the second largest roadway network in the United States. In addition to over 80,000 miles of highway, NCDOT also owns and maintains over 13,500 bridges. Despite extensive growth in NCDOT's concrete pavements and concrete structures inventories in recent decades, specifications for concrete have changed little over the past 85 years. Current specifications (NCDOT 2018) are prescriptive and provide little room for innovation and have resulted in mixtures that are often over-designed for strength or have high cementitious materials and paste contents (Cavalline et al. 2020a). Resource reductions have driven the need for NCDOT to reduce maintenance costs and increase the service lives of all infrastructure. Performance engineered mixtures will help NCDOT ensure new concrete pavements and structures meet their service life goals, as well as reduce the resources required for maintenance.

PEM is also a part of NCDOT's efforts to meet sustainability goals, allowing the agency to focus on improving the durability of its concrete mixtures while also promoting solutions that meet economic and material supply challenges. NCDOT desires fly ash in most mixtures because of the durability benefits. However, fly ash shortages have been experienced throughout the years, and there is a need to find ways to specify and obtain mixtures with equivalent performance of fly ash mixtures. The PEM initiative has provided a means to explore "what if" scenarios, since performance specifications could allow contractors and suppliers to provide material substitutes and alter mixture proportions to address material shortages, capitalize on economic savings, and economize mixtures.

Other needs driving NCDOT's PEM-related research include the decision in 2018 to increase the allowable fly ash substitution rate from 20% to 30%. The agency desired data to support and encourage use of the higher substitution rate, as well as to account for slower early age strength gain. NCDOT also decided to allow Portland limestone cement (Type IL) in 2015. Some PEM-related research was performed to gather data to support use of this sustainable cement, which has a reduced carbon footprint (up to a 15% reduction in greenhouse gas emissions) (Cavalline et al. 2018 and 2020a).

The overall objectives of NCDOT's PEM initiatives are:

1. Establish preliminary specification recommendations and targets for selected PEM technologies, and some prescriptive provisions, including:

   a. surface resistivity
   b. w/cm, cementitious content (prescriptive provisions)
   c. shrinkage
   d. SAM
   e. potentially other tests included in AASHTO PP 84
2. Explore ways to reduce paste and cement contents
   a. optimized aggregate gradations
   b. increased SCM contents
   c. reduced cementitious materials contents
3. Support pilot project implementation
   a. pavement projects
   b. bridge projects
   c. bridge deck overlay projects
4. Support technology transfer to NCDOT division/regional personnel as well as industry stakeholders

To date, NCDOT has sponsored several research studies (Cavalline et al. 2018 and NCDOT 2021) and has deployed PEM testing in a shadow testing format at several pilot projects. Details regarding these research studies and implementation efforts are provided the following sections. Outreach to engage industry stakeholders and division and regional agency personnel has included multiple presentations on NCDOT's PEM initiatives at events including the FHWA Mobile Concrete Technology Center Open House, the North Carolina Concrete Pavement Conference, the North Carolina Rigid Pavement Committee Meeting, the NCDOT Research and Innovation Summit, and meetings with project teams at targeted pilot projects. As contractors are learning about NCDOT's movement toward performance specifications, they have been reaching out to agency personnel and the academic researchers supporting this effort, expressing interest in learning about the AASHTO PP 84 tests and pilot projects. NCDOT and their academic partners continue to work to engage additional stakeholders via presentations, word of mouth, and publications.

Use of PEM tests and evaluation of shadow specifications at two pilot project sites has been largely successful, and reception from the industry has been positive. The two pilot projects each involved two contractors, a concrete supplier and a testing firm, and agency personnel from two divisions, a regional laboratory, and the central office. These two pilot project sites are located in the Piedmont Region of North Carolina, near Charlotte, and additional details regarding these two projects are presented in a subsequent section. Contractor and agency personnel have largely found testing readily implementable into their QC or acceptance testing programs, and in some cases, contractors are choosing to continue use of selected PEM tests on additional projects outside of those used at pilot studies.

Interest has also been expressed by a third project team in a more remote area in the Mountain Region of North Carolina. This pilot project, which has a CM-GC delivery system would engage a third contractor, a construction manager, another testing firm, and agency personnel from another division. This project would provide the opportunity to evaluate PEM tests and targets for structural mixtures with a different set of materials and challenging delivery conditions due to the remote area of the work.

Tests and Testing

Of the PEM tests and specification provisions outlined in AASHTO PP 84, NCDOT is primarily interested in moving toward implementation of surface resistivity, SAM, and shrinkage, along with some use of prescriptive water-cementitious materials ratios and cement contents. Research is also ongoing to explore the benefits achievable through the use of optimized aggregate gradations with NCDOT's typical mixtures, such as reduced cement contents and economic savings. Although NCDOT and academic partners have not experimented with the AASHTO PP 84 workability tests, at least one contractor partner has been using this test. Other work as well as means to explore w/c ratios and alternative materials to support improved durability performance is also ongoing. A brief description of NCDOT's motivation, research findings, and implementation status is described in the following subsections. A summary of preliminary targets for PEM tests is provided in Table 28. These preliminary targets are being evaluated in field studies and ongoing laboratory testing and may change as new insight becomes available as part of NCDOT's PEM efforts.

Table 28 Preliminary Targets for Selected PEM Tests

Test	Method	Type of Concrete Mixture	Preliminary Target	Stage(s) Used
Surface resistivity	AASHTO T 358	Pavement	11.0 kΩ•cm	Mixture qualification and acceptance
		Structural	15.0 kΩ•cm, or 16.0 kΩ•cm can be required for applications where risk of chloride penetration is high	
SAM	AASHTO TP 118	Pavement, structural, or other air-entrained mixture	0.30	Mixture qualification and acceptance
Drying Shrinkage (unrestrained volume change)	ASTM C157 / AASHTO T 160	Pavement, structural, or other mixture of interest	420 με, but for concrete where reduced cracking potential is desirable, 350 με could be used	Mixture qualification only

Surface Resistivity

Due to the ease of the test and the value of the information provided, NCDOT is interested in implementing surface resistivity testing (AASHTO T 358) for most types of concrete, including pavement concrete, class AA structural mixtures, drilled pier mixtures, and class A (lower grade use) mixtures. Surface resistivity would potentially be used for mixture approval and for acceptance. Data correlating surface resistivity to rapid chloride permeability tests (AASHTO T 277) has been collected for a variety of mixtures as part of several research studies for approximately 10 years and were used to develop preliminary testing targets for structural and pavement concrete (Figure 46) (Cavalline et al. 2020a). Testing targets and shadow specifications are being evaluated as part of pilot projects. For now, NCDOT aims to only specify the AASHTO T 358 resistivity test. Although formation factor testing has been performed on a limited number of specimens, additional research is needed to better understand the results of this test for typical materials and proportions used in North Carolina mixtures. Ongoing study is also aiming to identify 28-day resistivity targets that correlate well to 56-day resistivity for fly ash mixtures. This should streamline the use of resistivity for acceptance and reduce the specimen curing and storage burden.

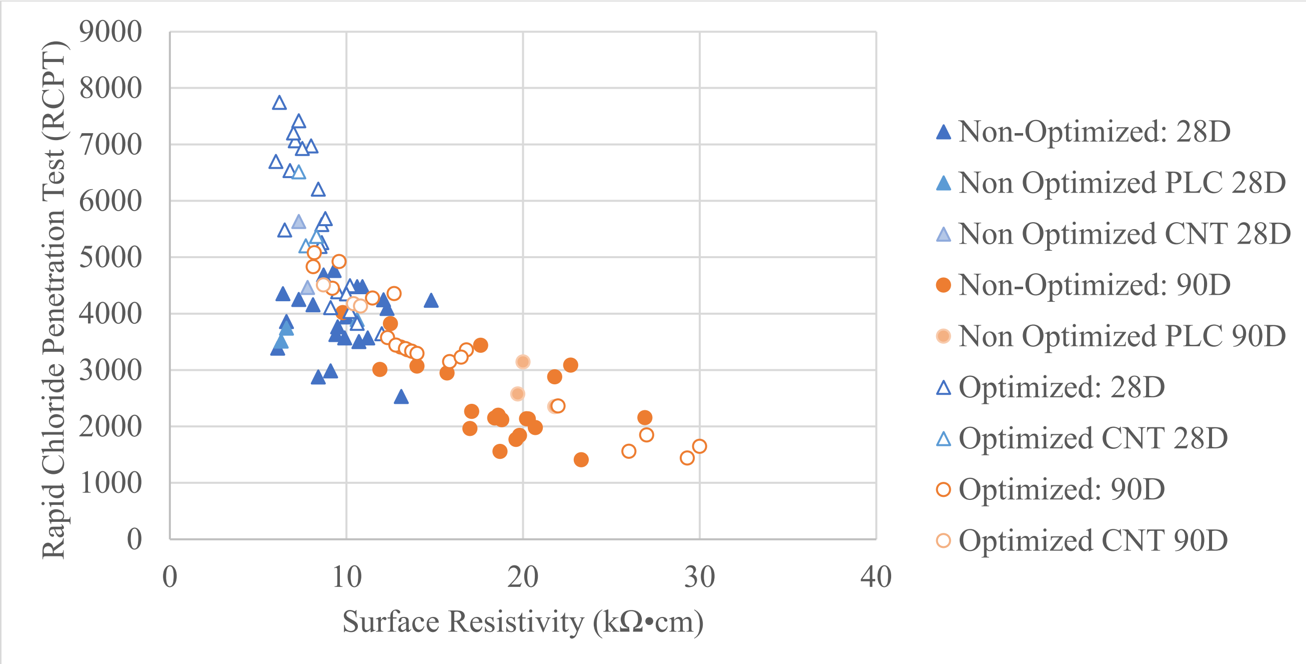

Figure 46 Partial collection of data correlating surface resistivity to rapid chloride permeability for a variety of NCDOT's typical pavement and structural mixtures at 28 days (28D) and 90 days (90D) of age. Both optimized gradation and non-optimized gradation mixtures are shown, along with mixtures containing Type IL cement and carbon nanotubes (CNT).

SAM

Although North Carolina has a moist climate and an abundant number of freeze-thaw cycles annually, NCDOT's concrete infrastructure has historically not exhibited extensive freeze-thaw distresses. Nevertheless, the value of the SAM for use in some projects is being explored. SAM tests (AASHTO TP 118) have been performed for a number of concrete mixtures batched in laboratory studies. The SAM would be used for mixture approval and potentially in quality control or quality assurance during production. For many mixtures, freeze-thaw tests have been performed (ASTM C666) and spacing factors of hardened concrete (ASTM C457) have been determined to help identify the SAM number of interest for NCDOT shadow specifications. Field data is also being collected at pilot project sites. Although SAM data collected during the first pilot study showed excessive variability, steps were taken to provide additional SAM training for the second pilot project. A training session for NCDOT and contractor personnel (hosted by the SAM developer) has resulted in an improvement in the quality of the data collected for the SAM. This field data, paired with laboratory data, will be used to help identify a performance target and shadow specification provisions.

Shrinkage

Volumetric shrinkage (ASTM C157) tests may be of interest for use in performance specifications in projects where reduced cracking is desired. ASTM C157 test data has been collected for a wide range of pavement and structural concrete mixtures as part of research studies. These results have indicated that AASHTO PP 84's recommended target of 420με at 28 days of air storage may be readily met by most NCDOT mixtures, and a target between 350 to 400με could be used. Shrinkage specifications would be used in the mixture qualification stage only. As part of a pilot project, NCDOT is working with a supplier, testing company, and academic partner to perform a study of the variability in test results that could be expected through multiple laboratories. Future shadow studies may provide additional insight into the targets appropriate for different mixture types.

Optimized Aggregate Gradation

Paste and cement contents for NCDOT's mixtures have historically tended to be high, and optimized aggregate gradations may be one way to encourage a reduction in both. Reductions in paste content and cement content would provide economic savings and could provide enhanced durability as well. NCDOT has sponsored a research study aimed at quantifying the benefits that could be achieved through optimized aggregate gradation for pavement and structural mixtures (NCDOT 2021). Compressive strengths of the optimized gradation mixtures tend to be similar to those of the conventional mixtures, revealing that use of optimized gradations in these mixtures could potentially support reduction of paste content by 2% to 3% and reduction of cementitious materials content of approximately 10%. Durability testing is ongoing. It is hoped that this data could encourage contractors and suppliers to explore use of an intermediate sized aggregate to optimize the gradations used in future concrete projects.

Water-Cement Ratio

Cementitious Materials—Types and Content

NCDOT's standard specifications include a maximum w/c ratio and a minimum and maximum cement content for most types of mixtures. NCDOT desires to obtain concrete with lower cement contents to improve the durability and sustainability of infrastructure components and knows that specified maximum w/c ratios could be lowered to also improve concrete mixtures. Ongoing research to support PEM implementation is exploring the mechanical properties and durability performance of mixtures of typical and high w/c-cement ratios. This data could help NCDOT decide to lower the maximum w/cm and cementitious content specification provisions.

NCDOT is also supporting research to support use of higher SCM contents and to encourage use of Type IL cement and ternary blends (Type IL cement with fly ash). Type IL cements have been found to provide equivalent performance to Type I/II cements used in laboratory studies. Findings have also clearly shown the durability benefits of use of higher (30%) replacements of fly ash and have demonstrated that the pairing of Type IL cement with fly ash results in even greater durability performance improvements. Due to the slower strength gain anticipated from use of higher fly ash contents, additional study was performed to review the opening to traffic specifications for use.

Implementation and Status

Pilot Project—Concrete Pavement

NCDOT understands that successful movement toward performance specifications will require stakeholder input and engagement. In 2018, NCDOT received funding to support PEM implementation as part of FHWA's Demonstration Project for Performance Engineered Mixtures (AASHTO PP 84).

Funding to support three categories of implementation were secured (Praul 2018):

- Category A: Incorporating two or more AASHTO PP 84-17 tests in the mixture design/approval process. Shadow testing was acceptable.
- Category B: Incorporating one or more AASHTO PP 84-17 test in the acceptance process. Shadow testing was acceptable.
- Category D: Requiring the use of control charts, as called for in AASHTO PP 84-17.

A contractor interested in gaining more experience with using PEM approaches to improve their QC partnered with NCDOT to use a design-build concrete paving project as NCDOT's first pilot project. The project was a design-build urban interstate project: a stretch of I-85 north of Charlotte, NC. Approximately 5.3 miles of mainline pavement was the focus of the PEM testing. The existing four-lane interstate (two lanes in each direction) was widened to provide four additional lanes (two lanes in each direction) to support an eight-lane interstate. The new pavement is 12 inches thick dowelled jointed concrete paved on a non-woven geotextile interlayer and a 1¼ inch asphalt surface course interlayer (SF9.5A) placed on stabilized subgrade. Lanes were each 12 feet wide.

PEM tests were included as shadow specifications only. QC tests performed by the contractor during the pilot project included the Box Test, the SAM test, and surface resistivity. Data was collected during both phases of the project, during the 2018 and 2019 construction seasons. The contractor found the Box Test highly useful in assessing the workability of mixtures, and the test was performed each time the mixture was adjusted. Surface resistivity testing was performed on almost all cylinders tested for compressive strength. Technicians stated that resistivity testing was straightforward and fairly easy to incorporate into their testing program. Mixtures used for the mainline paving readily met the proposed target of 11 kΩ•cm by 90 days (often by 56 days). NCDOT found implementation of the resistivity meter for acceptance testing straightforward and noted that the agency can equip laboratories with this device for a low cost. SAM tests were typically performed by the contractor once per day, but as mentioned previously, test results were variable and additional training of agency and contractor personnel was scheduled prior to the next pilot project to help improve these test results.

Overall, the demonstration project was a success. The contractor noted that they could accomplish the PEM tests without additional QC personnel, and indicated they intend to use PEM tests on future projects. Both agency and contractor personnel appreciated the insight the PEM tests gave on the potential durability of the project. See Figures 47 and 48. Details can be found in Cavalline et al. (2020b) and FHWA (2020).

Figure 47 Batch plant used by contractor to produce mainline paving mixture included in PEM pilot project.

Figure 48 Mainline concrete pavement for I-85 PEM pilot project for concrete paving mixtures.

Pilot Project—Structural Concrete

Capitalizing on the success of the initial pilot project, NCDOT moved forward with implementation of PEM tests on a second pilot project, with the effort focused this time on structural concrete mixtures. This pilot project engaged a set of new stakeholders, including a second contractor, another testing agency, and a concrete supplier. The structural concrete pilot project is the I-485 widening project in south Charlotte. This design-build project includes widening of the existing interstate along an 18.2 mile corridor, with the objective of building high-occupancy toll (HOT) lanes along the entire stretch of roadway. The project includes 17 structures, with nine bridges being the focus of the PEM shadow testing. Early in the project, representatives from the contractor, the NCDOT division and central office, the testing agency, the concrete supplier, and the academia partner met to discuss the tests of interest (surface resistivity, SAM, and shrinkage) and developed a reasonable sampling and testing plan for the PEM shadow tests. Once the sampling and testing plan was agreed upon, a common spreadsheet for data entry was developed and shared. A live SAM training session was held at the jobsite (Figure 49).

Figure 49 SAM training provided by Oklahoma State University personnel.

Figure 50 SAM tests performed at bridge deck concrete placement.

This shadow project was ongoing at the time of the writing of this circular and concluded in 2022. Details are available in (Cavalline et al. 2023). Surface resistivity testing was performed by NCDOT on compressive strength cylinders as acceptance shadow tests. The concrete supplier also performed surface resistivity testing on QC cylinders prepared for this project and other projects. SAM testing was performed by NCDOT personnel during concrete placements for bridge substructure, superstructure, and decks (Figure 50). To assess mixtures for shrinkage potential, the supplier produced ASTM C157 prism specimens from two mixtures (a deck mixture and a drilled shaft mixture). A mini-round robin study was performed to test the same mixtures at three laboratories to investigate potential variability between testing facilities.

This project is ongoing, and data will be collected for the next year or two to inform NCDOT's next steps toward PEM. End goals for this pilot project include:

- Engaging additional stakeholders (contractors, producers, testing firms, and NCDOT division personnel) in the PEM effort, and solicit feedback on tests, targets, and use in future projects.
- Evaluating of the sampling and testing plan for use of PEM tests on structural concrete mixtures.
- Broadening the data set available to assess proposed targets for SAM, resistivity, and shrinkage.
- Evaluating the proposed testing targets for structural (class AA), drilled pier, and lower grade (class A) concrete.
- Revising the proposed targets and specification languages based on experiences and feedback from the project stakeholders.
- Broadening the pool of stakeholders that are aware of PEM tests and are interested in using them to improve the durability and sustainability of concrete.

Closing

PEM will help the agency specify and construct the infrastructure it needs for the twenty-first century and beyond. Incremental steps made by NCDOT toward PEM have provided confidence in the tests through laboratory research, facilitated engagement of a variety of stakeholders, and allowed evaluation of the sampling and testing programs and target values for a range of types of concrete mixtures. Although no specification changes have been made yet, shadow specifications for surface resistivity and shrinkage developed through research are being evaluated at pilot projects. Ongoing work is being performed to develop a proposed shadow specification for the SAM.

The agency is taking the approach that all stakeholders can benefit from PEM, with contractors allowed to innovate to provide concrete that delivers what is needed, both efficiently and reliably. Improved QC is part of the PEM effort, and NCDOT has supported the development of contractor QC guidance for PEM as part of an ongoing research study (NCDOT 2021). One additional focus that NCDOT is working on in conjunction with academic partners is quantifying the benefits of PEM—both benefits to the contractor and to the agency. Although the benefits of PEM have not been quantified yet, it is anticipated that they will include cost savings associated with the use of more economical materials, lower cement contents, and increased use of SCMs. Durability benefits will also be incurred due to increased use of SCMs at higher substitution rates, use of SCMs with Type IL cements, use of PEM tests (surface resistivity, shrinkage, and SAM), and improved contractor QC.

References

Cavalline, T.L., Tempest, B.Q., Blanchard, E.H., Medlin, C.D., and Chimmula, R.R. Improved Data for Mechanistic-Empirical Design for Concrete Pavements. Final Report, Project FHWA/NC/2015-03, North Carolina Department of Transportation, 2018.

Cavalline, T.L. Tempest, B.Q., Biggers, R.B., Lukavsky, A.J., McEntyre, M.S., and Newsome, R.A. Durable and Sustainable Concrete Through Performance Engineered Concrete Mixtures. Final Report, Project FHWA/NC/2018-14, North Carolina Department of Transportation, 2020a.

Cavalline, T.L., Tempest, B.Q., Hunter, B.J., White, F.D., and Ange, C.M. Post-Construction Report for North Carolina DOT Demonstration Project, Implementation of Performance Engineered Concrete Mixtures (PEM)/AASHTO PP84. North Carolina Department of Transportation, 2020b.

FHWA. MCTC-Field Report – I-85 Widening, Charlotte, North Carolina. 2020. https://intrans.iastate.edu/app/uploads/sites/7/2020/09/MCTC-North-Carolina-Visit_Field-Report_9_18_20.pdf

NCDOT. "Continuing Towards Implementation of Performance Engineered Concrete Mixtures for Durable and Sustainable Concrete." Research Project 2020-13. Accessed August 6, 2021. https://connect.ncdot.gov/projects/research/Pages/ProjDetails.aspx?ProjectID=2020-13

NCDOT. Standard Specifications for Roadways and Structures. Raleigh, NC. 2018.

Praul, M.F. (2018). "FHWA Program Update." National Concrete Consortium, April 2018. Available at: https://intrans.iastate.edu/app/uploads/2018/07/03-Praul-FHWA-Update.pdf.

Conclusion

The Performance Engineered Concrete Paving Mixtures Transportation Pooled Fund (TPF-5(368)) has introduced state highway agencies to new and improved tests and technologies that measure engineering properties that are much more closely related to a pavement's long-term field performance than previous approaches have been. This significant advancement in testing technologies allows for a shift away from prescriptive requirements like strength, slump, and total air content, toward performance-related criteria that are much better indicators of durability, such as transport properties, shrinkage, freeze-thaw resistance, and workability.

To encourage the adoption of PEM concepts, FHWA offered various levels of incentive funding to state agencies to help offset the costs of additional shadow testing, data collection, and reporting. The intent of the shadow projects was to give state agencies exposure to PEM and new testing methods, with each state agency selecting an approach to implement PEM requirements that meets their local conditions and contracting environment. Seven of the 19 pooled-fund states accepted incentive funding, and results from six of those states are presented in the previous sections of this circular.

In broad strokes, every state agency recognized benefits of implementing PEM concepts as part of the shadow projects, although the benefits experienced varied from across states. From these PEM pilot projects it is clear that each agency's experience is unique, and results and benefits are a function of each state's current state of practice. Most of the state agencies participating recognize the opportunity that PEM provides to reduce paste content in their concrete paving mixtures by using optimized aggregate gradations. The resulting reduction in cement content, lowered cost, and enhanced sustainability were clear benefits to both agency and industry. Improved freeze-thaw durability via lower permeability was also a focus of these PEM pilot projects. Most agencies noted that although initially hesitant if not resistant, the industry quickly recognized the significant advantages offered by embracing PEM concepts, including improved consistency, better smoothness, and greater workability. The projects also afforded an opportunity for industry and agency to partner more closely and collaborate more effectively.

Every one of the agencies participating in the PEM pilot projects indicated that they are pursuing updates to their concrete specifications with PEM concepts, planning additional pilot projects, or recognize that PEM concepts are the future of concrete paving specification moving forward. This seems to confirm that the PEM initiative has in fact resulted in beneficial changes in the way concrete paving mixtures are designed, monitored, and accepted, resulting in more durable and economical concrete pavements, that also enhance their overall sustainability.

PEM was successful in addressing the mixture up to the point of delivery. In order to ensure success after the mixture is delivered to the paving site, proper construction operations are needed. These include use of the appropriate amount of vibration for consolidation as well as effective finishing, curing, saw cutting, and sealing operations. Construction operations should be the focus of the efforts undertaken during the next pooled-fund project, Performance Centered Concrete Construction (P3C) TPF Solicitation 1582, ending July 2023. The P3C pooled-fund project will look at evaluating the impact of construction activities on the durability of modern concrete mixes. This effort will involve working with agencies, contractors, machine manufacturers, and researchers to determine the actions needed to be taken on the grade to ensure sustainable concrete pavement performance.

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001