Performance-Engineered Concrete Paving Mixtures

Final Report
December 2022

National Concrete Pavement Technology Center

IOWA STATE UNIVERSITY
Institute for Transportation

Sponsored by
Iowa Department of Transportation
(InTrans Project 17-629)
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Transportation Pooled Fund TPF-5(368)

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The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of developing and implementing innovative technology and best practices for sustainable concrete pavement construction and maintenance.

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The mission of the Institute for Transportation (InTrans) at Iowa State University is to save lives and improve economic vitality through discovery, research innovation, outreach, and the implementation of bold ideas.

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16. Abstract

This Performance-Engineered Concrete Paving Mixtures Transportation Pooled Fund—TPF-5(368)—brought newer concrete pavement technologies to state agencies and assisted states in the adoption of specifications and test methods that will help them deliver on the promise of concrete durability.

The Federal Highway Administration (FHWA), 19 state transportation agencies, and 4 national associations representing the concrete paving industry came together to fund this project, which was dedicated to maximizing pavement performance. The focus of the work was to address mixtures up to the point of leaving the batch plant.

The objective was the deployment of performance-engineered mixtures (PEM), which involved building off the foundational work that the FHWA and PEM champion states have done. The emphasis was on implementation, education and training, adoption of specification language to increase the likelihood of achieving durable pavement performance in the field, and continued development relating early-age concrete properties to pavement performance.

This report covers the efforts, results, and accomplishments of this TPF. While progress was made, more work needs to be done. With PEM approaches, concrete pavement should perform better and last longer with a lower environmental impact. This will enable agencies to lower costs by minimizing maintenance operations, keeping the flow of traffic undisturbed for longer periods of time and increasing safety for the traveling public.

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PERFORMANCE-ENGINEERED CONCRETE PAVING MIXTURES

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December 2022

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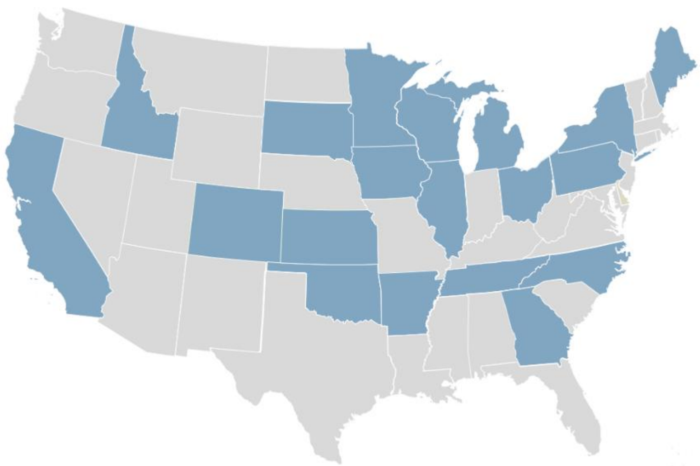

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EXECUTIVE SUMMARY

This Performance-Engineered Concrete Paving Mixtures Transportation Pooled Fund—TPF-5(368)—brought newer concrete pavement technologies to state agencies and assisted states in the adoption of specifications and test methods that will help them deliver on the promise of concrete durability.

Problem Statement and Project Justification

State transportation agencies and concrete pavement professionals have traditionally accepted concrete based on measurements like strength, slump, and air content. These measurements have had very limited correlation to future performance. However, recent developments in concrete testing technologies have yielded methods that are better predictors of long-term performance.

Pooled Fund Background

The Federal Highway Administration (FHWA), through a Cooperative Agreement with the National Concrete Pavement Technology Center (CP Tech Center), had been working with 30 member-state transportation agencies through the National Concrete Consortium (NC^2) to identify the specification approach and key testing technologies that are needed for concrete pavements to have increased durability.

The testing technologies had been developed, and the next critical activities were deployment of the new testing technologies, development of practical specifications and quality assurance/quality control (QA/QC) recommendations, and correlation of specification limits with durable field performance.

The FHWA, 19 state transportation agencies, and 4 national associations representing the concrete paving industry came together to fund this project. It was a coalition of federal, state, and industry leaders dedicated to maximizing pavement performance.

Project Objective, Focus, and Methods

The objective of this project was to focus on the deployment of performance-engineered mixtures (PEM). This involved building off the foundational work that the FHWA and the PEM champion states had done, with emphasis on implementation, education and training, adoption of specification language to increase the likelihood of achieving durable pavement performance in the field, and continued development relating early-age concrete properties to pavement performance.

Pooled Fund Project Description/Summary and Scope

The PEM pooled fund project was broken down into the following tasks:

- **Implementing what is known:** Support study participants with implementation of performance-engineered paving mixtures within their states through education, training, and project-level assistance.

- **Performance monitoring and specification refinement:** Provide field performance data for use in making decisions on specification limits for strength, shrinkage, freeze-thaw durability, transport, aggregate stability, and workability.

- **Measuring and relating early-age concrete properties to performance:** Build on the foundational work in available measurement technologies in order to design and control concrete pavement mixtures around key engineering properties and address improved testing methods for increased accuracy and reduced cost.

The focus of the work was to address the mixture up to the point of leaving the batch plant.

Accomplishments

Implementation

During the implementation task, PEM technology transfer activities included presentations at various workshops and webinars, specification support, and test support, in addition to shadow project support. The project also resulted in considerable discussion and activity in a number of spheres:

- State implementation
- Industry implementation
- Transportation Research Board (TRB) committee interest
- Federal Aviation Administration (FAA) research project funding

Website

A PEM website was developed at www.cptechcenter.org/pem to provide quick access to the following information:

- PEM program information
- Interactive map of shadow project and testing locations
- Instructional videos on test methods and test method summaries
- PEM newsletters
- PEM shadow project reports from state agencies and the FHWA
- State specification review table
- Technical advisory committee (TAC) meeting notes
- Reginal state-industry meeting notes

- Sponsor information

Workshops and Webinars

During the five-year pooled fund project, technology transfer for PEM was provided at 82 workshops, meetings, and webinars across the country. The presentations were provided by the CP Tech Center and members of the PEM research team.

Specification Support

The pooled fund member states were contacted by the research team in 2019 to gain an understanding of their current pavement specifications relating to PEM. A table was developed on how their specifications addressed the six PEM properties: strength, transport, shrinkage, freeze-thaw resistance, aggregate stability, and workability. This table is available at this link: https://intrans.iastate.edu/app/uploads/sites/7/2020/07/PEM-State-Spec_Reviews-Table-2020-07-02.pdf

In 2021, the research team again reached out to member states to see if they had made changes or were considering changes to their specifications based on what they had learned from the PEM program. In many cases, shadow testing, open house demonstrations, workshops, and other forms of technical transfer led to improvements within their specifications.

Test Support

Members of the PEM research team from Iowa State University, Oklahoma State University, and Oregon State University offered test support for the new PEM tests including the Vibrating Kelly Ball (VKelly), Box test, super air meter (SAM), resistivity and formation factor, and Phoenix. Formal test training was provided in 12 of the 19 pooled fund member states. Other forms of test support included webinars, workshop presentations, and guidance documents.

Shadow Project Support

To encourage the use of PEM, the FHWA offered various levels of incentive funding to state agencies to help offset the costs of additional shadow testing, data collection, and reporting. Seven of the 19 pooled fund states accepted incentive funding, and members of the research team coordinated shadow projects with state agencies.

The intent of the shadow projects was to give state agencies exposure to PEM and new testing methods. When possible, open houses were held during shadow projects to provide education on the PEM program and demonstrate new PEM tests.

Data were collected by state agencies, members of the research team, and, in some cases, the FHWA's Mobile Concrete Technology Center (MCTC). Reports are available online with links to them in an appendix of the final report for this TPF.

Virtual Regional State Agency–Industry Meetings

The PEM research team organized virtual regional meetings with state agency members and industry. The focus of the meetings was to get feedback from the state agencies regarding their implementation of PEM and to also include industry as part of the discussions.

Monitoring

The monitoring phase included the development and management of the PEM database. This included data received from state agencies from the shadow test projects. Monitoring also included sampling and testing of cores from the Long-Term Pavement Performance (LTPP) SPS-2 test sites that have been in service for years. Finally, the annual update of AASHTO PP 84, now AASHTO R 101, was provided.

Test Refinement

Water Content

Under this project, the research team at Oklahoma State University worked with the Minnesota DOT (MnDOT) and the FHWA Mobile Concrete Lab to use the Phoenix device in the field and gather feedback.

Based on the feedback, the team made a number of changes to the test, and a test method was developed to use the Phoenix device to measure the moisture content of aggregate, expanding the usefulness of the test method. Finally, a standard test method was developed for the Phoenix device to be used to measure the water content of fresh concrete.

These test methods were shared, and several changes were made. The current test methods are being published by MnDOT as a state test method. This will allow other organizations to use the test methods in the future and provide a stable version to take to larger state agencies.

Thermodynamic Modeling

Under this project, the research team at Oregon State University used a previously developed modeling framework to predict the properties of concrete samples obtained from states and LTPP sites. The model is very useful for predicting performance as well as the carbon footprint and sustainability as it relates to service life.

VKelly

The purpose of the VKelly test is to indicate how a mixture will respond to vibration, providing more information than the yield stress reported by the slump test.

Feedback from some of the states that were provided with VKelly devices was that the system was labor intensive and not user friendly, although in some cases it was felt that the data were valuable. It was reported that a number of operators were using a variety of vibrators and head sizes leading to large variability in the data produced.

During this project, a vibrator manufacturer was able to redesign the system including mounting a speed-controlled motor directly above the ball, thus reducing energy loss and improving the ease of conducting a test. Work is still ongoing to automatically report the rate of penetration to provide an instantaneous readout.

Key Findings and Results

Through the PEM pooled fund, the project team learned the following:

- Each state agency is unique in the way it specifies concrete pavements; Table 2 in AASHTO R 101 gives agencies choices on the selection of PEM properties and standard test methods in the areas of strength, shrinkage, freeze-thaw durability, transport, aggregate stability, and workability.
- Successful PEM shadow projects were the result of coordination and communication between state agencies and industry.
- New test methods require training and practice following standard methods to achieve desired results.
- Contractors involved in shadow projects were supportive and continue to use the tools provided.
- Sustainability is improved when utilizing PEM approaches.
- Additional technology transfer is needed for state and local agencies, industry, and the private sector to increase their exposure to PEM and its benefits.
- The goals of the pooled fund project were achieved including implementation, education and training, adjustment of the specification values, and continued development of tools to relate early-age concrete properties to performance.

Implementation Readiness and Benefits

The PEM pooled fund showed success in the form of improved specifications at the agency level that have been accepted by contractors. Intensive evaluation, demonstration, training, education and implementation efforts have meant that a number of states and contractors have adopted approaches through this TPF and are reporting reduced costs, improved reliability, and improved sustainability.

While the funding from this pooled fund is ending, the need continues to implement the PEM program and to extend the effort to include tests to monitor the impacts of construction activities (such as the addition of water and admixtures, vibration, finishing, and curing of mixtures until concrete pavements are ready for traffic loads).

The story of PEM needs to continue to be told so that more agencies have an opportunity to achieve the benefits that PEM offers. The outcome of PEM implementation is success for all parties involved—from the design engineer to the material producer to the pavement contractor to the agency, and, finally, to the users of the transportation facility.

Progress was made, but more work needs to be done. With PEM approaches, concrete pavement should perform better and last longer with a lower environmental impact. This will enable agencies to reduce costs by minimizing maintenance operations, keeping the flow of traffic undisturbed for longer periods of time and increasing safety for the traveling public.

Future Work

To ensure success after a concrete 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. The team recommends concentrating on these construction operations during the next TPF, Performance-Centered Concrete Construction (P3C).

This new TPF project is intended to follow the model used by the PEM pooled fund project to carry out the following:

- Develop specifications, testing methods, and procedures for the use of new mixture materials, including cement, supplementary cementitious materials (SCMs), and admixtures
- Establish a sound understanding of the workmanship involved in concrete paving and its effects on performance properties
- Develop/select appropriate test methods for evaluation at or behind the paver
- Select pass/fail criteria
- Provide documentation, training, and other resources to encourage agencies and contractors to adopt specifications and practices reflecting these suggestions
- Consider training for contractors in the appropriate construction methods to use for new mixtures with lower cement contents, with special attention paid to temperature control and

monitoring for mixtures with slow initial set times and to curing methods that allow for full hydration

The P3C pooled fund will lean on agencies, contractors, machine manufacturers, and researchers to develop a detailed scope of work starting with the determination of which actions need to be taken on the grade to ensure sustainable pavement performance. Test methods and limits will be determined to measure the following:

- Uniformity
- Segregation
- Consolidation
- Air void system
- Durability and strength
- Smoothness
- Cracking

Successful completion of the project will involve the development of specifications and guidance tools for technology transfer, including videos, written documents, and training programs.

INTRODUCTION

Justification

Discussion regarding the need to move toward performance-based specifications for concrete paving mixtures has been ongoing for many years. The challenge with achieving this goal has always been in finding effective methods of measuring the performance characteristics that directly relate to pavement durability and structural longevity.

At the same time, many agency specifications for paving mixtures have become bloated because they are comprised of a patchwork of fixes seeking to correct unintended consequences of previous fixes. Further, dependence on monitoring the process involved in concrete production has been significant, but reduced staffing levels have made continuation in this manner impractical.

In response, discussions between the Federal Highway Administration (FHWA), American Concrete Pavement Association ACPA, and the National Concrete Pavement Technology Center (CP Tech Center) staff led to the initiation of the Performance Engineered Mixtures program that was tasked with helping agencies find answers to a set of questions:

- What are the critical properties of a mixture in a given application?
- How can these properties be measured?
- When should they be measured?
- What are appropriate pass/fail criteria?

The program also sought to provide guidance to suppliers to help them meet these requirements.

Consultation with national experts from all sectors of the concrete pavement community led to the development of a relatively short list of critical concrete properties:

- Resistance to the passage of fluids through the concrete (permeability or transport)
- Resistance to damage from winter weather (resistance to paste freeze-thaw damage and the chemical effects of deicing chemicals)
- Reduced shrinkage (to minimize cracking and warping in dry regions)
- Good aggregate stability (resistance to alkali-silica reaction and aggregate freeze-thaw damage)
- Adequate strength (to meet design requirements)
- Good workability (including response to vibration)

Academic researchers stepped up to deliver innovative test methods that aimed to rapidly and reliably measure some of these properties:

- Transport properties assessed using electrical resistivity and formation factor

- Workability assessed using the Vibrating Kelly Ball (VKelly) or Box Test
- Air-void system assessed using the Super Air Meter (SAM)
- Water-to-cementitious materials (w/cm) ratio assessed using the Phoenix

Performance Engineered Concrete Paving Mixtures Transportation Pooled Fund—TPF-5(368)—was established to continue the work to implement the PEM process into everyday practice. As a result, the team was able to develop the document that is now American Association of State and Highway Transportation Officials (AASHTO) R 101, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures. At the same time, proportioning tools like the CP Tech Center's concrete mixture proportioning spreadsheet, which incorporates the Tarantula curve, have allowed suppliers to prepare sustainable, efficient, and workable performance-engineered mixtures (PEMs) that meet the specified requirements while significantly reducing the mixtures' carbon footprints.

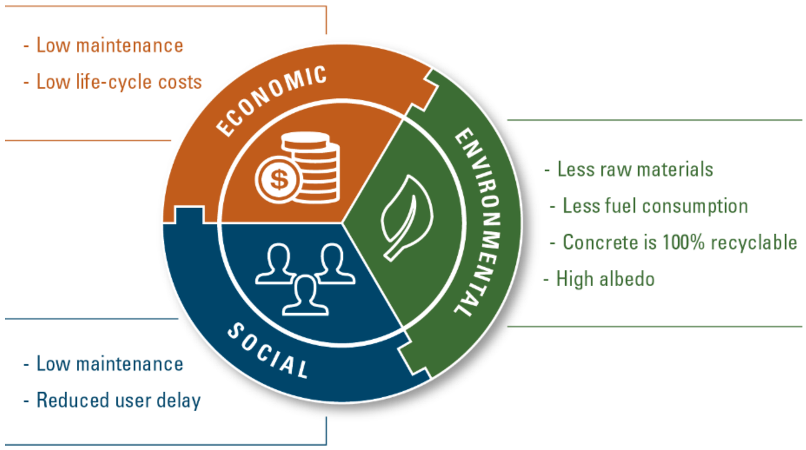
Intensive evaluation, demonstration, training, education, and implementation efforts through this TPF have meant that a number of states and contractors have adopted these approaches and are reporting reduced costs, improved reliability, and improved sustainability.

While the funding from this pooled fund is ending, there is a continued need to further implement the PEM program and to extend the effort to include tests to monitor the impacts of construction activities (such as the addition of water and admixtures, vibration, finishing, and curing of mixtures until concrete pavements are ready for traffic).

This report summarizes the benefits and impacts of the PEM pooled fund project and suggests areas of future work.

Sustainability

Based on an understanding of sustainability as a balance of economic, environmental, and social needs, the PEM approach can be shown to improve all three of these factors in a new or overlaid pavement. Figure 1 illustrates the ways PEM is sustainable.



After U.S. Department of Energy Office of Energy Efficiency & Renewable Energy's Bioenergy Technologies Office (BETO) vision diagram (https://www.energy.gov/eere/bioenergy/sustainability)

Figure 1. PEM sustainability

Social benefits include improvements in safety and traveler well-being when the reduced need to conduct repairs or rehabilitation reduces lane closures, traffic flow disruptions, and user delays over the (extended) life of the pavement.

In terms of environmental benefits, it is possible to reduce CO_2 emissions during the construction phase by reducing cement contents in combination with optimized aggregate gradations. These optimized aggregate gradations allow for improvements to mixture workability with a parallel reduction in paste volume. Historically, mixtures have been specified with minimum cement contents that are often in excess of how much is really necessary. It is also common to address performance issues in a mixture by adding cement. However, increasing cement content can have a negative effect in terms of increased CO_2 emissions, increased shrinkage potential, and increased costs without necessarily improving performance. The PEM approach also encourages the judicious use of supplementary cementitious materials (SCMs), which in turn reduces the carbon footprint of the mixture.

Optimized aggregate gradations coupled with the right amount of cement have been demonstrated to facilitate the construction of smoother pavements (Fick et al. 2019), which in turn has a marked impact on reducing the fuel consumption of vehicles over the life of the pavement. Such benefits are likely to exceed the carbon impact of construction activities.

A significant economic benefit of the PEM approach is that improving the quality of a pavement mixture will likely increase the life of a pavement, both in terms of directly improving resistance to traffic and environmental stresses and in terms of reducing the risk of premature failures. Extended life means longer periods between replacement, which, in addition to the economic benefits, means lower environmental impacts of construction materials and practices.

Table 1 summarizes the overlaps between the PEM approach and the tenets of sustainability.

Table 1. Linking PEM to sustainability

	Measurable	Phase	Impact	Who	Side Effect	Cost	When
Reduce cement content	Environmental Product Declaration	Construction	Point of delivery	All	None	Reduced	Now
Increased use of SCMs	Environmental Product Declaration	Construction	Point of delivery	All	None	Reduced	Now
Smoothness	Yes	Use phase	Reduces others' footprint	Contractor	Improved safety	Reduced	Now
Long life	Yes	Use phase	Later	Agencies	Improved safety	Reduced	Now

IMPACT

The PEM pooled fund project has resulted in considerable discussion and activity in a number of spheres, as discussed in this chapter.

State Implementation

Pooled fund member states took the initiative to participate in the PEM program to better understand the changes that are needed in order to specify, measure, and deliver better concrete. States made improvements to their specifications, performed new test methods, collected data, and completed reports on the findings.

Agencies and industry, beyond the organizations participating in the pooled fund project, are moving toward implementation of PEM principles. As the pooled fund states gain experience, particularly through the PEM Implementation Incentive Program projects, other states are learning about the success and looking to similarly improve their concrete programs. The recent emphasis on concrete sustainability has helped to increase the focus on PEM, as a number of pilot projects have demonstrated that incorporating PEM principles invariably results in more sustainable concrete.

Examples demonstrating the organic growth of PEM in states that did not participate in the pooled fund include the following:

Massachusetts Department of Transportation

- Developed a comprehensive draft PEM specification incorporating several new technologies and practices
- Engaged with FHWA to finalize the specification with a goal of implementing PEM principles in pilot projects in 2023

West Virginia Department of Highways

- Developed a special provision (shadow testing) on resistivity testing for bridge deck concrete
- Adopted the Tarantula curve for optimizing the gradation of all concrete (contractors' option)
- Lowered cementitious materials content by 40 lb/yd^3 for all concrete (contractors' option)
- Purchased SAM and surface resistivity (SR) meters for each district
- Developed a special provision (shadow testing) for SAM testing
- Participated in a series of *Live from the MCTC* PEM-related training webinars

Connecticut Department of Transportation

- Engaged with FHWA for assistance in developing a resistivity specification, with a target for implementation on projects in 2023

South Carolina Department of Transportation

- Implemented the Tarantula curve on some major concrete paving projects
- Hosted FHWA Mobile Concrete Technology Center (MCTC) for a project site visit and PEM open house
- Requested continuing engagement with FHWA to update concrete specifications and practices
- Considering resistivity testing and Box Test

Wyoming Department of Transportation

- Considering adoption of resistivity testing, Tarantula curve, and the Box Test in specifications
- Hosted FHWA MCTC for a project site visit and PEM open house

Industry PEM Implementation

Industry associations have made their state chapters and individual members aware of PEM and the advantages it provides. This has helped move PEM forward in practice. Examples include the following:

- Pennsylvania—Following the state's PEM pilot project, industry representatives approached the Pennsylvania Department of Transportation (PennDOT) and asked for a joint committee to develop a PEM specification. The group has been formed and is currently working on the specification.
- Ohio—The Ohio Concrete Association reached out to FHWA and borrowed three surface resistivity meters from the MCTC Equipment Loan Program. The group subsequently engaged with the Ohio Department of Transportation (ODOT [Ohio]) and is developing a resistivity specification.
- North Carolina—The contractor for the state's PEM shadow project showed interest in PEM early in 2018 to improve quality control and support the North Carolina Department of Transportation's (NCDOT's) PEM initiatives. The contractor was supportive of the program and, based on the success of the shadow project, intends to implement guidelines on future projects.
- Iowa—The contractor for the state's initial PEM shadow project expressed appreciation for the MCTC's involvement and the entire PEM initiative. The contractor went on to utilize a PEM approach to three subsequent projects with the Iowa Department of Transportation (Iowa DOT).

The FHWA MCTC has worked closely with contractors in various PEM and non-PEM states in introducing and implementing new technologies. A list of the specific work includes the following:

- The MCTC offers an optimized gradation spreadsheet tool to assist in the development of optimized mixtures. More than 30 contractors from across the country have adopted this tool for their use.
- The MCTC's *Live from the MCTC* is a virtual training series on PEM and non-PEM tests/technologies. Recent PEM sessions were presented to contractors in Arkansas, West Virginia, Florida, and Pennsylvania.
- The MCTC loans PEM- and non-PEM-related equipment to contractors. The program can cite numerous examples of contractors borrowing equipment, evaluating it, and purchasing their own when they return the borrowed piece. Nearly all of the available equipment is on loan.

A number of conferences have included sessions about PEM, including the last two international conferences hosted by the International Society of Concrete Pavements.

Transportation Research Board

A variety of Transportation Research Board (TRB) committees have shown interest in PEM, including the Durability of Concrete and the Concrete Pavement Construction and Rehabilitation committees. Many sessions were held and continued to be held at TRB annual meetings. Some examples include the following:

- The Concrete Pavement and Construction and Rehabilitation committee conducted a session on PEM state experiences in 2021.
- A PEM circular is currently being finalized on the PEM implementation experience in Iowa, Minnesota, Wisconsin, New York, North Carolina, and Michigan.
- There is a session planned for 2023 on performance-centered concrete pavement construction.

Federal Aviation Administration

The Federal Aviation Administration (FAA) has funded a research project through the Airport Concrete Pavement Technology Program (ACPTP) that was awarded to Oklahoma State University with the aim of implementing the PEM approach in airfield pavements. Activities include recommending changes to the Item P-501 concrete pavement specification, which includes mixture proportioning guidelines for pavements thicker than those typically used in highway applications.

DEVELOPMENT OF AASHTO R 101

The genesis of a concrete mixture standard that included performance characteristics began with conversations between the CP Tech Center, FHWA, and ACPA representatives in 2012 prior to the initiation of the pooled fund.

Minutes of the National Concrete Consortium (NC^2) meetings more than 10 years ago reveal the need for what was then called “durability-based specifications” to take advantage of innovative technologies and test methods and begin correlating laboratory data with field performance.

Several key decisions were made around this time, including the following:

- The focus would be on mixtures only, up to the point where the truck leaves the plant, and other construction-related activities would be addressed at a later date.
- There was a need to decide on the properties that are critical to defining the potential longevity of a pavement made using a given mixture.
- Tests, with appropriate pass/fail criteria, would be required to address these properties.
- Not every property would be critical in every region or circumstance.
- A guidance document and training resources would be needed to implement changes to state specifications.
- Shadow projects would be necessary to demonstrate the impacts of such changes.

Figure 2 is an image from a planning meeting during the development of the PEM program.

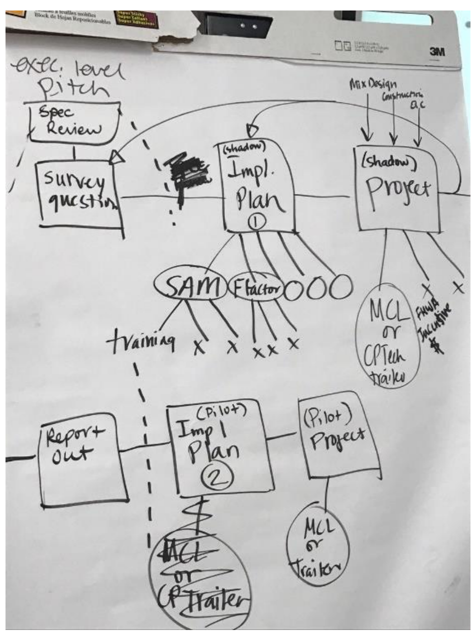


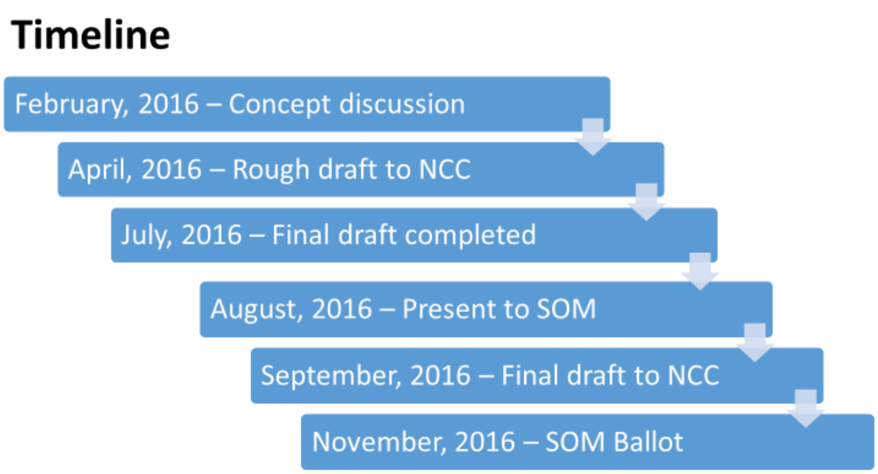
Figure 2. Flipchart notes from an early PEM planning meeting

An Expert Task Group (ETG) was established to brainstorm and identify the critical properties that should be included in specifications for concrete paving mixtures. Six performance-related properties were eventually agreed upon:

- Transport properties
- Aggregate stability
- Strength
- Cold weather resistance (in cold locations)
- Shrinkage (in dry locations)
- Workability

Engagement with the academic community led to consideration of tests that would be useful in assessing some of these properties. Requirements for the tests were that they should be useful, cost-effective, rapid, and repeatable.

The PEM team then began work on developing specifications that include performance characteristics addressing the level of performance needed for concrete. Rather than developing a one-size-fits-all approach, the team determined that a standard practice addressing both performance-based and prescriptive approaches would allow agencies to make choices that best fit their circumstances. A second deliverable proposed was a guidance document that provides detailed discussion of performance measures, the background and reasoning for new tests, and options for addressing the six critical properties in such a way as to optimize concrete performance to fit the existing conditions. The original timeline to develop the proposed standard is shown in Figure 3.



SOM = subcommittee on materials

Figure 3. AASHTO R 101 timeline

After considerable discussion with both agencies and industry, the AASHTO Subcommittee on Materials voted to ballot the developed document as a Provisional Standard in the fall of 2016. The ballot passed (with comments) and was published in 2017 as AASHTO PP 84-17.

The first version of AASHTO PP 84 was 64 pages long, including six appendices that contained draft method statements for the new test methods. The first 11 pages were the core of the standard, with Section 6 and Table 3 describing the various properties and the performance and prescriptive options to evaluate each. The remainder of the document consisted of appendices and the commentary.

The commentary provided background information on the various parameters discussed and explained how to select the right method and limit for a given situation. The commentary was originally included in the AASHTO standard, but as users became more familiar with the tests and concepts, the decision was made to keep the commentary as a standalone report. The intent is to host the report on the CP Tech Center website.

After the 2017 publication of the provisional standard, annual revisions were made to the recommended practices and associated test methods until publication of the 2021 version. The test methods described in the appendices were published as new standards, and the guidance went from 64 to 13 pages long, with Table 2 in the standard being the heart of the document. The AASHTO Committee on Materials and Pavements voted to move AASHTO PP 84 to a full standard at the 2021 annual meeting, and the document was published in 2022 as AASHTO R 101, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures.

Table 2 summarizes the AASHTO publications referenced in R 101-22.

Table 2. AASHTO publications referenced in R 101-22

Number	Title
T 358-22	Surface Resistivity Indication of Concrete’s Ability to Resist Chloride Ion Penetration
T 363-22	Evaluating Stress Development and Cracking Potential due to Restrained Volume Change Using a Dual Ring Test
T 365-20	Quantifying Calcium Oxychloride Amounts in Cement Pastes Exposed to Deicing Salts
T 395-22	Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method – Previously TP 118
T 396-22	Box Test in Slipform Paving of Fresh Portland Cement Concrete – Previously TP 137
TP 119-22	Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test
TP 129-21	Vibrating Kelly Ball (VKelly) Penetration in Fresh Portland Cement Concrete – Approved to become T 403 in July 2023
TP 135-22	Total Pore Volume in Hardened Concrete Using Vacuum Saturation
TP 136-22	Degree of Saturation of Hydraulic-Cement Concrete

TEST METHODS

Background

This chapter discusses the test methods included in AASHTO R 101-22, Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures. The standard practice was developed to provide state highway agencies (SHAs) with tools to prepare a specification for concrete pavement mixtures that moves closer to measuring and basing acceptance on parameters linked to performance.

The assumption in pavement structural design is that the concrete will be durable. However, durability is not an intrinsic, measurable property of concrete. Instead, it is a set of material properties required for the concrete to resist the environment it serves (TRB 2013). For instance, the same concrete placed in a mild, dry climate may remain wholly intact for decades yet rapidly disintegrate if exposed to chemical deicers in a wet, freeze-thaw environment. Both the environment and materials must be considered together to specify and construct durable concrete pavements.

Many current concrete paving specifications base acceptance largely on slump, total air content, thickness, and strength. While this has largely worked for a long period of time, materials and demands have changed over the years, and it has become necessary for specifications to change as well. Today, the old way of specifying concrete provides a limited correlation with failure mechanisms caused by durability-related distresses. The need for a change in the way concrete is specified is apparent as source materials change, mixtures become more complex, more aggressive winter maintenance practices are implemented, and demand increases to build systems more quickly, more cheaply, and with increased longevity.

A significant barrier to the adoption of pure performance-based specifications, or even performance-related specifications, has been the need for standardized test methods that assess the ability of a concrete mixture to resist the environment to which it is exposed. The AASHTO R 101-22 standard practice includes test methods that measure performance-related parameters, and ongoing efforts are underway to demonstrate their effectiveness under field conditions.

The following parameters are critical when considering the longevity of concrete pavement:

- Low fluid transport properties
- Freeze-thaw resistance
- Resistance to chemical deicers
- Aggregate stability
- Sufficient strength
- Low risk of cracking and warping due to drying shrinkage
- Workability

The tests discussed in AASHTO R 101 were selected for their ability to measure these critical properties while also having the following attributes:

- Usefulness
- Standardization
- Low cost
- Sufficient reliability
- Rapidity
- Ability to be conducted by a wide range of users

The following sections discuss the tests suggested for each property.

Overview of Tests

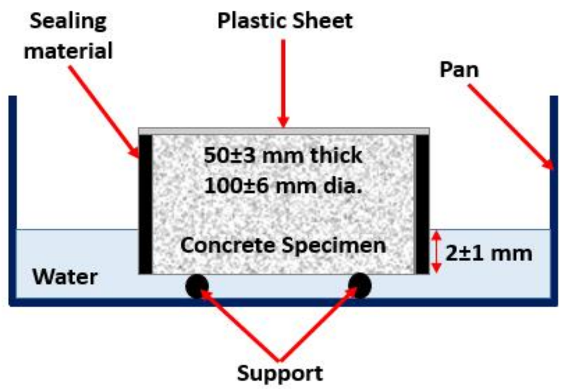
Transport Properties (Section 6.6)

The transport of fluids into concrete is critical because all durability-related distresses involve the transport of moisture into concrete and other substances, such as chloride ions for corrosion or sulfate ions for external sulfate attack. Four test methods that have been employed to assess transport properties in paving concrete in the United States are as follows:

- ASTM C1585, Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concrete
- AASHTO T 277, Standard Method of Test for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
- AASHTO T 358, Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration
- AASHTO TP 119, Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test

Sorptivity – ASTM C1585

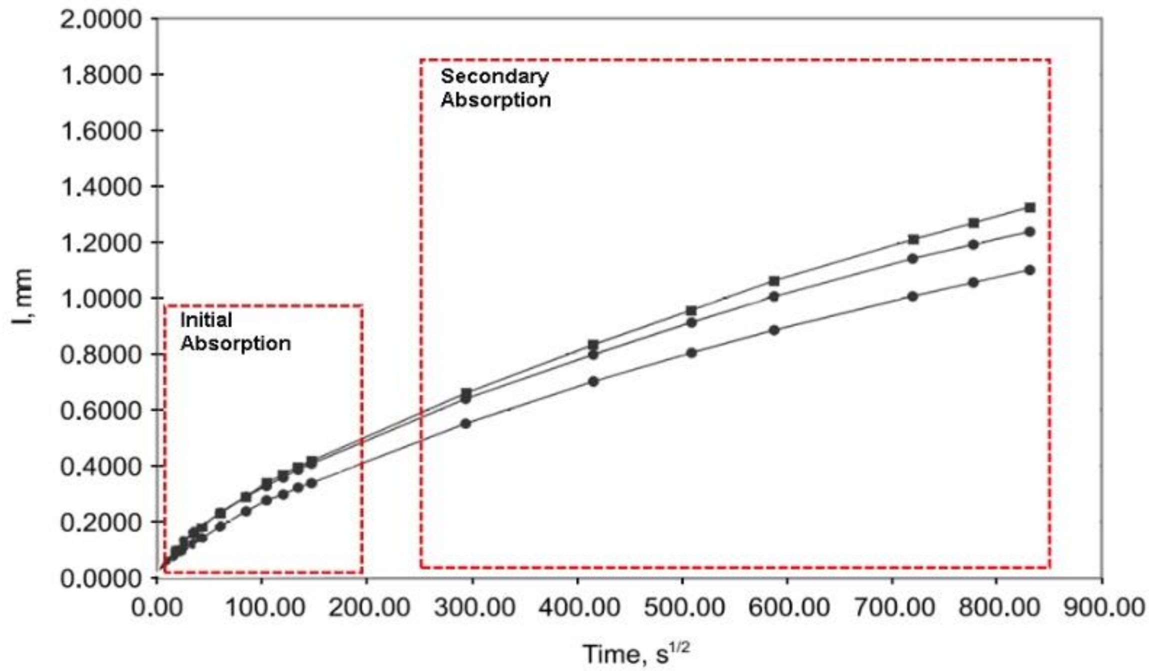
ASTM C1585 is a simple absorption test in which the rate of water absorption (I) is measured into a conditioned concrete sample (50 mm thick by 100 mm diameter [2 in. thick by 4 in. diameter]) at specified intervals for a minimum of 8 days. A schematic of the test setup is shown in Figure 4.



After ASTM C1585

Figure 4. Specimen setup in ASTM C1585

The rate of water absorption (mm/√s) is defined as the slope of a best fit line of I plotted against the square root of time (√s). It is typically observed that the slope makes a definitive change at some point, and thus two absorptions are defined: the initial absorption and the secondary absorption. This is illustrated in Figure 5.



Steve Lane, Virginia Transportation Research Council

Figure 5. Initial and secondary absorption

The absorption can be converted to the degree of saturation (S), defined as the ratio of the absolute volume of absorbed water to the total volume of water-accessible pores. The degree of saturation at the intersection between the initial and secondary absorption is related to the point where the capillary pore system becomes saturated.

Rapid Chloride Penetration Test – AASHTO T 277

AASHTO T 277 has gained acceptance by many highway agencies. It involves the measurement of the total charge passed by 60 VDC in 6 hours across a 50 mm thick, 100 mm diameter (2 in. thick, 4 in. diameter) concrete specimen that has been placed between sodium hydroxide (NaOH) and sodium chloride (NaCl) solutions. The test measures the conductivity of the saturated concrete, including the effects of all dissolved ions (Hearn et al. 2006). The test results in coulombs are used to make a general assessment of the concrete's chloride ion penetrability compared to ASTM C1556 (bulk diffusion test). Table 3 shows the typical specified values (AASHTO T 277). It should be noted that the assessment is not specific, but instead the chloride penetrability is assigned a qualitative rating.

Table 3. Chloride ion penetrability based on charge passed

Charge Passed (coulombs)	Chloride Ion Permeability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

Source: AASHTO T 277

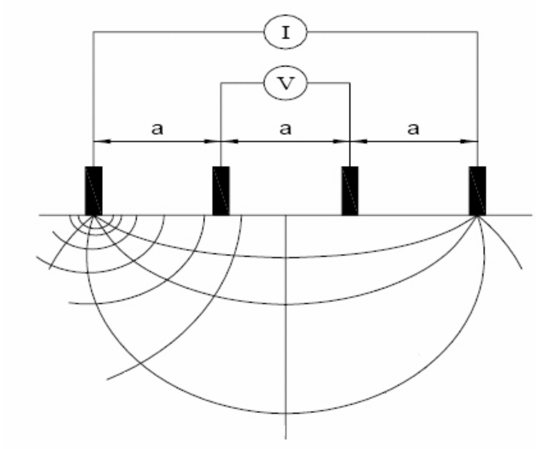
This test suffers some limitations, including the following (Stannish et al. 2000):

- The current passed is influenced by all ions in the pore solution, not just chloride ions.
- The measurements are made before a steady-state migration is achieved.
- The temperature of the specimen increases due to the applied voltage.

Surface Resistivity – AASHTO T 358

The surface resistivity test evaluates the electrical resistivity of water-saturated concrete, providing a rapid means to assess the concrete's ability to resist moisture penetration. AASHTO T 358 takes approximately 5 minutes to conduct, does not involve chemicals, and is generally easier to perform than AASHTO T 277. The surface resistivity test is also nondestructive; therefore, test specimens can subsequently be tested again at latter ages or used for other testing. For these reasons, AASHTO T 358 is gaining popularity.

In AASHTO T 358, the resistivity of saturated concrete cylindrical specimens (100 mm diameter by 200 mm length, or 150 mm diameter by 300 mm length [4 in. diameter by 8 in. length, or 6 in. diameter by 12 in. length]) is measured using a four-pin Wenner probe array, as illustrated in Figure 6. An AC potential difference is applied in the outer pins of the Wenner array, generating current flow in the concrete. The two inner probes measure the potential difference generated by this current, from which the resistivity of the concrete is calculated. The resistivity, in Ohms-cm, has been related to the resistance of the specimen to chloride ion penetration.



Castro et al. 2010

Figure 6. Schematic of the four-point Wenner array probe setup

AASHTO T 358 still suffers some limitations, in that the results depend on the sample geometry, test temperature, degree of saturation, and how the sample was stored (Spragg et al. 2012, Weiss 2014). To address these limitations, work has been completed to standardize the sample conditioning, testing condition, and geometry. In addition, to normalize the results of this and other electrical tests, the formation (F) factor is calculated, which is directly related to the concrete pore volume and connectivity as well as to the conductivity of the pore solution (Weiss 2014).

Uniaxial Resistivity – AASHTO TP 119

AASHTO TP 119 is similar AASHTO T 358, in that an electrical current is passed through saturated concrete cylindrical specimens (100 mm diameter by 200 mm length, or 150 mm diameter by 300 mm length [4 in. diameter by 8 in. length, or 6 in. diameter by 12 in. length]) and the resistance calculated. But instead of being conducted at the surface of the specimen, the current is passed uniaxially through the length of the specimen, which has two electrode plates at either end (see Figure 7).

Spragg et al. 2013a

Figure 7. Test setup for determining uniaxial resistivity

The uniaxial resistivity test, also known as the bulk resistivity test, has advantages and disadvantages compared to AASHTO T 358. The advantages include the following:

- One measurement instead of four
- Not as sensitive to surface variations
- Simple geometric correction
- Larger volume of material sampled

One disadvantage of the uniaxial resistivity test is that to be used with a four-pin resistivity device, the pins need to be attached to plates. Other points to consider include the following:

- The condition of the specimen before and during testing is critical to repeatability.
- The results of this test can be used to calculate the F factor.

Table 4 lists the recommended resistivity values between surface resistivity tests and the rapid chloride penetration test (RCPT).

Table 4. Relationship between surface resistivity tests and RCPT

ASTM C1202 Classification (1)	Charge Passed (Coulombs) (1)	Direct Resistivity (kOhm-cm) (2)	Berke Empirical (kOhm-cm)	Paredes Empirical (kOhm-cm) (3)	Apparent Surface Resistivity (102 mm x 205 mm) (kOhm-cm) (4)
High	>4,000	<5.2	<4.9	<6.5	<9.7
Moderate	2,000–4,000	5.2–10.4	4.9–8.76	6.5–11.3	9.7–19.3
Low	1,000–2,000	10.4–20.8	8.8–15.6	11.3–19.9	19.3–38.6
Very Low	100–1,000	20.8–207	15.6–105.9	19.9–136.6	38.6–386
Negligible	<100	>207	>105.9	>136.6	>386

Source: Spragg et al. 2013b
1. ASTM C1202-10
2. Calculated using Ohm's law and geometry
3. Corrected for geometry
4. Bulk resistivity multiplied by geometry factor

Freeze-Thaw Durability (Section 6.5)

In some climates, concrete pavements are subjected to multiple annual freezing and thawing cycles. If any concrete undergoes freezing and thawing in a critically saturated state (above approximately 85% saturation), damage will occur within a few cycles (Jones et al. 2013, Bentz et al. 2001).

The formation of ice is expansive, resulting in an approximate expansion of 9% when liquid water transitions to ice, and changes the chemistry of the remaining pore solution, making it more concentrated, resulting in the generation of stress within the concrete (Powers 1945, Powers 1954, Powers 1955, Powers and Helmuth 1956, Marchand et al. 1995, Penttala 1998, Scherer and Valenza 2005).

It is well known that the freeze-thaw durability of hydrated cement paste (HCP) in concrete is influenced by the size and volume of air bubbles purposefully entrained in the concrete and its permeability (ACI 2016b, Wilson and Tennis 2021). The entrained air helps improve freeze-thaw durability in many different ways. First, it provides a well-distributed pore system that extends the time it takes for concrete continuously exposed to water to reach critical saturation. The quality of the entrained air (spacing) impacts the critical degree of saturation, with higher quality air-void systems being greater than 85% and lower quality air-void systems potentially being less. The entrained air voids also act as pressure relief valves as the water in the pores freezes (Tunstall et al. 2021).

The w/cm ratio also directly impacts the volume of the concrete's capillary pores, directly affecting the rate at which fluid is absorbed and transported. Concrete made with a high w/cm ratio has an increased volume of capillary pores that saturate relatively quickly, resulting in an increased initial rate of absorption (Todak et al. 2015).

Air Content – AASHTO T 152

Section 6.5.1.2 of AASHTO R 101-22 provides a design alternative to use an air content between 5% and 8%, determined according to AASHTO T 152, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method. The pressure method is based on Boyle's law, which relates pressure to volume. Fresh concrete is placed in a pressure-type meter, and a predetermined pressure is applied that compresses the air within the concrete sample, including that within the aggregate (which is why the test is not suitable for use with lightweight or highly porous aggregates). The total air content present is read directly from the gauge of a calibrated Type B pressure meter.

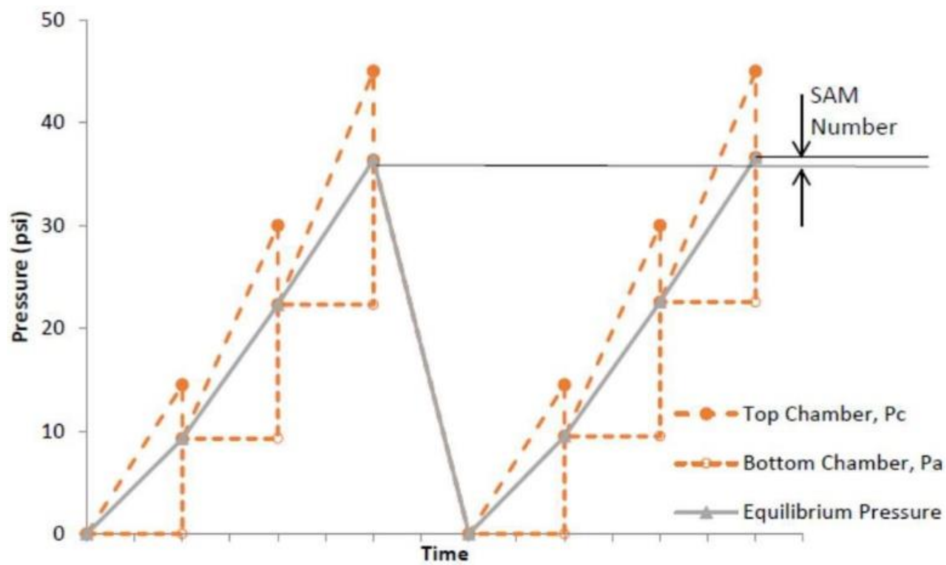
SAM Number – AASHTO T 395

Section 6.5.1.3 of AASHTO R 101-22 provides a design alternative for a SAM number less than or equal to 0.20 for mixture design and an air content greater than 4%. These are determined according to AASHTO T 395. For construction, a SAM number of 0.30 or less should be obtained. This higher SAM number is used in construction to account for the variability in air void systems, construction practices, and the test method. Since a lower SAM number is used in the mixture design, this creates a safety factor against failure in construction.

It is recognized that simply specifying total air content is not necessarily adequate, and therefore an alternate test that assesses the air-void system characteristics in fresh concrete is desirable. The most rigorous methodology to evaluate the air-void system in concrete is microscopically, through assessment of a polished concrete slab in accordance with ASTM C457, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. Because ASTM C457 can only be done on hardened concrete and requires a trained technologist using a microscope for 3 hours or more to execute, alternative methods are desirable.

An alternative method has been developed called the SAM method that measures the air-void system in fresh concrete. The SAM method has been standardized under AASHTO T 395, Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method. Instead of using a single testing pressure, AASHTO T 395 uses sequential pressurization to not only determine the volume of total air but also make an inference regarding the quality of the air-void system.

AASHTO T 395 uses a pressure meter setup that has been modified, with the dial gauge being replaced with a digital gauge. Two additional sequential pressurizations are applied at 0.21 MPa (30 lb/in.^{2}) and 0.31 MPa (45 lb/in.^{2}). After the first sequence, the pressure is released, and the sequence is repeated a second time. The difference in the equilibrium pressure at the highest pressure (0.31 MPa [45 lb/in.^{2}] in the top chamber) for the first sequence and second sequence is reported as the SAM number, as illustrated in Figure 8.



Ley et al. 2017

Figure 8. Sequential pressures applied in the SAM and calculation of the SAM number

The SAM number has been correlated to the air-void spacing factor obtained through ASTM C457 and the durability factor (DF) of concrete as assessed using AASHTO T 161 (Ley and Tabb 2013, Welchel 2014, Ley et al. 2017).

Damage Due to Deicers (Section 6.5.4)

Deicing chemicals based on magnesium and calcium chloride have been demonstrated to react with hydroxide hydration products to form very expansive calcium oxychloride compounds. These compounds are stable at temperatures just above freezing but decompose at standard room temperature, making their detection difficult.

A test method based on a low-temperature differential scanning calorimeter (LT-DSC) can evaluate the potential reactivity of a cementitious system with a salt solution by measuring the heat associated with calcium oxychloride formation (Weiss and Farnam 2015, Monical et al. 2015). This method provides a means for optimizing the composition of cementitious materials by reducing the potential for calcium oxychloride formation. Specific portland cement and SCM systems can be tested, making this a practical screening tool for selecting materials for use under anticipated deicing conditions.

Section 6.5.4.1 of AASHTO R 101-22 requires that the calcium oxychloride be determined to be less than 0.15 g calcium oxychloride (CaOXY) per 100 g cementitious paste as determined per AASHTO T 365. While this value was originally empirically defined, more recent research has indicated scientific boundaries for these limits (Ghantous et al. 2022).

Aggregate Stability (Section 6.7)

Aggregates typically occupy 60% to 75% of the concrete volume (Wilson and Tennis 2021). Ideally, these aggregates are clean, hard, strong, and durable and will contribute positively to the concrete pavement's economy, constructability, and long-term performance.

However, several mechanisms can affect the stability of certain aggregates in concrete, particularly when the concrete is subjected to a harsh environment that includes freezing and thawing under saturated conditions and exposure to chemical deicers (Taylor and Wang 2015). Screening of potential aggregates is required for both resistance to damage from cyclic freezing and thawing as well as damaging reactions that may occur between the aggregate and the highly alkaline concrete pore solution.

D-Cracking

Certain calcareous aggregates have a pore system that readily absorbs water yet releases it slowly when drying, leading to a high risk that the aggregate will remain in a critically saturated state. When subjected to cyclic freezing and thawing, these saturated aggregates expand and crack, causing damage to the concrete. This phenomenon is commonly referred to as D-cracking in pavements. D-cracking is initially visible as a series of fine cracks generally running parallel to the slab's joints, cracks, or free edges.

The most effective means of preventing aggregate freeze-thaw deterioration is to prohibit the use of susceptible aggregates by specifying that coarse aggregates pass specific freeze-thaw requirements.

Highway agencies experiencing D-cracking have developed screening protocols based on variations of AASHTO T 161, Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing. The concrete specimens tested in AASHTO T 161 must be prepared and cured using a procedure such as ASTM C1646, Standard Practice for Making and Curing Test Specimens for Evaluating Resistance of Coarse Aggregate to Freezing and Thawing in Air-Entrained Concrete.

Iowa has adopted a protocol, known as the Iowa Pore Index Test, based on chemical testing of the aggregate along with measurement of the water absorption rates under pressure.

Alkali-Aggregate Reactivity – AASHTO R 80

Most highway agencies in the United States have reported instances of ASR. ASR is a result of a chemical reaction between the hydroxyl ions of alkalis in the pore solution from the hydrated cement and certain siliceous rocks and minerals (including opal, chert, microcrystalline quartz, and acidic volcanic glass) that are present in some aggregates (Thomas et al. 2013). The reaction forms an alkali-silica gel that, under certain circumstances, can imbibe water, expand, and fracture the affected aggregate particles and surrounding paste. Extensive information is available regarding the mechanisms responsible for ASR and the strategies to mitigate it (Thomas et al. 2013). For highway applications, AASHTO R 80, Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction, provides the most comprehensive recommendations on mitigating ASR.

Shrinkage (Section 6.4)

Changes in the moisture content of a mixture result in volume changes that can lead to warping or cracking of a pavement slab. Moisture gradients naturally occur in slabs placed on the ground, where the bottom of the slab tends to be wetter than the top. This often results in differential drying shrinkage, which is responsible for upward warping in concrete slabs because the top of the slab is often drier than the bottom. In turn, this produces increased stress and roughness, especially in more arid climatic zones (Asbahan and Vandenbossche 2011, Karamihas and Senn 2012, Van Dam 2015).

In addition to drying shrinkage, concrete can also change volume due to self-desiccation, resulting in a type of shrinkage known as autogenous shrinkage, which is important to account for when the w/cm ratio is less than 0.40. If the combined drying and autogenous shrinkage is restrained by embedded reinforcement, the frictional drag of a slab on grade, load transfer devices at the joints, and so on, the result is stress as the concrete shrinks. If this stress exceeds the tensile strength of the concrete, cracking ensues.

Various strategies are used to assess and minimize the shrinkage of concrete and the tendency of concrete to crack when its volume changes due to changes in moisture. These strategies include the use of prescriptive measures based on minimizing paste volume or limiting unrestrained drying shrinkage, per AASHTO T 160, or the use of performance-based measures through an assessment of cracking tendency using ring testing, per AASHTO T 334 or T 363.

Limit Paste Volume

Section 6.4.1 of AASHTO R 101-22 recommends that paste volume shall not exceed 25% of the volume of the concrete.

Unrestrained Shrinkage – AASHTO T 160

An alternative approach to addressing shrinkage is to limit unrestrained shrinkage to less than 420 microstrain ($\mu\varepsilon$) at 28 days, per AASHTO T 160, Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete. After casting, concrete prisms are kept in molds for 23.5 ± 0.5 hours and then de-molded, and the initial length measurements are taken.

The two significant limitations of this test are that (1) early-age volume changes due to chemical and/or autogenous shrinkage that may have occurred within the first 24 hours are not assessed

(Weiss 1999, Goodwin 2006, Wilson and Tennis 2021) and (2) the specimens are unrestrained, so the effect of restraint on cracking is not measured. Regardless, the test provides valuable information on the drying shrinkage characteristics of concrete and is commonly used to specify concrete for slab-on-grade applications and bridge structures. The prescriptive limit of 420 $\mu\varepsilon$ at 28 days is a conservative value based on work conducted by Radlińska and Weiss (2012).

Workability (Section 6.8)

The American Concrete Institute (ACI) defines workability as "that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogeneous condition" (ACI 2021). As stated in ASTM STP 169D, the workability of concrete is to some degree a subjective measure, although several test methods are available to assess workability for various applications (Daniel 2006, Cook et al. 2013, Taylor et al. 2015).

For paving concrete, the most common test method used for quality control assessment of workability is AASHTO T 119, Test Method for Slump of Hydraulic Cement Concrete, or simply the slump test. Considered to indicate the consistency of an individual batch of concrete (Daniel 2006), the slump test is widely recognized to have a limited ability to assess workability for modern concrete paving mixtures (Cook et al. 2013, Taylor et al. 2015). To better understand the ease with which concrete can be consolidated and finished as it passes through a paving machine, its behavior under and immediately after vibration must be assessed. The vibration must adequately fluidize the stiff concrete to promote good consolidation, yet the concrete must have sufficient stiffness after the vibration passes so that the slipformed paving edges resist edge slumping. Taylor et al. (2015) provide an excellent summary of concrete workability and the test methods developed to assess it. The Box Test and the VKelly Test are two test methods that consider both the mixture's response to vibration and its stiffness after vibration.

VKelly Test – AASHTO TP 129

The primary documentation for the VKelly Test is from Taylor et al. (2015). Taylor et al. (2015) modified a conventional Kelly ball by adding a vibrator. The initial penetration of the Kelly ball is performed, and then the rate of penetration is measured with the vibrator on. To simulate field conditions, the vibration frequency is set to 5,000 vpm. The unit is stabilized using an adjustable steel frame, and the graduated stem is retained to facilitate measurement during testing. The rate at which the ball sinks is plotted against the square root of time. The slope of the line is reported as the VKelly index, and research has shown that a rate of 0.6 to 1.3 in./root second indicates that a mixture is likely to perform well in a slipform paving machine. The VKelly has been approved as a full standard to be published as AASHTO T 403 in July 2023.

Box Test – AASHTO TP 137

The Box Test (Cook et al. 2013, Cook et al. 2014) is designed to assess the ability of a concrete paving mixture to consolidate under vibration yet be stiff enough to maintain a straight edge after the vibration passes.

The Box Test is very simple in concept, consisting of a platform, two right-angled wooden side forms, and two clamps that form a "box" having roughly a 0.3 m^3 (1 ft^3) volume. Concrete is uniformly placed into the box to a depth of 240 mm (9.5 in.), and an internal vibrator running at 12,500 vpm is inserted over 3 seconds and removed over 3 seconds from the center of the box. The forms are then removed, and the concrete is qualitatively evaluated for the degree of consolidation and edge slumping. A visual inspection of the surface voids on the sides of the box is made, and the edge slumping of the formed box is measured.

The parameters in this test were developed to provide the same energy per volume that a typical concrete paving machine applies at typical speeds and vibrator frequencies. This test was validated with field paving measurements.

Test Method Summaries

Test method summaries are available on the PEM project website (https://cptechcenter.org/performance-engineered-mixtures-pem/) for the following:

- VKelly
- Box
- SAM
- Formation factor
- Phoenix

DATA

Considerable sampling and testing activities were conducted over the life of the PEM pooled fund project in order to validate the recommendations made. Field testing was performed and data were collected by state agencies, the research team, and the FHWA MCTC during the construction of paving projects throughout the pooled fund study period. In addition, the research team collected data from Long-Term Pavement Performance (LTPP) project Specific Pavement Study 2 (SPS-2) test sites that have been in service for years. All of the information was stored in a database.

Database

In addition to PEM test results, other relevant data from each project were collected that could be used to help explain the test results and resulting pavement performance. The database consisted of the following tables:

- Project Location
- Aggregate Gradations and Properties
- Mix Design Proportions
- Fresh Properties
- Hardened Properties
- FWD Data
- Core Samples
- Miscellaneous Project Information (drainage, de-icing activities)
- Pavement Distresses and Roughness
- In-Use Traffic
- Weather Data

A data collection spreadsheet was set up as a form for ease of navigation, allowing users to input a wide range of data for each project, as shown in Figure 9.

Performance Engineered Mixtures (PEM): Project Submission Forms

Basic Project Information

State:	Minnesota	
Route:	TH 35W	
Begin Milepost:	013+00.868	
End Milepost:	017+00.261	
Road Classification:	Urban Interstate	
Project Latitude (begin):	44.924796	
Project Latitude (end):	44.965765	
Project Longitude (begin):	-93.274518	
Project Longitude (end):	-93.260702	
LTPP climatic region (if known):	Wet-Freeze	
Concrete Paving Begin Date:	4/21/2020	
Concrete Paving End Date:	5/5/2020	
Type of Structure:	Pavement	
Pavement Type:	JPCP	
Overlay Type:	Not an Overlay	
Construction Type:	Slip-form	
Lane Width:	12	feet

Property	Test Date	Test Time	Station	Batch Number	Test Results	Test Units
Concrete Temperature	4/21/2020	7:15	Plant	3A21-43	60	Fahrenheit
Concrete Temperature	4/21/2020	7:30	660+15	3A21-43	60	Fahrenheit
Concrete Temperature	4/21/2020	9:08	655+50	3A21-43	59	Fahrenheit
Concrete Temperature	4/21/2020	10:08	651+75	3A21-43	62	Fahrenheit
Concrete Temperature	4/21/2020	11:20	647+75	3A21-43	62	Fahrenheit
Concrete Temperature	4/21/2020	12:25	643+00	3A21-43	61	Fahrenheit
Concrete Temperature	4/21/2020	13:10	640+50	3A21-43	61	Fahrenheit
Concrete Temperature	4/21/2020	13:20	640+00	3A21-43	61	Fahrenheit
Concrete Temperature	4/21/2020	13:58	638+50	3A21-43	62	Fahrenheit
Concrete Temperature	4/21/2020	14:15	638+50	3A21-43	62	Fahrenheit
Concrete Temperature	4/21/2020	15:00	635+00	3A21-43	61	Fahrenheit
Concrete Temperature	4/21/2020	15:15	635+00	3A21-43	61	Fahrenheit
Concrete Temperature	4/21/2020	15:40	631+00	3A21-43	62	Fahrenheit
Concrete Temperature	4/21/2020	17:00	627+00	3A21-43	60	Fahrenheit
Concrete Temperature	4/21/2020	18:15	623+20	3A21-43	63	Fahrenheit
Air Content	4/21/2020	7:15	Plant	3A21-43	10	percent
Air Content	4/21/2020	7:30	660+15	3A21-43	8.8	percent
Air Content	4/21/2020	9:08	655+50	3A21-43	8.8	percent
Air Content	4/21/2020	10:08	651+75	3A21-43	8.5	percent
Air Content	4/21/2020	11:20	647+75	3A21-43	8.4	percent
Air Content	4/21/2020	12:25	643+00	3A21-43	7.4	percent
Air Content	4/21/2020	13:20	640+00	3A21-43	7.7	percent
Air Content	4/21/2020	13:58	638+50	3A21-43	8.1	percent
Air Content	4/21/2020	14:15	638+50	3A21-43	6.9	percent
Air Content	4/21/2020	15:00	635+00	3A21-43	8.7	percent
Air Content	4/21/2020	15:15	635+00	3A21-43	8.1	percent
Air Content	4/21/2020	15:40	631+00	3A21-43	8.8	percent
Air Content	4/21/2020	17:00	627+00	3A21-43	7.5	percent
Air Content	4/21/2020	18:15	623+20	3A21-43	7.7	percent

Figure 9. Example of spreadsheet used for data entry

The spreadsheet offered the ability for users to add hundreds of individual test results with project-specific stationing for both fresh and hardened concrete properties. Should individual test results be unavailable, the user could alternatively upload the average values of each test. Dropdown menus were used to serve two purposes: make the spreadsheet easier to use and standardize the responses from users. Certain cells included pop-up comments that provided clarification as to the information requested. Additionally, limits were set on different cells; for example, no text characters could be entered into a field that was formatted to take a numerical value (e.g., laboratory test results). Several iterations of review and revision were performed by members of the PEM team to check that, among other things, the cells were properly formatted, the relevant ASTM/AASHTO test procedures were referenced, and, most importantly, that the spreadsheet was easy to understand and use.

Visual Basic for Applications (VBA) code was created to extract the data within the spreadsheet and transfer it to the corresponding tables in the database. Once the data extraction process was tested and bugs removed, the spreadsheet was finalized and provided to users whenever PEM testing was conducted.

Data were entered into the spreadsheets by state agencies as they conducted PEM testing. The spreadsheets were provided to the research team for review to ensure that the data were in the proper format. For example, it was important to verify that stationing was entered as a number (2230) instead of text (22+30). There were also certain fields that had a predefined selection of input values, and these were also reviewed to ensure that users selected one of these options instead of inputting their own values. This effort was made so that analyses could be performed without any data modification being needed prior to data analysis.

Field Testing

The project included shadow testing performed by state agencies, the research team, and the FHWA MCTC, where PEM tests were run concurrently with the local department of transportation's (DOT's) standard quality assurance (QA) and quality control (QC) tests. The research team coordinated with state agencies to collect data using the spreadsheet. Data were then plotted and reviewed. Based on a review of the data, the following observations were made:

- Workability tests including the Box Test and VKelly were not performed for the majority of projects.
- Completion of the data entry forms from the state agencies took additional effort, and values for all of the fields were not available.
- SAM testing showed an overall average SAM number of 0.21 across all projects, and 14% of results were above the recommended acceptance limit of 0.30.
- SAM testing for NYSDOT showed an overall average SAM number of 0.18, and 5% of the results were above the recommended acceptance limit of 0.30. NYSDOT required a SAM number in the mixture design phase to be 0.20 or lower.
- The difference between the air content from the Type B air meter and the SAM was on average 0.1%, with a standard deviation of 0.58%. This means that, on average, the difference between the two measurements is negligible in practical terms. The published standard deviation between two Type B air meters is 0.29%.
- Feedback received indicated that training and equipment maintenance were necessary for use of the SAM.
- Resistivity data showed higher variability for samples conditioned in lime water than samples conditioned by other methods.
- Resistivity data were confounded by non-adherence to the published testing standards.
- Data plots for fresh concrete and hardened concrete testing are provided in Appendix C. Data plots corresponding to some of the listed observations are shown in Figures 10 through 18.

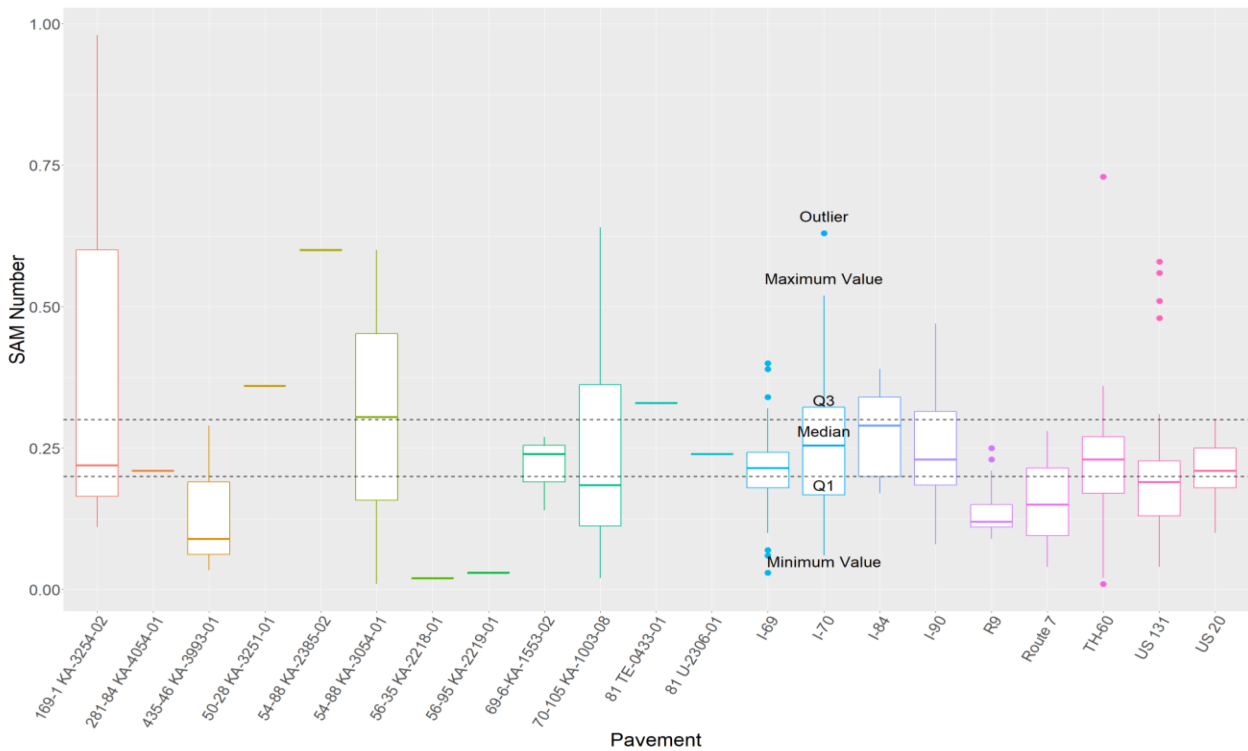


Figure 10. SAM box and whisker plots for pavement projects

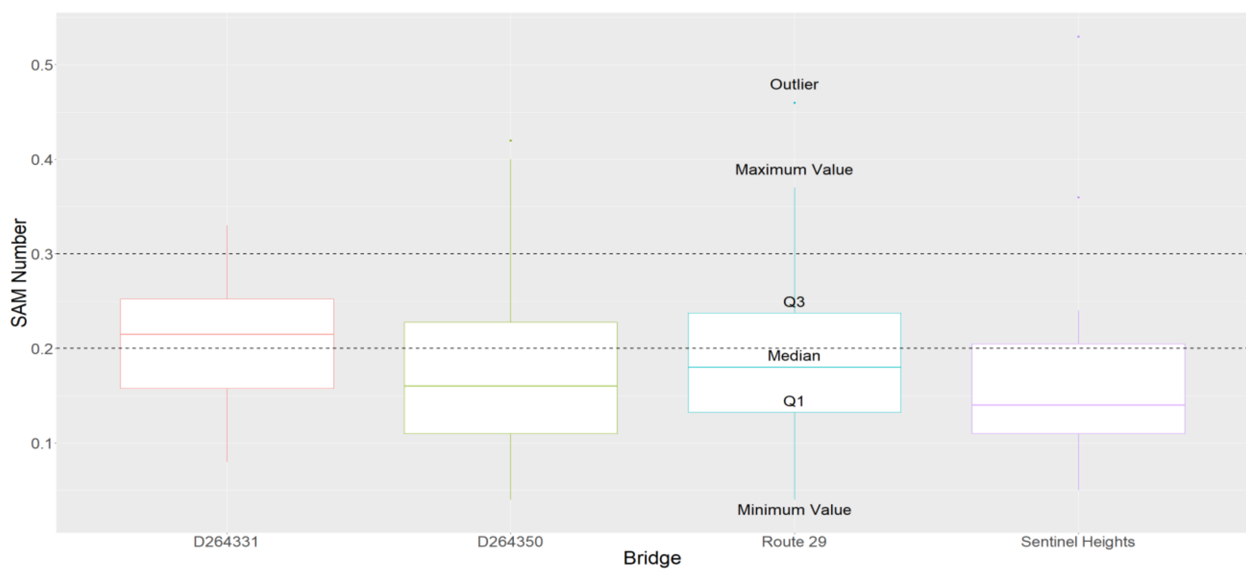


Figure 11. SAM box and whisker plots for bridge projects

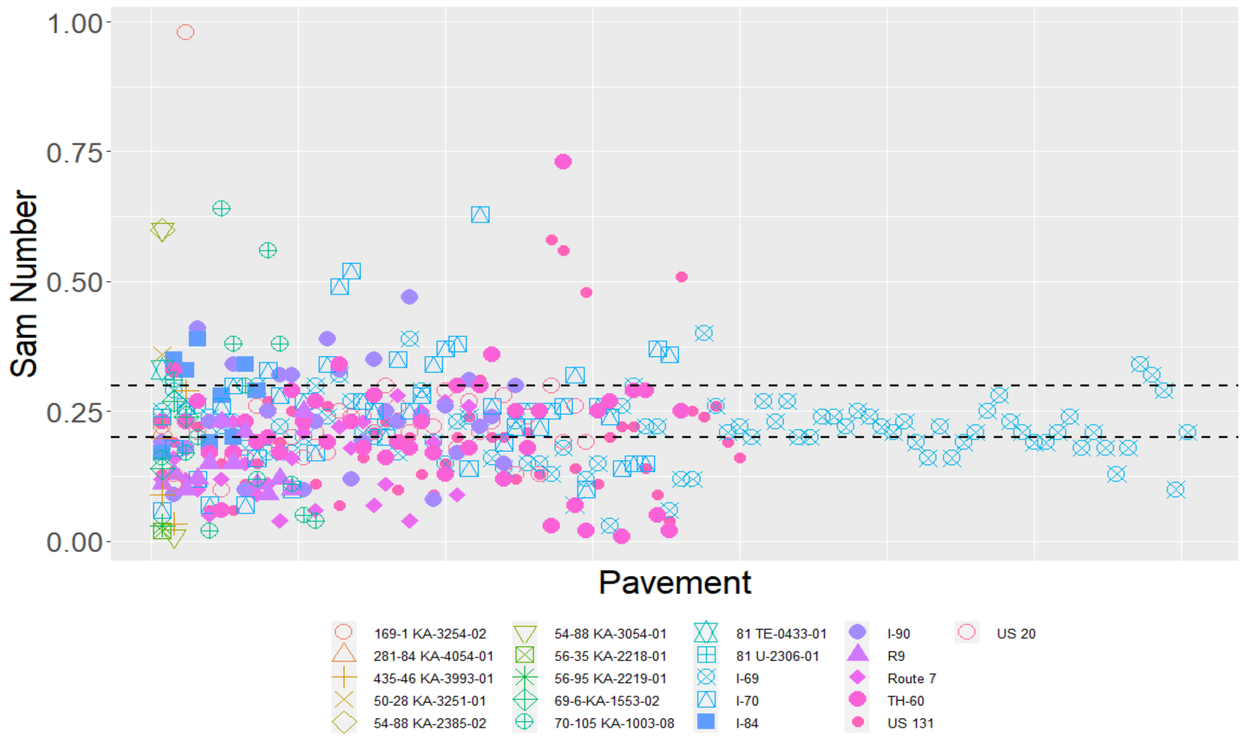


Figure 12. SAM scatter plot for pavement projects

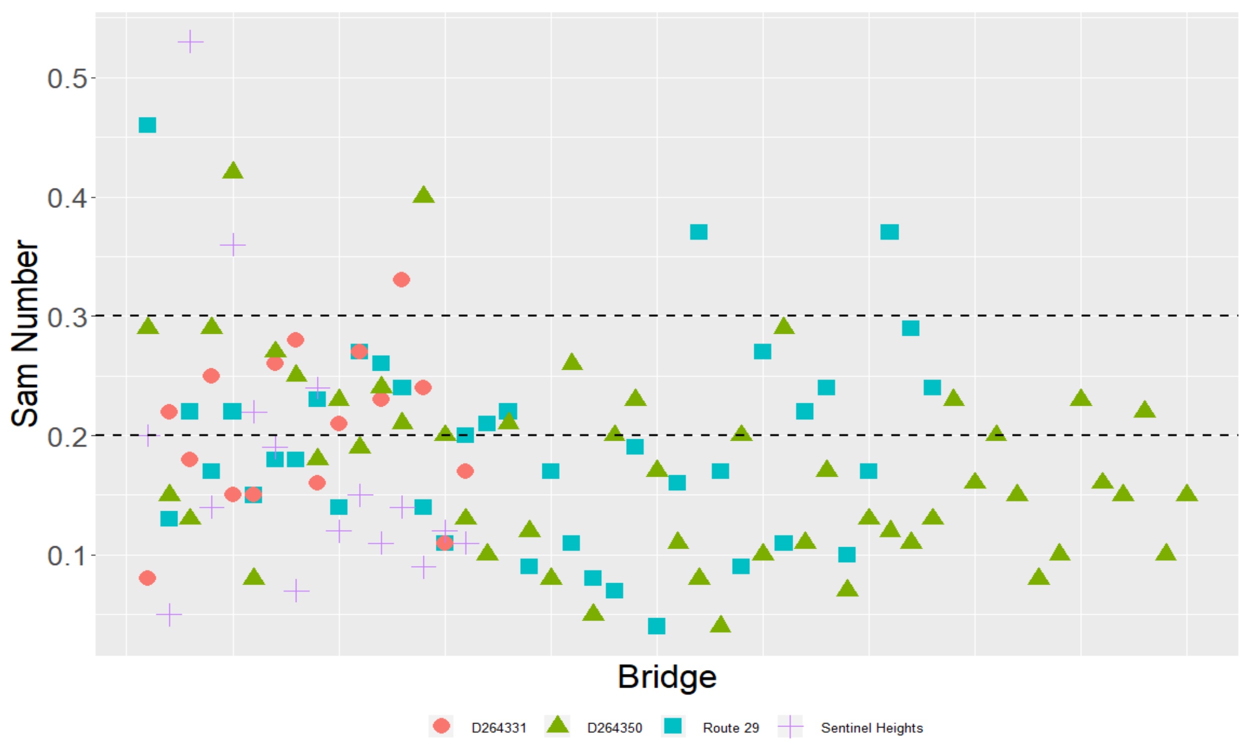


Figure 13. SAM scatter plot for bridge projects

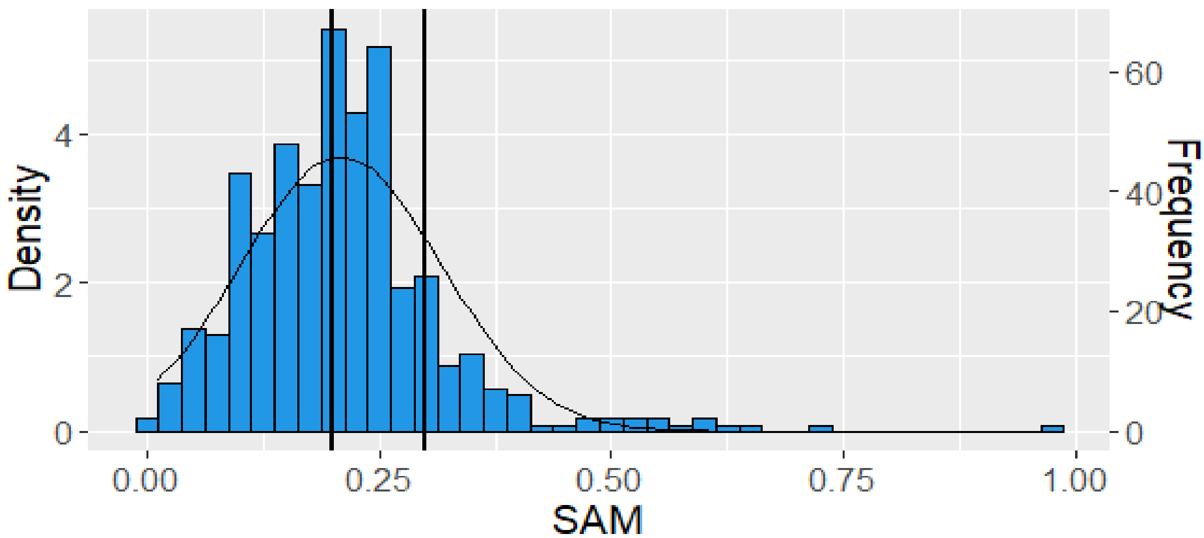


Figure 14. SAM histogram for all projects

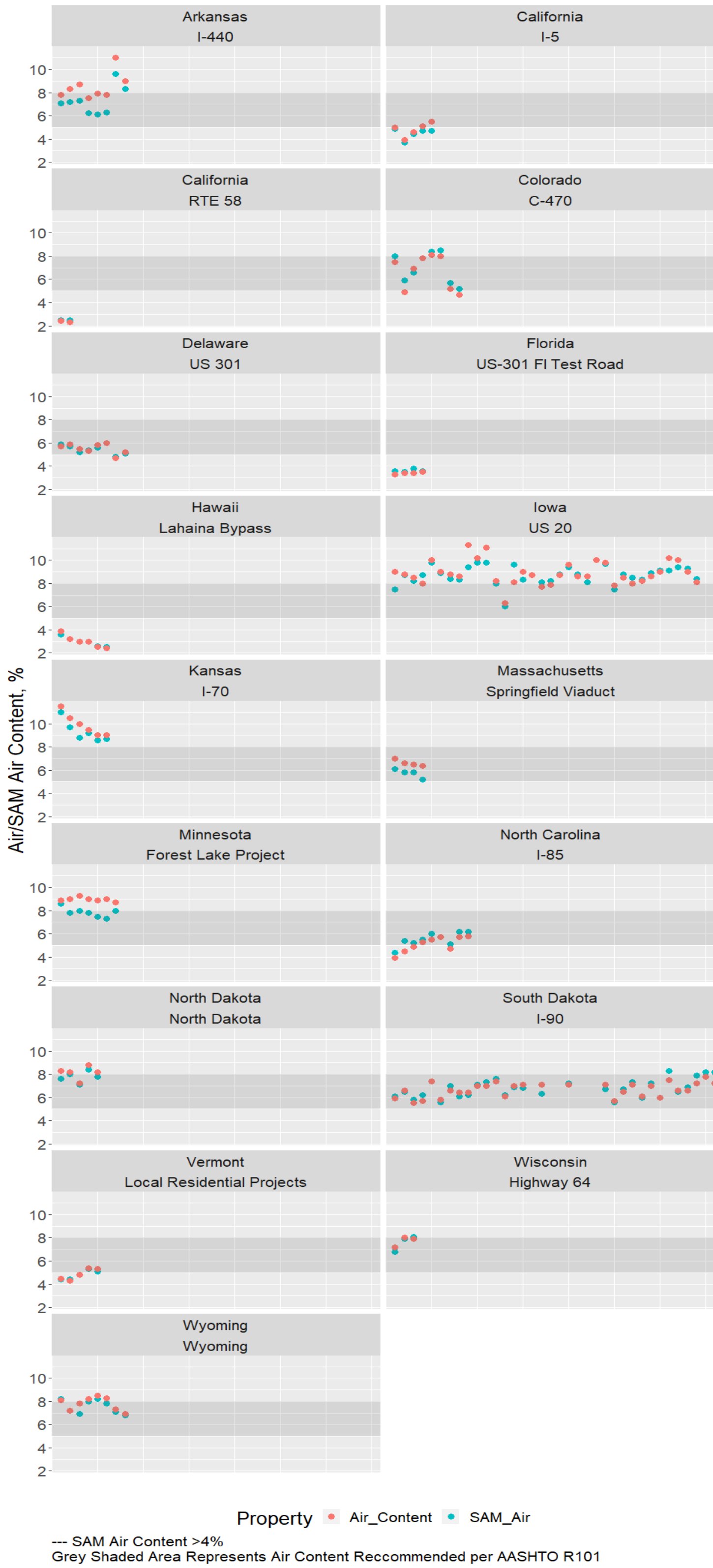


Figure 15. Relationship between air content by Type B meter and by SAM for various projects

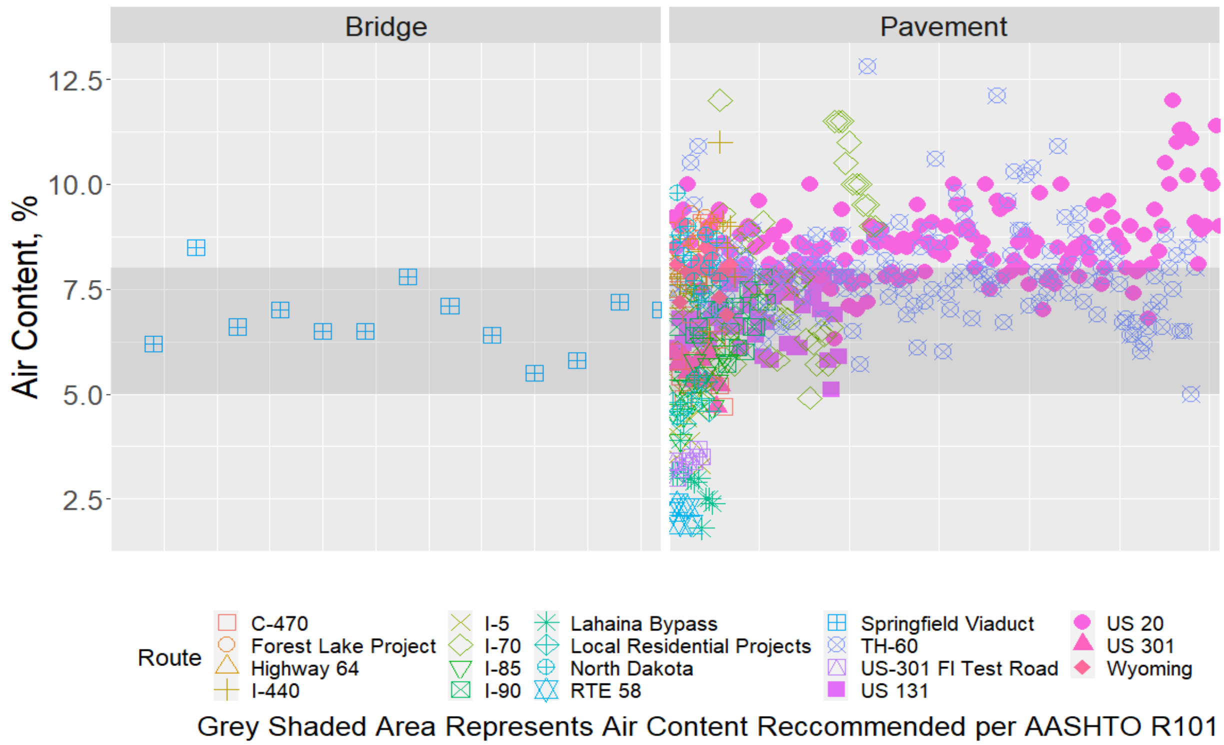


Figure 16. Air content for bridge and pavement projects

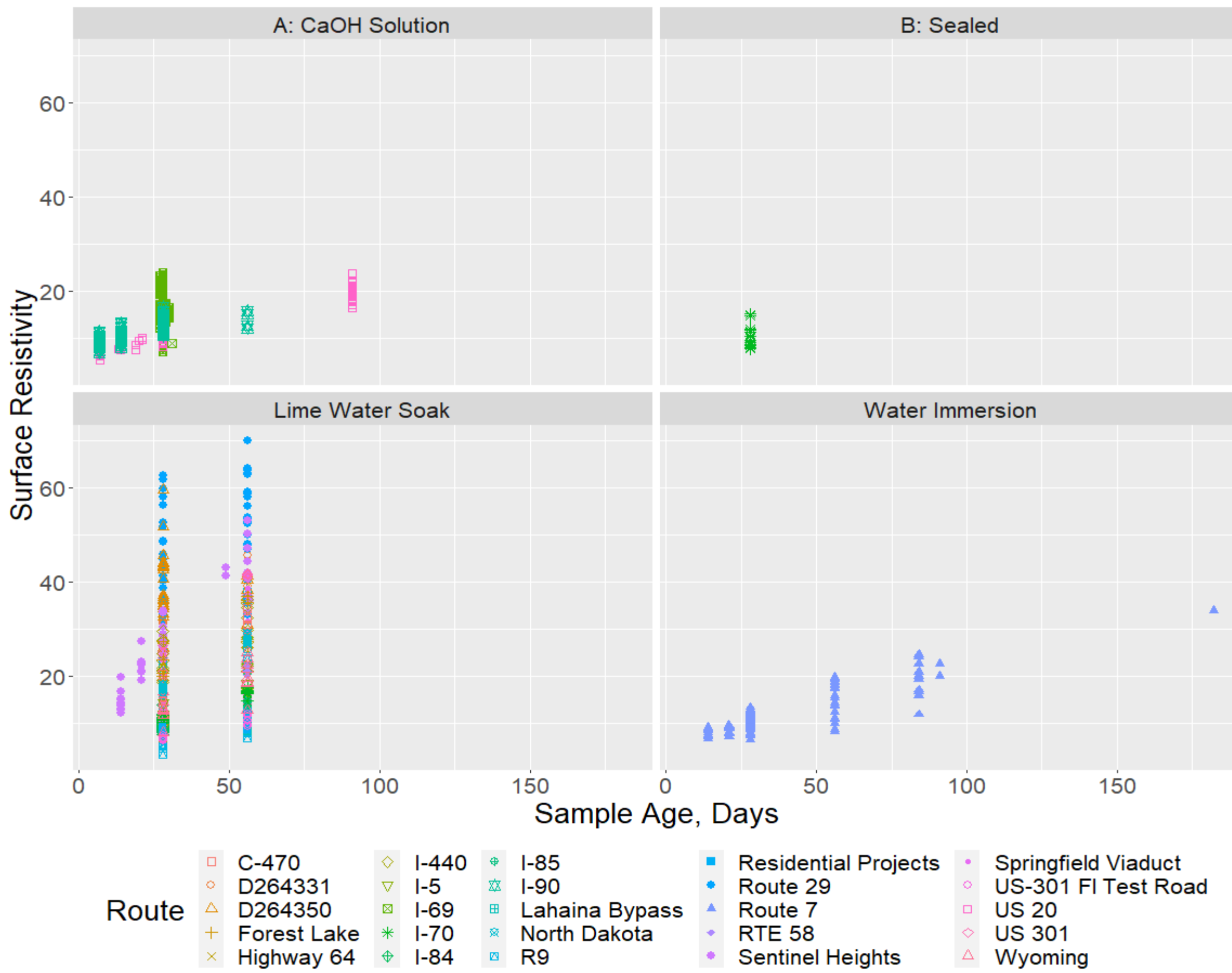


Figure 17. Surface resistivity for various preparation conditions

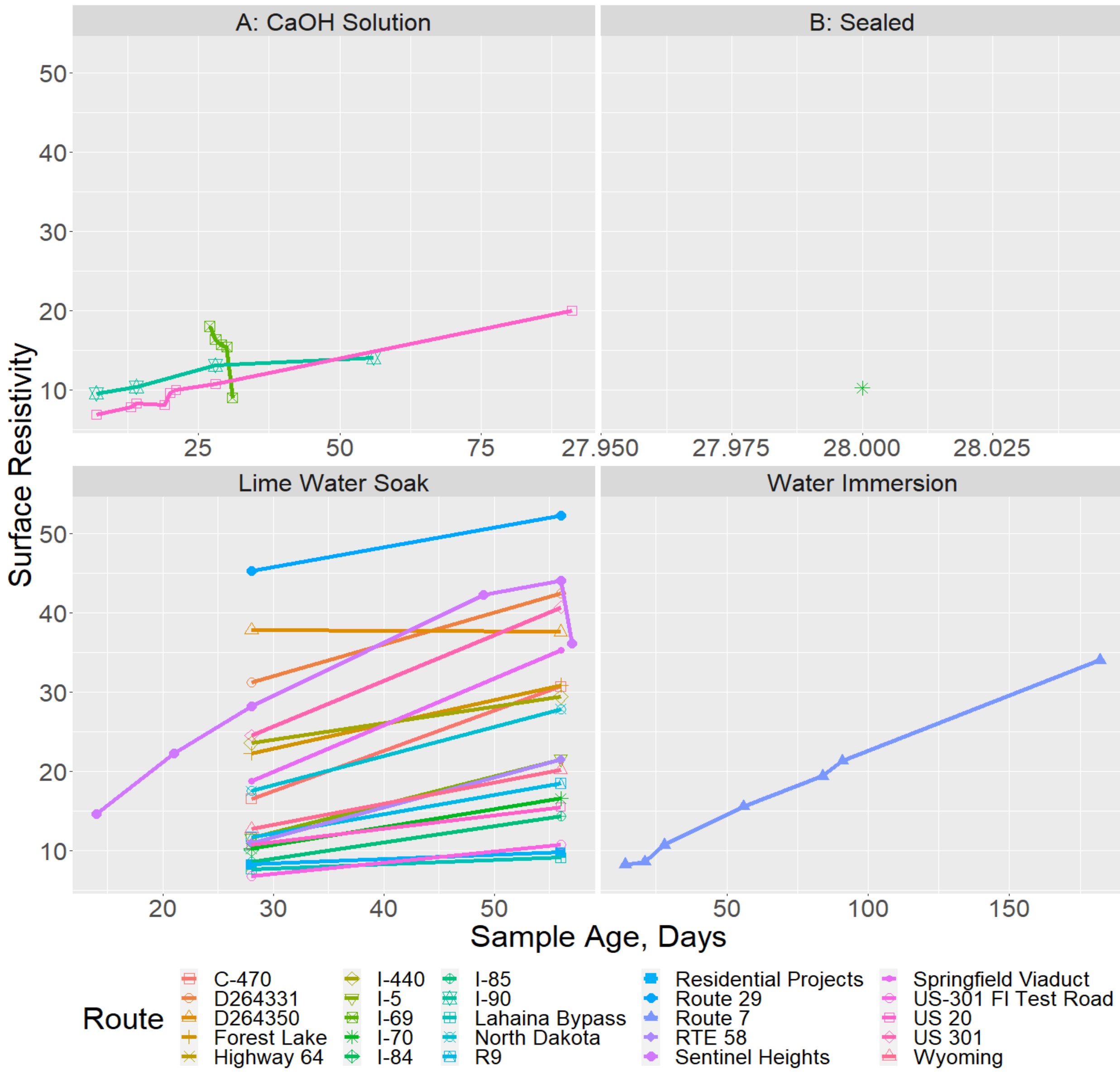


Figure 18. Surface resistivity versus age for various preparation conditions

PEM IN PRACTICE

Incentive Funding

In an effort to encourage the use of PEM, FHWA offered various levels of incentive funding to state agencies to help offset the costs of additional shadow testing, data collection, and reporting. Seven of the 19 pooled fund states accepted incentive funding (Figure 19). As part of the funding, a report was required at the conclusion of the project that included a summary of the shadow testing results. Links to reports from the state agencies are found in Appendix B.

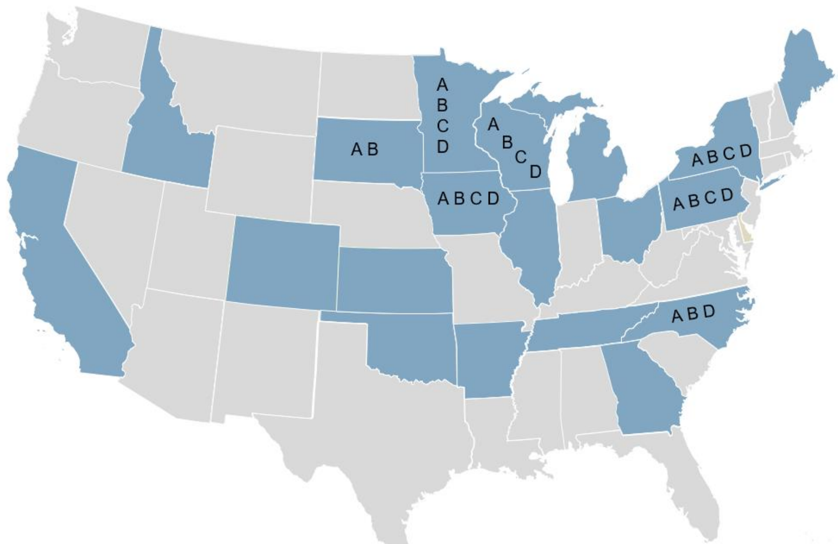


Figure 19. PEM states (shown in blue) and states receiving incentive funding

Table 5 lists the four categories of funding available.

Table 5. Incentive category types

Category	Description	Funding
A	Incorporating two or more PEM tests in the mixture design/approval process	$40,000
B	Incorporating one or more new tests in the acceptance process	$20,000
C	Requiring a comprehensive QC plan from the contractor that will be approved and monitored by the state agency	$20,000
D	Requiring the use of control charts as called for in AASHTO PP 84-17	$20,000

State Agency Experiences

PEM demonstration projects in Iowa and North Carolina are described below. PEM experiences from other pooled fund member states are available through the links to the state shadow project reports listed in Appendix B.

Iowa Experience

Concrete paving specifications evolved from recipe-based mixtures to so-called quality management concrete (QMC) mixtures in the late 1990s. In the latter case, the contractor is more involved in selecting 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 on several paving projects. PEM design and testing has allowed the Iowa DOT to improve concrete pavement sustainability.

In 2018, incentive funds were used for a project on US 20 in Woodbury County paved by Cedar Valley Corporation, LLC. The FHWA MCTC was on site to demonstrate the PEM test procedures as part of an open house held on August 1, 2018. The contractor performed quality control testing and PEM shadow testing and used a reduced cementitious materials content mix design that was validated with the PEM testing. As a result of the initial project, the company became interested in the PEM program and continued to perform testing on several paving projects over the next few years. Figure 20 shows the participants of the Iowa PEM Open House.

Jagan M Gudimettla, ATI Inc. for the FHWA Mobile Concrete Technology Center

Figure 20. Iowa PEM Open House

The contractor's mixture was based on the QMC requirements, which call for the following:

- A combined aggregate gradation in Zone II of the Shilstone coarseness/workability chart
- 6% air content
- w/cm ratio of 0.40
- Flexural strength (third point) of 640 lb/in.^{2} at 28 days

The volume of paste was calculated at 24.4%.

Figure 21 shows the paving on the Iowa PEM shadow test project.

Todd Hanson, Iowa DOT

Figure 21. Paving on US 20 by Cedar Valley Corporation, LLC

A reduced cementitious materials content mix was utilized on the shoulders. The CP Tech Center modified the contractor's aggregate proportions and recommended a cementitious content of 515 lb/yd^3. The original Class A shoulder mix was 550 lb/yd^3 (Figure 22).

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	

Figure 22. Iowa shadow project PCC mixtures

Prior to paving, the contractor created a trial batch of the PEM mix, and the Box Test indicated that the mix would be workable. The contractor used the PEM mix on the shoulders with success and indicated a desire to try the PEM mix on the mainline if there were any unpaved areas remaining. A link to the complete report including test results is available in Appendix B.

Based on the success of the shadow testing project, the contractor elected to continue shadow testing using the PEM test methods in order maintain proficiency and learn more about the methods. The average results for the project are shown in Table 6.

Table 6. Average test data from shadow projects in 2019

Location	SAM #	Box #	w/cm Ratio	Resistivity (kOhm-cm)
Polk I-35	0.23	1.2	0.39	11.89
Harrison I-29	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

Future implementation plans by the Iowa DOT include the following:

- Get more contractors involved and continue to gather information, especially with other aggregate combinations
- Update current QMC specifications for paving to include PEM testing
- Allow reduced cementitious materials content mixtures and validate with PEM testing and QC
- Investigate PEM mix design and testing for large bridge structures

North Carolina PEM Experience

NCDOT applied for $80,000 in PEM incentive funds to support PEM implementation in categories A, B, and D. Some of the FHWA funds were used internally to support equipment purchases, while the remainder was awarded to the University of North Carolina–Charlotte (UNC–Charlotte). UNC–Charlotte’s work included support of contractor testing and data collection at the pilot project site, analysis of the data received from the site, and preparation of a report. Figure 23 shows the paving on the NCDOT PEM demonstration project.

Tara Cavalline, University of North Carolina at Charlotte

Figure 23. NCDOT PEM demonstration project

Lane Construction was asked to partner in supporting a PEM demonstration project as part of the FHWA implementation funds program. The company suggested a design-build urban Interstate project it had been awarded that comprised a stretch of I-85 widening north of Charlotte, North Carolina (TIP Project I-3802B). The contract had been let prior to the decision of NCDOT to utilize this project for PEM demonstration, but the parties collectively agreed on scopes of work to support the work. The project included the widening of 5.3 miles of I-85 in Rowan County, North Carolina. The existing four-lane Interstate was widened to provide four additional travel lanes from north of Lane Street (Exit 63) to north of the US 29/UW 601 Connector (Exit 68). The pavement design thickness was 12 in. In addition to 500,000 yd^2 of concrete pavement, the project also included construction of six new bridges, two bridge replacements, two roundabouts, and associated storm drainage and asphalt pavement. The total project cost was \$140 million (Lane Construction 2020).

Overall, the PEM demonstration project was a success, in that the contractor and NCDOT personnel gained valuable experience. Comments from the contractor included the following:

- The training provided by the UNC–Charlotte team gave us unique exposure to new testing equipment and methods, which we did not have access to previously. Our personnel gained useful insight into the mechanical properties of concrete, which improved our understanding of the impact of concrete quality on pavement durability and longevity.
- With the help of the UNC–Charlotte team, we were able to quickly and easily implement the SAM and resistivity meter into our standard testing procedures. The SAM was used during routine sampling of plastic concrete during production, and the resistivity meter was used during routine breaking of hardened samples. We were pleased with the ease of these tests and did not find a need to provide additional—scarce—QC staff to support the extra testing.
- As a result of our project schedule, we were unable to apply the PEM criteria during the preliminary mix design phase. However, going forward, we intend to implement PEM guidelines on future portland cement concrete (PCC) pavement projects.

Comments from the NCDOT Materials and Tests Unit were as follows:

- The surface resistivity test is a very easy test to perform and is nondestructive.
- We will be able to equip each of our labs with a testing instrument for a low cost.
- We have typically completed cylinder compressive strength tests at 28 days. If surface resistivity specification targets are established at 56 or 90 days, the additional samples may pose a storage issue. Also, we would need to have a plan to address concerns about low surface resistivity test results at 56 and or 90 days.
- UNC–Charlotte research is identifying a 28-day surface resistivity target that generally correlates to a 56-day or 90-day resistivity value that predicts good durability performance. This would likely address the concerns above.
- More shadow testing will be completed with the SAM to get comfortable with this test.
- During this PEM demonstration project, many SAM numbers were above the preliminary target value of 0.3. Historically, we see good freeze-thaw resistance with our mixtures. Additional laboratory and field data using the SAM will be used to refine the performance target.
- The Box Test is a simple test that could provide the producer and contractor with beneficial information on the performance of their concrete paving mixtures.
- NCDOT could potentially add this as a requirement for pavement mix design submittals.
- NCDOT was very pleased with the results and the cooperation by all parties involved. For the most part, North Carolina has had very good concrete pavement performance with the prescriptive specifications that we currently utilize. The department will continue to explore PEM to see how these tests and other AASHTO PP 84 provisions will work with our daily operations.

As part of the FHWA MCTC Open House (Figure 24) held at the demonstration project, a large number of industry stakeholders and NCDOT personnel were able to become familiar with the PEM initiative.

Jagan M. Gudimettla, ATI Inc. for the FHWA Mobile Concrete Technology Center

Figure 24. NCDOT PEM Open House

Experience gained during this PEM demonstration project will guide two future PEM demonstration projects planned as part of NCDOT research project 2020-13, Continuing toward Durable and Sustainable Concrete through Performance Engineered Concrete Mixtures. A link to the PEM demonstration project report is included in Appendix B.

LTPP Program SPS-2 Sites

Background

In 1987, Congress authorized the LTPP program as part of the first Strategic Highway Research Program (SHRP). The initial five-year program was completed under direction of SHRP. Since 1991, FHWA has managed and funded the program. The program was created to document the long-term performance of different pavement structures using highly controlled construction and monitoring activities. Test sections were established across the United States and Canada and were organized into different studies. Each study focused on a different set of pavement parameters (materials, structure, climate, traffic) so that the influence of each pavement parameter on pavement performance could be evaluated. Since its inception, 19 different LTPP studies have been conducted.

One of the larger studies was the SPS-2 experiment, which focused on newly constructed jointed plain concrete pavements. The SPS-2 sites were constructed in 14 states between 1992 and 2000. The different factors evaluated included base type, concrete thickness, base thickness, drainage, climatic region, and traffic. SPS-2 also evaluated two different PCC mixtures, one with a low flexural strength (targeting 550 lb/in.^{2} at 28 days) and one with a high flexural strength (targeting 900 lb/in.^{2} at 28 days). In addition, DOTs could construct additional test sections, and some of these included a third PCC mix that represented a typical DOT-approved mix. With this experience focusing on concrete pavements, this experiment has provided the greatest amount of information on PCC mixtures compared to the other LTPP studies.

The objective of this part of the PEM project was to obtain samples from LTPP SPS-2 sections for evaluation using the PEM tests listed in AASHTO R 101 in order to develop predictive relationships between test results and field performance. Test results were compared to the performance of each section, and analyses of these data were performed to determine whether relationships existed between the PEM test results and the observed field performance of the SPS-2 sections.

SPS-2 Project Selection

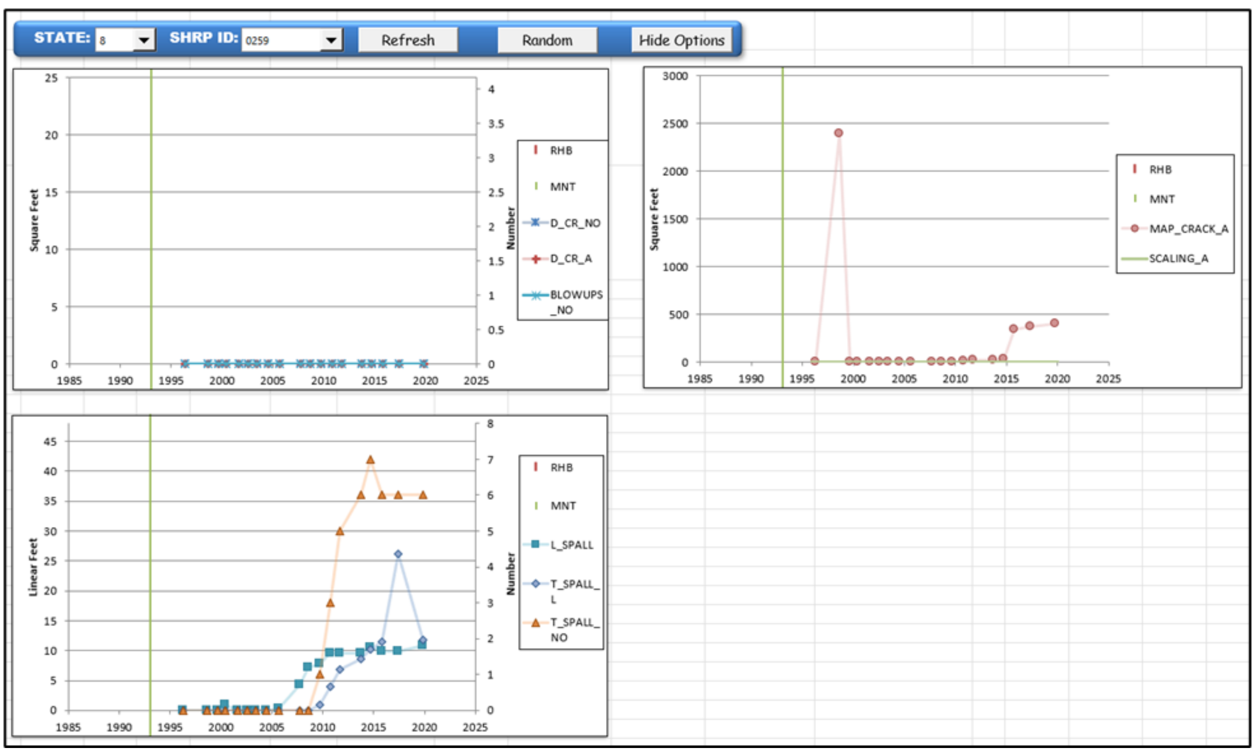
The LTPP program contains 2,581 pavement sections. Determining which sections to extract core samples from involved several steps, including identifying sections that may have experienced material-related distresses. Longitudinal and transverse cracking and other structural-related distresses were ignored, with candidate sites identified based on the following criteria:

- Joint deterioration and discoloration
- Sudden onset of late-age map cracking and D-cracking
- Progressive transverse and longitudinal spalling

The first step in this process was to identify the LTPP sections that had developed these distresses, as determined from the LTPP manual distress surveys. FHWA hosts a website called Infopave that contains the LTPP data. Distress data for the sections were downloaded and used to determine the first occurrence of each distress. Because material-related distresses take time to develop, early-age distresses were assumed to be caused by other factors (e.g., most likely construction related). Sections that had later-age development of map cracking, durability cracking, or spalling (both transverse and longitudinal) were marked for further analysis.

In total, 473 LTPP sections were identified in the preliminary analysis: 92 in-study sections and 381 out-of-study sections. While some out-of-section sections appeared to be good candidates for study in this project, it was not possible to determine whether the original concrete pavement remained or had been replaced. Given the costs associated with performing coring, it was decided to focus on in-study sections only.

A second screening was conducted on the 92 in-study sections of interest. A spreadsheet tool (Figure 25) was developed that plotted all distresses from every manual distress survey conducted on each section.



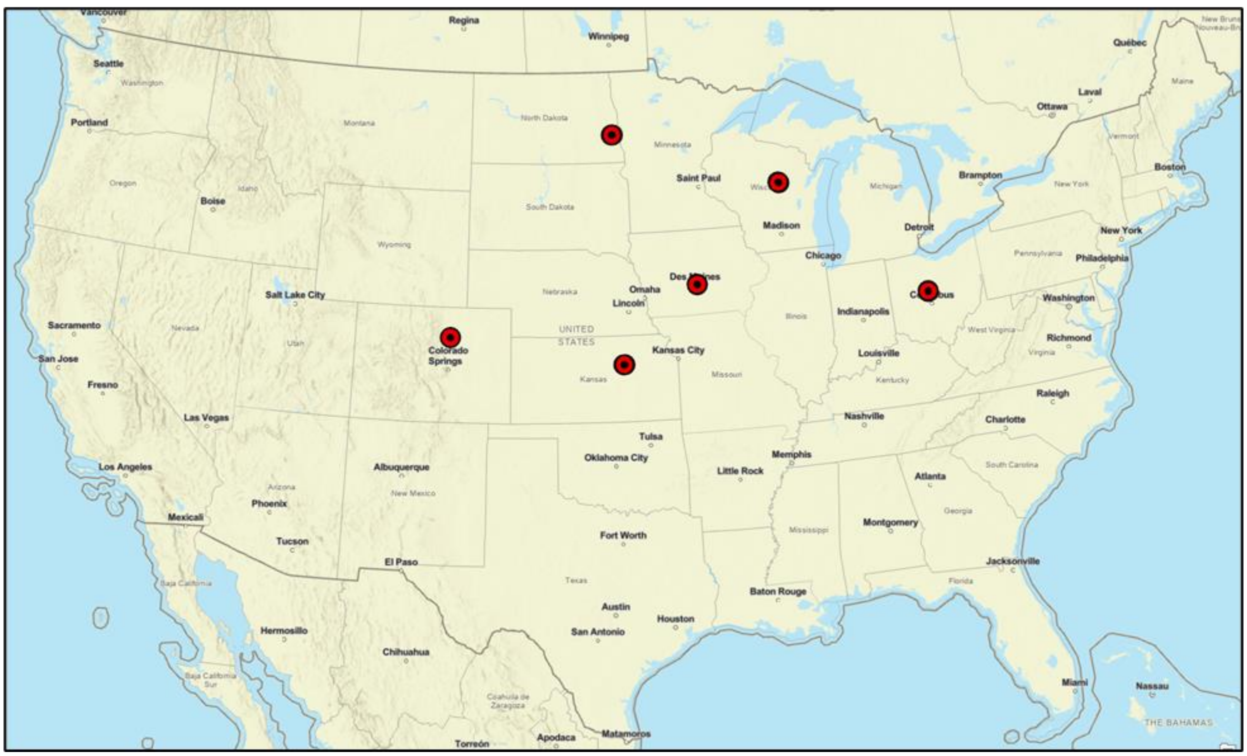
Nick Weitzel, Nichols Consulting Engineers, CHTD

Figure 25. Spreadsheet-based tool to quantify distress progression on LTPP sections

The tool also showed the maintenance and rehabilitation work performed on each section to help explain any drops in observed pavement distress. The goal was to identify how the distresses developed over time and to rank the sections based on how likely the sections were to develop material-related distresses.

While this analysis was being conducted, the team learned that the LTPP data collection contractor (DCC) was visiting several SPS-2 projects in the summer and fall of 2021 to conduct distress surveys and collect profile/roughness data. Conducting coring during the DCC's visits permitted a time- and cost-effective chance to complete this work during the DCC's lane closures. The decision was made to obtain core samples from the six SPS-2 projects being visited by the DCC and to core as many sections as possible within a single day.

The six SPS-2 projects visited were in Colorado, Iowa, Kansas, North Dakota, Ohio, and Wisconsin, as shown in Figure 26.



Nick Weitzel, Nichols Consulting Engineers, CHTD

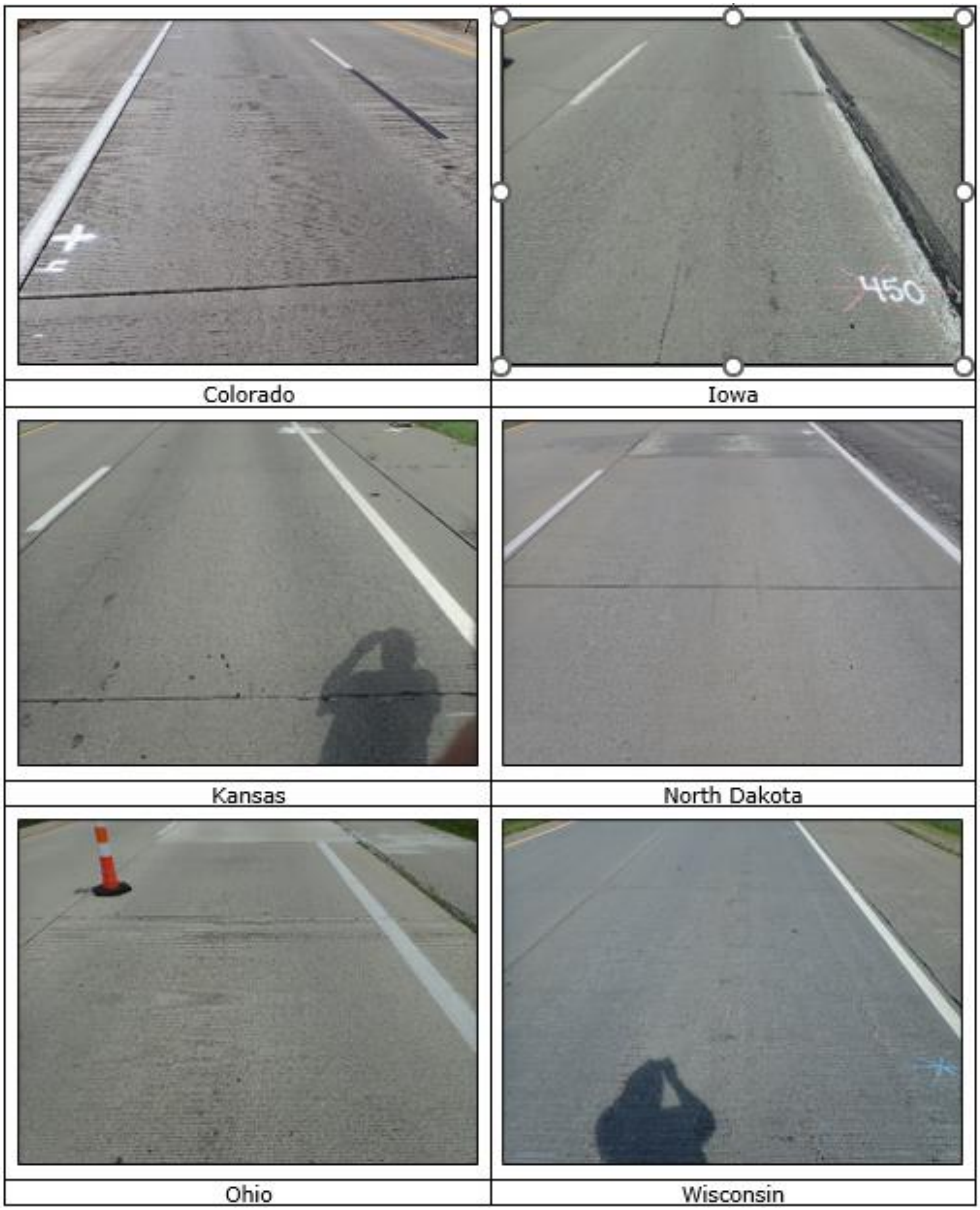
Figure 26. Map showing the location of the six SPS-2 projects visited

These are primarily Midwestern states, where material-related distress in concrete pavements is more common than in other parts of the United States. Coordination with the DCC started in late April 2021.

Project Performance

This section presents an overview of the conditions observed at each SPS-2 project visited in 2021.

The Colorado project was found to be in good condition overall. There were not a lot of visual signs of material-related distress aside from some stained surface cracks in the shoulder of section 08-0222. The Iowa project was found to be in fair condition at the slab interiors but had significant joint deterioration at the transverse joints. The joints of several sections had significant deterioration at mid-depth near the dowel bars, where a void approximately 4 in. in diameter had formed. The Kansas project was in good-to-fair condition, with most sections having significant map cracking, which was generally more prominent in the longitudinal direction. There was also some transverse and longitudinal spalling. The North Dakota project was found to be in good condition. The Ohio project was in fair condition, with joint spalling and repairs. The Wisconsin project was found to be in good condition. Most sections had about 100 to 300 ft of total spalling, most of which was longitudinal spalling along the outside joint with the shoulder. Photographs of typical conditions are presented in Figure 27.



Nick Weitzel, Nichols Consulting Engineers, CHTD

Figure 27. Typical condition of each SPS-2 project

SPS-2 Database

Records from Infopave were imported into a database that combined some PEM test results with information on the mix designs, mix properties, performance, weather, and traffic. The objective of the database was to evaluate trends within the data that related the PEM test results with field performance.

For each SPS-2 project, three sections were identified in advance with the objective of obtaining core samples from each of the PCC mixtures placed because there were often three different concrete mixes used (low-strength, high-strength, and typical state mix). Table 7 summarizes the coring results from the SPS-2 sections.

Table 7. Summary of SPS-2 coring operations

SPS-2 Project	Date(s) Cored	Sections Cored	Number of Cores Obtained
Colorado	06/23/2021	3	7
Iowa	09/21/2021–09/22/2021	6	18
Kansas	12/08/2021–09/2021	6	17
North Dakota	07/28/2021	6	20
Ohio	09/28/2021–09/29/2021	6	19
Wisconsin	08/04/2021–08/05/2021	8	19
	Totals:	***35***	***100***

Laboratory Testing of SPS-2 Core Samples

The 100 cores obtained from the LTPP SPS-2 sections were sent to Oklahoma State University and Oregon State University for a wide range of PEM-related tests, with the goal of characterizing the concretes' durability properties.

In total, 36 cores were sent to Oklahoma State University, all of which were taken from areas that did not have any visual signs of distress. These cores were evaluated using ASTM C457 to characterize the air-void system of the concrete. A summary of the ASTM C457 results is presented in Table 8.

Table 8. Summary of ASTM C457 results obtained by Oklahoma State University

State	LTPP Section	Air Content (%)	Specific Surface (in.$^{-1}$)	Spacing Factor (in.)	Chord Frequency (in.$^{-1}$)	Avg. Chord Length (in.)	Paste to Air Ratio
Colorado	L-08-0222	5.0	529	0.0099*	6.6	0.0076	6.6
Colorado	L-08-0223	6.3	455	0.0083*	7.1	0.0088	3.8
Colorado	L-08-0259	1.4**	798	0.0108*	2.8	0.0050	20.2
Iowa	L-19-0217	8.1	445	0.0057	9.0	0.0090	2.5
Iowa	L-19-0220	3.8**	466	0.0126**	4.4	0.0086	8.5
Iowa	L-19-0215	8.4	426	0.0057	8.9	0.0094	2.4
Iowa	L-19-0218	4.7*	471	0.0113*	5.5	0.0085	6.8
Iowa	L-19-0219	11.1	381	0.0047	10.6	0.0105	1.8
Kansas	L-20-0204	2.5**	426	0.0170**	2.7	0.0094	13.6
Kansas	L-20-0202	4.3*	524	0.0108*	5.6	0.0076	7.8
Kansas	L-20-0206	3.2**	378	0.0163**	3.1	0.0106	9.4
Kansas	L-20-0205	6.6	244	0.0149**	4.0	0.0164	3.7
Kansas	L-20-0207	3.0**	495	0.0116*	3.6	0.0081	7.9
Kansas	L-20-0259	2.1**	498	0.0144**	2.6	0.0080	13.2
North Dakota	L-38-0221	7.1	473	0.0062	8.4	0.0085	2.9
North Dakota	L-38-0222	3.6**	599	0.0097*	5.4	0.0067	8.2
North Dakota	L-38-0259	4.7*	547	0.0091*	6.4	0.0073	5.8
North Dakota	L-38-0218	6.5	456	0.0098*	7.4	0.0088	4.6
North Dakota	L-38-0220	3.8*	785	0.0117*	4.6	0.0082	7.9
North Dakota	L-38-0219	4.2*	562	0.0082*	5.9	0.0071	4.9
Ohio	L-39-0212	1.6**	538	0.0160**	2.2	0.0074	20.1
Ohio	L-39-0211	3.9**	423	0.0139**	4.1	0.0095	8.4
Ohio	L-39-0207	3.9**	289	0.0184**	2.8	0.0183	6.8
Ohio	L-39-0261	3.2**	508	0.0114*	4.1	0.0079	8.2
Ohio	L-39-0260	2.7**	356	0.0175**	2.4	0.0112	9.6
Wisconsin	L-55-0214	5.1	791	0.0056	10.1	0.0051	4.6
Wisconsin	L-55-0262	4.9*	601	0.0076	7.4	0.0067	4.8
Wisconsin	L-55-0215	2.9**	887	0.0066	6.5	0.0045	8.3
Wisconsin	L-55-0262	4.7*	546	0.0085*	6.4	0.0073	5.1
Wisconsin	L-55-0266	5.4	856	0.0052	11.6	0.0047	4.5
Wisconsin	L-55-0264	8.2	533	0.0055	10.9	0.0075	2.9
Wisconsin	L-55-0265	8.6	580	0.0049	12.4	0.0069	2.8

* Marginal air content or spacing factor
** Poor air content or spacing factor

The most interesting result of the ASTM C457 testing is how often the parameters would suggest marginal to poor air-void system characteristics for protecting against paste freeze-thaw damage. As indicated in Table 8, qualitative assessment of the air content and spacing factor was made (with orange shading indicating marginal and red shading indicating poor) based on the following criteria:

- Air content: ≥ 5% good; between 4% and 5% marginal; ≤ 4% poor
- Spacing factor: ≤ 0.008 in. good; between 0.008 in. and 0.012 in. marginal; ≥ 0.012 in. poor

Based on these criteria, most cores had air-void system parameters normally considered to be marginal to poor, a surprising finding given that the air content of the fresh concrete would have been measured during construction.

For two projects in Colorado, the air content in the hardened paste was adequate whereas the spacing factor was marginal, and for two projects in Wisconsin the air content was marginal to poor yet the spacing factor suggests that the hardened paste has adequate protection against freeze-thaw damage.

In combination, these results indicate the importance of not only measuring the air content of the fresh concrete but also the need to thoroughly assess the characteristics of the air-void system during construction, such as through use of the SAM (AASHTO T 395).

Oregon State University evaluated 64 cores obtained from the SPS-2 sites and an additional 49 cores collected from other studies, taken from areas with and without visual signs of distress. Oregon State University's findings are summarized as follows:

- The long-term performance of concrete pavements was evaluated using the tests specified in AASHTO R 101-22. Specifically, the parameters evaluated were total porosity (Φ_{tot}; AASHTO TP 135-22), matrix porosity (Φ_{mat}; evaluated using the "bucket test"), apparent formation factor (F_{app}; AASHTO TP 119-22), saturated formation factor (F_{sat}; AASHTO TP 119-22), calcium hydroxide (CH) content, and CaOXY formation potential (AASHTO T 365-20). A prediction framework provided reference values for the performance measures for these mixtures. One hundred thirteen cores were tested from eight states.
- Inadequate core consolidation (considered when porosity has a coefficient of variation greater than 25% of the expected value) was found in 66.1% of the cores evaluated. Honeycombing and high volumes of entrapped air were observed in these cores, likely due to low-workability mixtures or high w/cm ratios. Approximately 30% of the cores had a very high measured F_{app}, likely due to matrix discontinuity caused by insufficient paste volume (less than 22% paste volume) or due to incomplete matrix saturation (like in the case of the Kansas sample due to the core size).
- The predictions and measurements for well-compacted cores was within 5% for Φ_{tot} and 20% for F_{app}.
- For the poorly compacted cores, the measured F_{app} was greater than the theoretical maximum apparent formation factor (F_{max}), leading to potential false positives during durability evaluation. Therefore, F_{app} measurements should be coupled with Φ_{tot} to evaluate concrete pavements.
- The measured CaOXY formation potential agrees with the literature trends. Beyond a CH content of 1 g per 100 g powder, a 1 g increase in CH content resulted in a 2 to 4 g increase in CaOXY per 100 g powder that could form.

The laboratory testing conducted by Oklahoma State University and Oregon State University indicated the difficulty in using in-service concrete to "back out" predictive relationships. The SPS-2 sites that were cored all suffered some type of progressive distress that could likely be linked to a durability problem. The air-void system analysis suggested a possible lack of paste freeze-thaw durability. The observation of poor consolidation and, in some cases, low paste volume suggests that poor workability due to poor mixture proportioning were contributing factors.

TECHNOLOGY TRANSFER

State Agency Shadow Testing and Open Houses

In a handful of locations, the state agency performed shadow testing in addition to receiving a visit from the CP Tech Center and/or the MCTC. Where possible, an open house was organized as a collaborative effort led by the CP Tech Center with input from the MCTC, industry, and the state agency. Table 9 lists the shadow testing locations and corresponding open houses. In some states, a presentation was made at the concrete workshop following the testing.

Table 9. PEM shadow testing and open houses

Location	Date	Attendance	CP Tech	MCTC
Colorado	May 17, 2018	50	X	X
Minnesota	July 18, 2018	47	X	X
Iowa	August 1, 2018	24	X	X
South Dakota	September 28, 2018	60	X	
North Carolina	May 15, 2019	62	X	X
Illinois	August 6, 2019	42	X	
Kansas	August 8, 2019	60	X	X
California	October 29, 2019	30	X	
New York	May 10, 2022	80	X	X

In addition to the open house locations, additional PEM-related projects were tracked across the country. Figure 28 shows the locations of PEM projects that took place during the pooled fund project.

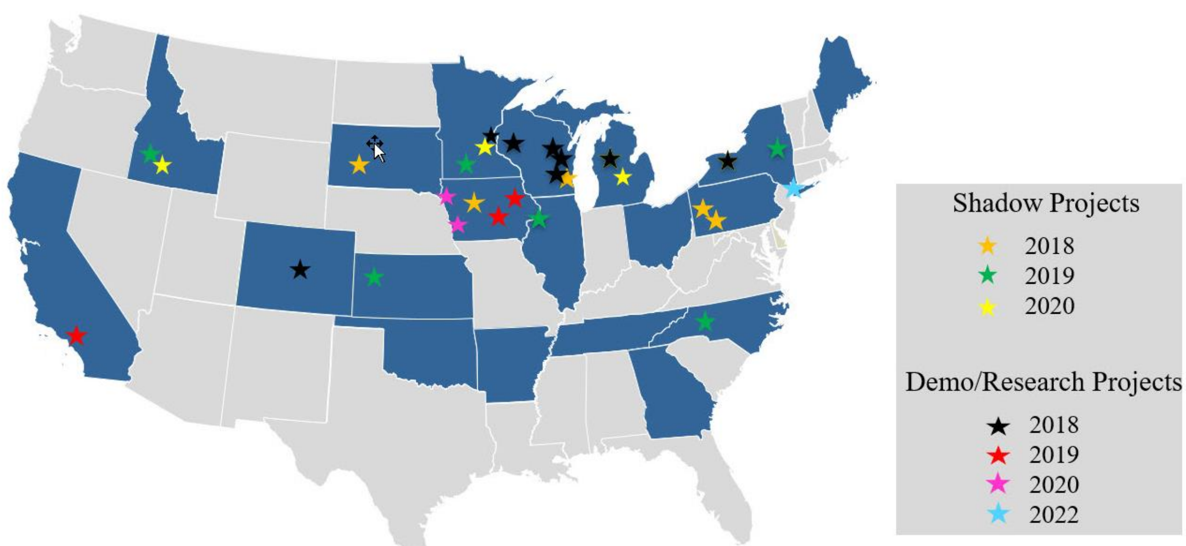


Figure 28. PEM projects

Shadow projects were defined as locations where data were collected by the state agencies and submitted to the research team for evaluation. Demonstration and research project sites were not necessarily tied to data managed by the research team.

PEM Presentations and Webinars

Information on performance-engineered mixtures has been presented at several paving association workshops, state agency meetings, and conferences, as shown in Table 13 in Appendix A. A total of 82 presentations were made from 2017 through 2022 in 30 states or online.

As part of the pooled fund project, each member state was offered training in the form of test training (as described in the following chapter), a virtual webinar, or an in-person one-day workshop. The workshop was offered as a general overview of the PEM program to agency engineers and executives. The agenda for the workshop included the following items, with time allotted for group discussion:

1. Road to PEM – Why Change Things?
2. Group Discussion – What Makes a Good Specification?
3. AASHTO R 101 – Philosophy and Goals
4. Group Discussion – Barriers to Performance Evaluation
5. Science and tests for PEM (Property-Test-Remedy)
6. Group Discussion – What's Next?
7. PEM in Practice – Quality, Implementation, Training

The one-day workshop presentations will continue to be offered for training as part of the Technical Transfer Concrete Consortium (TTCC) TPF-5(437) project to pooled fund member states in 2023 and 2024. Table 10 lists the locations of the one-day workshops.

Table 10. PEM one-day workshops

State	Location	Date	Attendance
Tennessee	Nashville, TN	August 23, 2021	26
Georgia	Atlanta, GA	March 8, 2022	30

In the Georgia workshop, there was consensus from the Georgia DOT (GDOT) to investigate optimized aggregate gradation mixtures. A few industry representatives participated in the workshop and were in support of the approach. Planning is currently underway for the CP Tech Center to sample and perform PEM tests on the state's standard PCC pavement mixture as part of an upcoming mainline paving project. This baseline-type testing will document the properties of the standard mixture. Moving forward, a future pilot project will include an optimized aggregate gradation mixture. Testing will be performed on the pilot project PEM mixture, and comparisons can be made between the two mixtures to measure the improvements offered by the PEM mixture. Figure 29 shows a photograph from the Georgia one-day workshop.

Figure 29. Georgia one-day workshop

TEST TRAINING

SAM Training

Table 11 lists the host state DOTs (when applicable), locations, dates, and details of the SAM training completed during the PEM project by a team from Oklahoma State University.

Table 11. Summary of SAM training completed for the PEM project

Location	Date	Training
Lafarge visit to Stillwater, OK	July 1	SAM class and training
CDOT, Denver	January 10, 2019	Two-day SAM class and training
ITD, Boise	March 18, 2019	Two-day SAM class and training
ITD, Pocatello	May 9–10, 2022	Two-day SAM class and training
Iowa DOT, Iowa State University, CP Tech Center, Ames	October 24–25, 2017	SAM class one-day lab work
Iowa State University visit to Stillwater, OK	June 2017	SAM class and hardened air void analysis
KDOT, Topeka	April 8–9, 2019	Two-day SAM class and training
KDOT, Topeka	October 2018	Hardened air void analysis
KDOT visit to Stillwater, OK	May 2018	Hardened air void analysis
KDOT visit to Stillwater, OK	August 2019	Hardened air void analysis
MDOT, Lansing	August 2018	SAM class and training
MDOT, Lansing	March 22, 2018	SAM class and training
NYSDOT, New York State Chapter ACPA, Buffalo	November 6, 2019	SAM presentation
NYSDOT, Utica	March 12, 2019	SAM class
NYSDOT, Albany	June 2017	SAM
NYSDOT, Albany	June 2016	SAM
NCDOT, Charlotte	April 26, 2021	SAM class and training
NCDOT, Charlotte at UNC–C lab	June 24, 2015	SAM class
ODOT [Oklahoma], Tulsa	October 28, 2018	SAM class and training
ODOT [Oklahoma], Stillwater	December 2017	SAM class
ODOT [Oklahoma], Oklahoma City	August 2022	Phoenix training
ODOT [Oklahoma], Tulsa	September 2022	Phoenix training
WisDOT	August 22, 2018	SAM class and training
WisDOT, UW Platteville	August 23, 2018	SAM class and training
WisDOT, Milwaukee and Behnke	October 3–6, 2017	SAM class training and field work

The typical agenda for the SAM training is shown in Table 12.

Table 12. SAM training schedule

Morning Agenda	Afternoon Agenda
Bring meters in for calibration, leak check, and repair	Discussion about progress and testing with water
Pretest knowledge about the SAM	Test with concrete
Presentation about the SAM	Calibrate the SAM
Test the SAM with water	Conclude

The training primarily focused on the SAM and the Phoenix, although some training on the Box Test and resistivity testing was done at certain locations. The training consisted of a combination of lectures and hands-on activities. It was important to begin by telling the participants why the SAM is useful and to have participants run the test initially with water. Work was also performed with concrete at many of the sessions. Many of the training sessions included written and hands-on performance tests. The training sessions were primarily designed for DOT operators, but many of the training sessions included industry technicians as well.

In Kansas, Michigan, New York, North Carolina, Oklahoma, and Wisconsin and at Iowa State University, a train-the-trainer session was held to train a local expert who would then train others in the future. The value in this was that these local experts would be able to use their knowledge to train others in their respective states.

In addition to the formal training on the SAM, Tyler Ley conducted regular meetings with representatives from New York, Colorado, Wisconsin, Kansas, Minnesota, and Oklahoma to discuss their progress with implementing PEM. Key topics in many of these discussions included the SAM and PEM-related air content testing. The discussions typically consisted of monthly or bimonthly meetings where the state could ask Ley about any PEM topic or other issue regarding concrete. This allowed deep discussions in which Ley learned more about each organization and how it performs current tests and its plans for future testing. Ley also discussed durability issues with the states and devised different ways to try and help them overcome these issues.

These regular meetings and conversations led to major changes in each state regarding use of the SAM and PEM-related air content testing, which illustrates the importance of being persistent and helpful to states on their path forward. For example, New York State DOT (NYSDOT) has a PEM specification that it is actively using on certain projects. The Colorado DOT (CDOT) had some important internal discussions about the SAM and realized that the quality of its testing needs to improve. The Wisconsin DOT (WisDOT) funded a research project about PEM in which it developed data on its own projects and completed several shadow projects. The Kansas DOT (KDOT) has started its own SAM program and is also working on a specification to implement the SAM. The Minnesota DOT (MnDOT) implemented a shadow specification and changed its specifications that require testing after the paver. Minnesota also was the first state to try the Phoenix. The state has completed hundreds of field tests with the Phoenix and is looking to implement the technology. Oklahoma was the second state to try the Phoenix and has more of these instruments than any other state. The state is using it now to gather data and has plans to hire testing companies to use the Phoenix on several major projects.

VKelly Training

Training on the VKelly test was included during all of the open houses listed in the previous chapter. In addition, a detailed video on how to conduct the test method was published on the CP Tech Center's PEM website (https://cptechcenter.org/performance-engineered-mixtures-pem/).

VKelly equipment was built as part of the pooled fund project and shipped to the following agencies and organizations that expressed interest in using it:

- Illinois State Toll Highway Authority
- Indiana DOT (INDOT)
- Iowa DOT
- Michigan DOT (MDOT)
- MnDOT
- Nebraska DOT (NDOT)
- South Dakota DOT (SDDOT)
- WisDOT
- Manitoba Transportation and Infrastructure
- CDOT
- KDOT
- Ash Grove Cement Company laboratory

VKelly test training was provided by the CP Tech Center, Oklahoma State University, and the MCTC. Figure 30 shows the approximate locations of the test training (blue dots) along with the approximate shipping locations of the VKelly equipment (red dots).

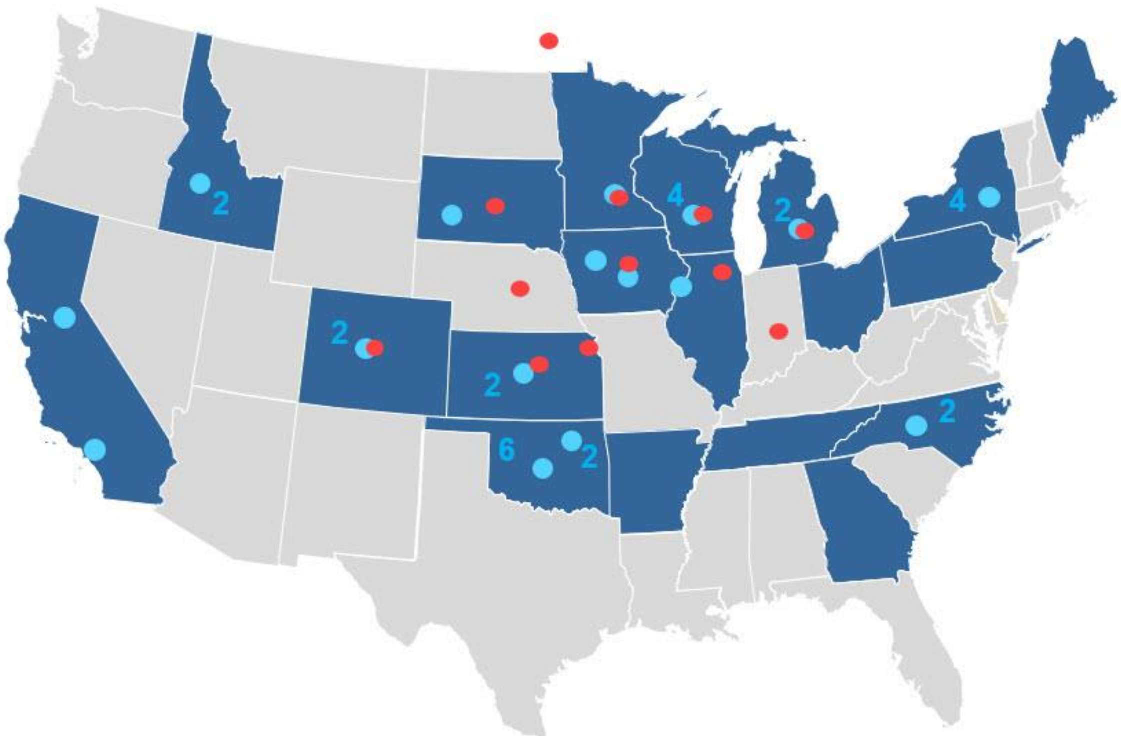


Figure 30. Approximate test training locations (blue dots) and VKelly equipment shipping locations (red dots)

STATE AGENCY SPECIFICATIONS

State Discussions

One of the ways to measure the advancement of PEM within state agencies is to review the state specifications for concrete paving as they relate to PEM. Calls were made to each of the pooled fund member states in 2019 to review the state specifications in terms of how they addressed the six PEM properties:

- Strength
- Transport (resistivity)
- Freeze-thaw durability
- Aggregate stability
- Shrinkage
- Workability

A table summarizing the findings of the calls made to the pooled fund member states in 2019 is available at https://intrans.iastate.edu/app/uploads/sites/7/2020/07/PEM-State-Spec_Reviews-Table-2020-07-02.pdf.

In 2021, another round of calls was made to the participating state agencies to see whether and how their specifications had changed based on the states' experience with PEM. The findings showed that a number of state agencies had made or were planning to make changes to their specifications based on PEM initiatives. Figure 31 illustrates the general shift between 2019 and 2021 in the number of states indicating movement toward or an interest in incorporating PEM into their specifications.

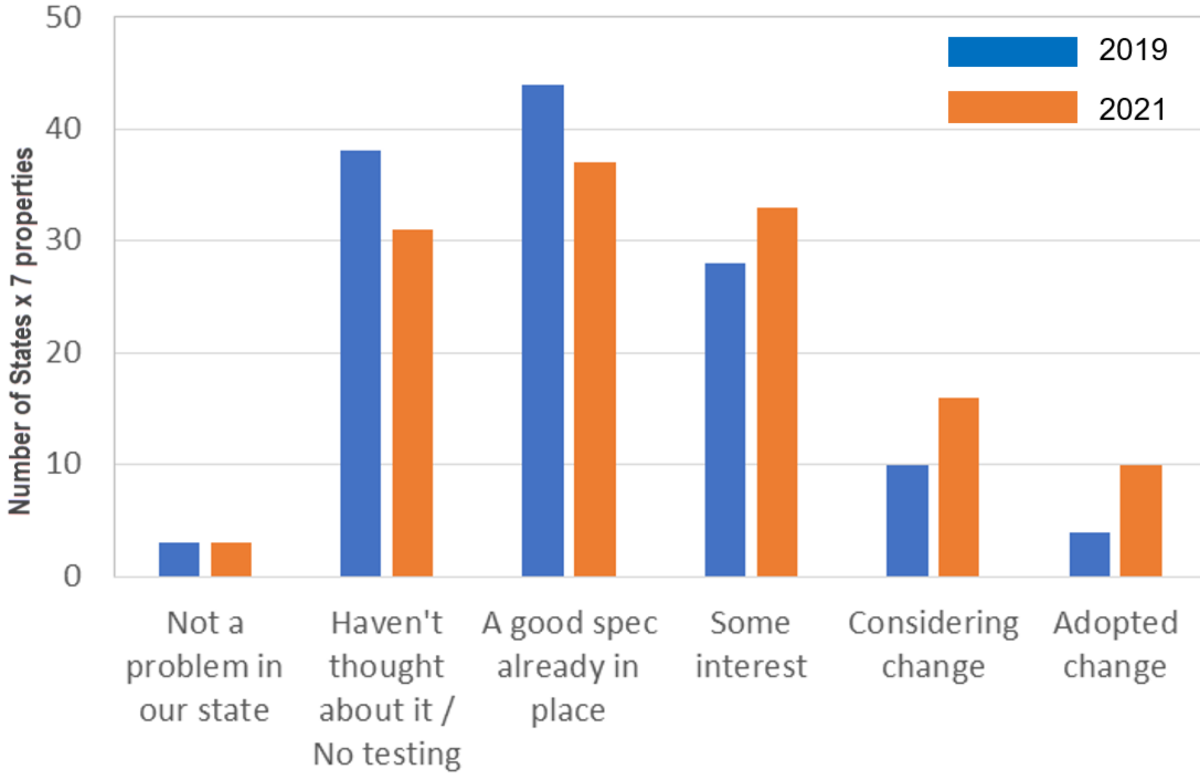


Figure 31. PEM advancement in state specifications

Specification Changes

The following PEM pooled fund member states have either adopted or are considering PEM-related changes to their pavement specifications.

Colorado

Colorado revised its specifications in October 2019. The state removed maximum and minimum cementitious materials content requirements, allowed optimized gradation, and required use of the Box Test in mix proportioning (< 0.25 in. edge slump and ranking of 2 or less). Transport requirements include an RCPT result of less than 2,500 coulombs at less than 56 days (ASTM C1202) or a surface resistivity greater than 12 kΩ-cm at 28 days (AASHTO T 358). The unrestrained shrinkage requirement is less than 0.05% at 28 days (CP-L 4103). A Colorado contractor has also noted that it is significantly easier for mixtures proportioned using the tools provided through the PEM project to deliver low smoothness numbers. In turn, this will reduce the life-cycle carbon footprint of vehicles using the pavement.

Georgia

The Georgia Tech Research Corporation is currently working on research project RP 20-19, Recommendations for Future Specifications to Ensure Durable Next-Generation Concrete. The findings of the study will allow GDOT to consider changes to its specifications related to PEM. Georgia is also planning to conduct PEM shadow testing on its current standard mix to determine baseline properties with the intention of completing a pilot project with an optimized aggregate gradation and evaluating pavement performance improvements.

Idaho

Prior to the PEM pooled fund project, Idaho's PCC pavement specification had a minimum cementitious materials content of 660 lb/yd^3. In 2019, a shadow project included an optimized aggregate gradation mixture with a reduction of 10% cementitious content. Idaho has since changed its PCC pavement specification by reducing the minimum cement content to 600 lb/yd^3 and allows a further reduction if an optimized aggregate gradation is utilized.

Iowa

The Iowa DOT has utilized its QMC mixture since the late 1990s. Contractors on QMC projects are more involved in selecting a well-graded aggregate combination 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 on a number of paving projects. The PEM program has allowed the 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 mix design and testing for large bridge structures.

Michigan

Michigan began allowing optimized aggregate gradation mixtures in 1996 and mandating its use in mainline paving in the early 2000s. About five years ago, optimized aggregate gradation was introduced to structural mixtures due to its success in paving applications. Currently, the state requires the use of optimized aggregate gradation mixtures on all high-performance concrete mixtures for pavements and structures. Michigan has a SAM certification program offered by the Michigan Concrete Association (MCA) in conjunction with MDOT and is currently collecting information on SAM usage. In 2020, the following were advanced from Special Provisions (SP) into MDOT's standard specifications: use of SCMs, contractor-provided mixes, and optimized aggregate gradation mixtures.

Minnesota

MnDOT has had many years of experience with optimized aggregate gradation, low w/cm mixtures, and high SCM replacements. The state is evaluating its ASR specifications to determine whether lower cementitious contents would require the same level of mitigation of reactive aggregates. MnDOT will continue to use the Phoenix to measure w/cm ratio and may look at implementation of the device into its specifications in the next couple of years. The state is looking at its specifications to identify areas of improvement with regard to sustainability.

New York

Over the past several years, NYSDOT has been working on developing a PEM specification with the main goal of reducing the carbon footprint of its pavements without impacting the quality or life of the pavement. Moving forward, the state will be requiring the Tarantula curve and has called out specific sieve sizes to be used in the sieve analysis to provide clarity regarding the optimized aggregate gradation. The option to use a 6 in. x 12 in. cylinder as a resistivity sample was removed to avoid confusion and simplify conversion factors as NYSDOT moves toward the exclusive use of 4 in. x 8 in. cylinders. The state has moved from some interest is the SAM to considering a requirement for use of the SAM at the mix design phase and as an acceptance test. In an effort to further reduce cement use, the state is evaluating an increase in SCM amounts.

North Carolina

PEM is part of NCDOT’s efforts to meet its sustainability goals, which will allow the state to improve the performance and durability of its pavements and meet economic challenges. Due to the success of North Carolina’s PEM shadow project in 2018–2019, a structural concrete pilot project using the PEM approach was designated that will include multiple new bridge structures and deck overlays with specification provisions and performance targets for resistivity, SAM number, and shrinkage. Moving forward, North Carolina is also considering implementing PEM specifications on additional projects using a shadow project approach in order to assess proposed targets. The state is also considering a reduction of the current prescriptive w/cm ratio limits and cement contents.

Wisconsin

Wisconsin adopted the Box Test as a mix design requirement for slipform paving projects. It has also implemented optimized aggregate gradation in Section 501 of the 2022 standard specifications. The state is allowing a reduction in minimum binder contents when proportioning is based on the CP Tech Center concrete mixture proportioning spreadsheet. WisDOT requires the SAM test as part of the mix design requirements. During paving operations, the state requires the SAM test and the resistivity test for information only on certain bid items.

ACCOMPLISHMENTS

The scope of the PEM pooled fund project included three main tasks: implementation, monitoring, and test refinement. The accomplishments resulting from each of the tasks is described in this chapter.

Implementation

In fulfillment of the implementation task, PEM technology transfer activities included presentations at various workshops and webinars, specification support, test support, and shadow project support. A PEM website was developed that provides the following information:

- PEM program information
- Interactive map of shadow project and testing locations
- Instructional videos on test methods and test method summaries
- PEM newsletters
- PEM shadow project reports from state agencies and FHWA
- State specification review table
- Technical advisory committee (TAC) meeting notes
- Reginal state-industry meeting notes
- Sponsor information

Figure 32 shows a screenshot of the PEM website, available at https://cptechcenter.org/performance-engineered-mixtures-pem/.

Figure 32. PEM website

Workshops and Webinars

During the five-year pooled fund project, technology transfer for PEM was provided at 82 workshops, meetings, and webinars across the country. The presentations were provided by the CP Tech Center or members of the PEM pooled fund project research team.

Specification Support

The pooled fund member states were contacted by the research team in 2019 to gain an understanding of their current pavement specifications relating to PEM. A table was developed summarizing how their specifications addressed the six PEM properties: strength, transport, shrinkage, freeze-thaw resistance, aggregate stability, and workability. This table is available at https://intrans.iastate.edu/app/uploads/sites/7/2020/07/PEM-State-Spec_Reviews-Table-2020-07-02.pdf.

In 2021 the research team again reached out to pooled fund member states to see whether they had made changes or were considering changes to their specifications based on what they had learned from the PEM program. In many cases, shadow testing, open house demonstrations, workshops, and other forms of technology transfer led to changes to their specifications. Figure 31 illustrates the advancement of PEM based on the pooled fund member states' specifications.

Test Support

Members of the PEM pooled fund project research team representing Iowa State University, Oklahoma State University, and Oregon State University offered test support for the new PEM tests, including the VKelly, Box Test, SAM, resistivity, formation factor, and the Phoenix. Formal test training was provided in 12 of the 19 pooled fund member states. Other forms of test support included webinars, workshop presentations, and guidance documents.

Shadow Project Support

Members of the PEM pooled fund project research team coordinated shadow projects with state agencies. The intent of the shadow projects was to expose the state agencies to PEM and new testing methods. Data were collected by state agencies, members of the research team, and, in some cases, the MCTC. Details on the shadow projects are provided in Table 9.

Virtual Regional State Agency-Industry Meetings

The PEM pooled fund project research team organized virtual regional meetings with state agency members and industry. The focus of the meetings was to get feedback from state agencies regarding their implementation of PEM and to include industry as part of the discussions. Figure 33 shows the state-industry regional meeting locations.

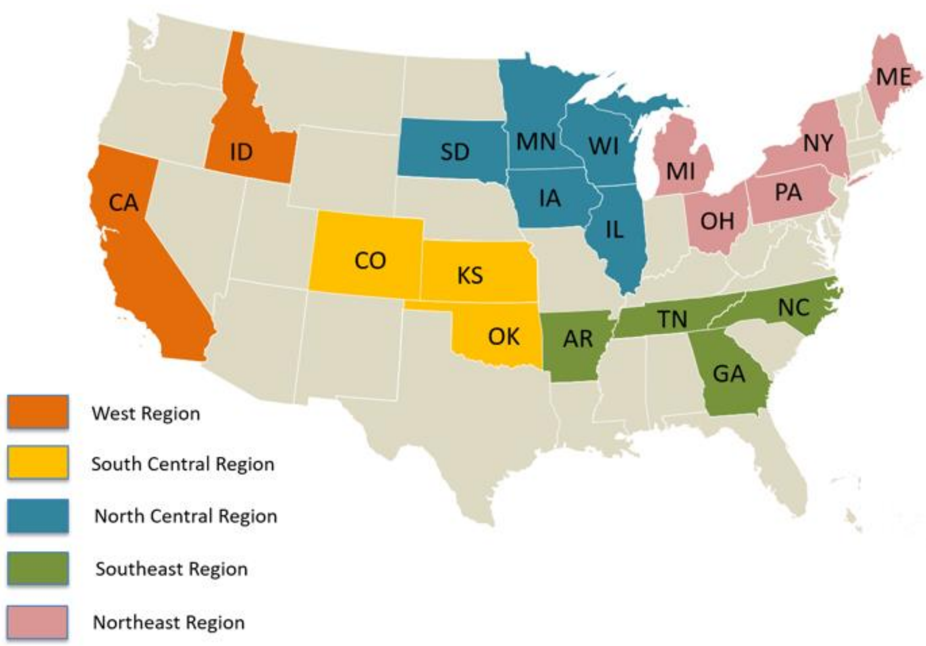


Figure 33. State-industry discussion group locations

The meetings included a series of questions related to the implementation of PEM, including the following:

- Has your state agency recently implemented any new tests to your concrete program or are you planning to implement any in the near future?
- Do you currently leverage QC in your specifications? In other words, do you require QC, and does the state do any monitoring of QC? This question is NOT asking if you use contractor data for acceptance.
- Have you engaged your agency construction staff in PEM discussion/planning? If so, what are the details?
- Have you made, or will you be making, specification changes to transition from prescriptive requirements to a performance approach? Some examples of this are as follows:
    - Eliminating slump testing for acceptance
    - Eliminating minimum cementitious content requirements
    - Eliminating single aggregate gradation requirements
- Which statements describe your agency's approach to PEM:
    - We are satisfied with the status quo and do not envision making significant changes.
    - We will be keeping our program as is but plan to add a new test or two.
    - We are enhancing our specification approach and adding QC requirements.
    - We plan to develop robust QC requirements and include some level of agency monitoring of QC.
    - We will be reducing/eliminating prescriptive requirements and moving to a performance approach.
- The current PEM initiative focuses heavily on the mix and mix design ("design the mixture properly for its service environment"). Moving forward, do you see the next step toward performance specifications as an effort to develop ways to assess the impact of construction activities? (The ultimate goal is the ability to test the concrete to ensure that you "build the concrete to perform in its service environment.") Some examples include the effects of pumping/transport, vibration, and real-time curing assessment.

One of the more common outcomes of the meetings was an expressed need for additional PEM test training for industry, including consultants and material testing companies. The regional meetings occurred from September 2020 through January 2021. Minutes from the regional meetings are available at the following links:

- North Central: https://intrans.iastate.edu/app/uploads/sites/7/2020/10/MTG_2020-09-15_PEM-North-Central-notes.pdf
- Northeast: https://intrans.iastate.edu/app/uploads/sites/7/2020/11/MTG_2020-10-21_PEM-Northeastern_notes.pdf
- Southeast: https://intrans.iastate.edu/app/uploads/sites/7/2020/12/MTG_2020-11-9_PEM-South-East_notes-from-call.pdf
- South Central: https://intrans.iastate.edu/app/uploads/sites/7/2020/12/MTG_2020-12-17_PEM-South-Central_notes-from-call.pdf
- West: https://intrans.iastate.edu/app/uploads/sites/7/2021/01/MTG_2021-01-05_PEM-Western-Region_notes.pdf

Monitoring

The monitoring task included the development and management of the PEM database. The database included data received from state agencies during the shadow projects. Nichols Consulting Engineers, Inc. (NCE, Inc.) developed and managed the database. The CP Tech Center contacted state agency representatives to coordinate the shadow testing with open house events and to collect the shadow testing information using the standard data entry form.

The monitoring phase also included the sampling and testing of cores from the LTPP SPS-2 project sites. NCE, Inc. provided the effort for this task.

Finally, the annual updates to AASHTO PP 84 and now AASHTO R 101 were provided by Diversified Engineering Services, Inc. For details on the standard, refer to the Development of AASHTO R 101 chapter above.

Test Refinement

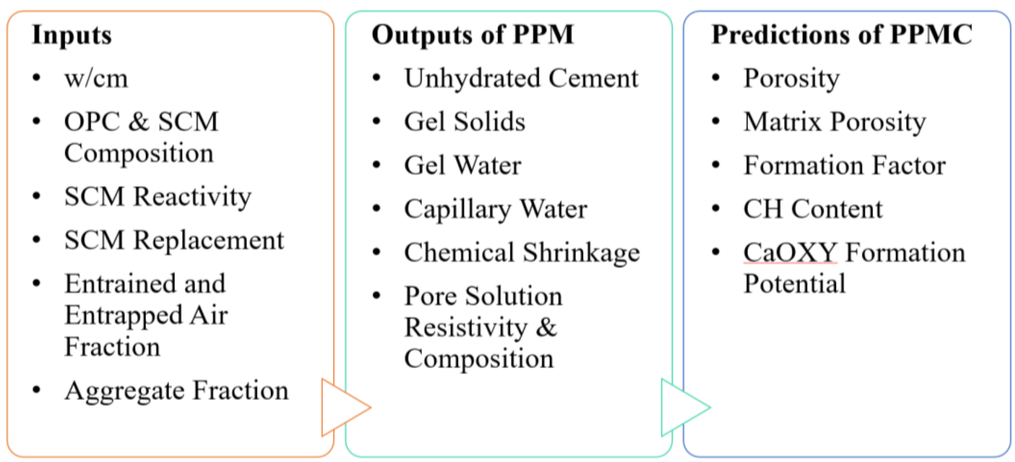
Water Content

Under this pooled fund project, the research team at Oklahoma State University worked with MnDOT and the FHWA MCTC to use the Phoenix in the field and gather feedback. Based on that feedback, the team made a number of changes to the test. First, the test originally used a 6 in. x 12 in. plastic cylinder mold that was trimmed to be 3.9 in. tall. Based on feedback, the test was modified to use a metal mold of the same dimensions. This made it easier to empty and clean the mold and so made the test easier to run. Next, the pans and loading forks used in the test were changed. The original test used a wire mesh bag to enclose the concrete specimens and place them on commercial cooking pans. These were changed to manufactured pans. This change required a new loading fork to be used in the test and a new metal mesh lid. Several iterations were needed to find pan dimensions that would not warp under the heat differential from cooling. Several mesh lids were developed and tried until a satisfactory lid design was found. Also based on feedback, the controller on the unit was modified to make it much simpler to use. This simplified the test and made testing easier for the operator. Based on feedback from MnDOT, a test method was also developed to use the Phoenix to measure the moisture content of the aggregate. The test can be completed in 5 minutes, which enhances the usefulness of the test method.

Finally, a standard test method was developed for using the Phoenix to measure the water content of fresh concrete, and a separate test method was developed to measure the moisture content of the aggregates. These test methods were shared with MnDOT, the Oklahoma DOT (ODOT [Oklahoma]), KDOT, NYSDOT, the Utah DOT (UDOT), and the FHWA MCTC for comments. Based on the comments received, several changes were made. The current test methods are being published by MnDOT as a state test method. This will allow other organizations to use the test in the future and will provide a stable version of the test to take to larger standards organizations.

Thermodynamic Modeling

Under this pooled fund project, the research team at Oregon State University used a previously developed modeling framework to predict the properties of concrete samples obtained from states and the LTPP sites. The inputs for the prediction framework (as described in Figure 34) are the amount and chemical composition of the ordinary portland cement (OPC); the amount, chemical composition, and degree of reactivity of the SCM; the maximum degree of reactivity (DOR*) of the SCM; and the mixture design (w/cm ratio, volume of entrained and entrapped air, volume of paste, and volume of aggregate).



PPM = pore partitioning model; PPMC = pore partitioning model for concrete
Jason Weiss

Figure 34. Calculation framework used to predict concrete performance

Work on this project included gathering these inputs for use in modeling, developing the models, and then evaluating the influence of various parameters and assumptions. The outputs of the calculations are properties that can be measured by the tests recommended in AASTHO R 101-22 for CaOXY, porosity, formation factor, sorption, and strength. Modeling results were compared with data from over 113 cores that were used to determine physical results from the eight states where cores were taken: Colorado, Iowa, North Dakota, Wisconsin, Kansas, Ohio, Indiana, and Minnesota. The model is very useful for predicting performance as well as the carbon footprint and sustainability of a pavement in relation to its service life.

VKelly

The purpose of the VKelly test is to indicate how a mixture will respond to vibration, providing more information than the yield stress reported by the slump test. Feedback from some of the states that were provided with VKelly devices suggested that the system was labor intensive and not user friendly, although in some cases it was felt that the resulting data were valuable. It was reported that a number of operators used a variety of vibrators and head sizes, leading to a large variability in the data produced.

During this pooled fund project, a vibrator manufacturer was able to redesign the system, including mounting a speed-controlled motor directly above the ball, thus reducing energy loss and improving the device's ease of use. Work is still ongoing on a way for the device to report the rate of penetration automatically, which would provide an instantaneous readout.

CLOSING AND FUTURE WORK

Key Findings and Results

Through the PEM pooled fund, the project team learned the following:

- Each state agency is unique in the way it specifies concrete pavements; Table 2 in AASHTO R 101 gives agencies choices in the PEM properties and standard test methods to use.

- The success of the PEM shadow projects was the result of coordination and communication between state agencies and industry.

- New test methods require training and practice in following standard methods for the tests to achieve the desired results.

- Contractors involved in the shadow projects were supportive and continue to use the tools provided through the PEM pooled fund project.

- Concrete pavement sustainability is improved when PEM approaches are used.

- Additional technology transfer activities are needed to further expose agencies and industry to PEM and its benefits.

- The goals of the pooled fund project were achieved, including the implementation of PEM in practice, the delivery of education and training on the PEM approach and tests for PEM properties, adjustment of the specification values used in concrete paving, and the continued development of tools to relate early-age concrete properties to performance.

Future Work

The expected outcome of PEM implementation is success for all parties involved, from the design engineer, material producer, pavement contractor, and agency to the users of the transportation facility. With the PEM approach, concrete pavement is expected to perform better and last longer with a lower environmental impact. This will enable agencies to lower costs by minimizing maintenance operations, keeping the flow of traffic undisturbed for longer periods of time and increasing the safety of the travelling public.

The PEM pooled fund project has shown success, especially in the form of improved specifications at the agency level that have been accepted by contractors. While progress has been made, additional work needs to be one. The PEM approach needs further advocacy and dissemination so that more agencies have an opportunity to achieve the benefits that PEM offers.

The PEM pooled fund project addressed the need to specify, measure, and deliver concrete pavement mixtures that perform as intended for their design lifetime. The focus of the work was on 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.

The team recommends that construction operations be the focus of the efforts undertaken during the next pooled fund project, Performance Centered Concrete Construction (P3C). With this pooled fund, the intention is to follow the model used by the PEM pooled fund project to carry out the following:

- Establish a sound understanding of the workmanship involved in concrete paving and its effects on performance properties
- Develop/select appropriate test methods for evaluation of the concrete at or behind the paver
- Select pass/fail criteria for concrete based on the selected test methods
- Provide documentation, training, and other resources to encourage agencies and contractors to adopt specifications and practices reflecting the suggestions resulting from the project

The P3C pooled fund project will involve reaching out to agencies, contractors, machine manufacturers, and researchers to develop a detailed scope of work starting with the determination of the actions that need to be taken on the grade to ensure sustainable concrete pavement performance. Test methods and specification limits will be determined in order to measure the following:

- Uniformity
- Segregation
- Consolidation
- Air-void system
- Durability and strength
- Smoothness
- Cracking

Successful completion of the project will involve the development of specifications and guidance tools for technology transfer, including videos, written documents, and training programs.

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APPENDIX A. PEM PRESENTATIONS

Table 13 lists all of the presentations delivered as part of the pooled fund project where PEM was discussed.

Table 13. PEM presentations delivered as part of the pooled fund project

Date	Meeting	Presentation	Location
1/13/2017	WI RMCA	Mixture Proportioning	Wisconsin Dells, WI
1/18/2017	NE ACPA	Performance-Engineered Mixtures	Lincoln, NE
2/16/2017	WI CPA	Performance-Engineered Mixtures	Appleton, WI
2/28/2017	MOKAN	Performance-Engineered Mixtures	Kansas City, MO
3/28/2017	PA CPA	Performance-Engineered Mixtures	Harrisburg, PA
8/11/2017	PCA	Performance-Engineered Mixtures	Webinar
9/18/2017	CAPTG	Performance-Engineered Mixtures	Halifax, NS
10/2/2017	NRMCA	Performance-Engineered Mixtures	Dallas, TX
11/9/2017	BCC	Internal Curing	Ames, IA
11/15/2017	NY CPA	PEM/Aggregates	Albany, NY
1/7/2018	TRB	PEM Overview	Washington, DC
3/2/2018	NRMCA	CP Tech/PEM Update	Houston, TX
3/5/2018	PCA	CP Tech/PEM Update	Houston, TX
4/24/2018	NC^2	PEM Pooled Fund Update	Coeur D'Alene, ID
5/16/2018	TRC, AR	Preservation, PEM	Little Rock, AR
6/12/2018	ACPA Mid-Year Meeting	PEM For Concrete Pavements	Denver, CO
7/18/2018	PEM Open House, MN	The PEM Initiative	Minneapolis, MN
7/25/2018	PCA Professor’s Workshop	Mixtures for Pavements	Skokie, IL
8/1/2018	PEM Open House, IA	The PEM Initiative	Holstein, IA
8/28/2018	PCA Products and Standards Committee	CP Tech/PEM Update	Chicago, IL
9/18/2018	NC^2	PEM Pooled Fund Update	Saratoga Springs, NY
10/1/2018	NRMCA	PEM for Contractors	Washington, DC
10/29/2018	NC Concrete Pavement Conference	Performance-Engineered Mixtures	Greensboro, NC
11/27/2018	ACPA Annual Meeting	PEM CPU Session/CP Tech Update	Ft. Lauderdale, FL
12/5/2018	Missouri AGC	Performance-Engineered Mixtures	Lake of The Ozarks, MO
12/14/2018	Caltrans	Performance-Engineered Mixtures	Oakland, CA
1/14/2019	Transportation Research Board	PEM: A New Path for QA for Concrete Pavements	Washington, DC
2/6/2019	Concrete Council of St. Louis	PEM, Specs, Assets	St Louis, MO
2/6/2019	Iowa Concrete Paving Association	Progress for Performance-Engineered Mixtures	Des Moines, IA

Date	Meeting	Presentation	Location
2/11/2019	SD Workshop	PEM and I-90 PEM Testing	Deadwood, SD
2/20/2019	ACPA Pennsylvania Workshop	Overview of PEM Approach	Harrisburg, PA
2/20/2019	ACPA Pennsylvania Workshop	Performance-Engineered Mixtures Showcase	Harrisburg, PA
3/4/2019	PCA/NRMCA Annual Meetings	Progress with Performance-Engineered Mixtures	Tampa. Fl
3/14/2019	ACPA/New York Conference	Performance-Engineered Mixtures	Albany, NY
4/2/2019	NC^2	PEM Update	Denver, CO
5/2/2019	TDOT	PEM Workshop	Nashville, TN
5/6/2019	Missouri Concrete Conference	Performance-Engineered Mixtures	Rolla, MO
5/14/2019	PEM Open House, NC	The PEM Approach	Salisbury, NC
6/5/2019	PEM Open House, CA	PEM Quality/Test for Quality	Sacramento, CA
7/21/2019	ASCE	PEM Tests	Chicago, IL
7/22/2019	ASCE International Airfield and Highway Pavement Conference	Concrete PEM Pooled Fund, COOP Agreement, and State Implementation	Chicago, IL
8/6/2019	IL CPA	PEM Workshop	Moline, IL
8/22/2019	MCT	Proportioning	Ames, IA
9/9/2019	NC^2	Performance-Engineered Mixtures	Kalispell, MT
10/15/2019–10/16/2019	MO/KS Chapter, ACPA	Performance-Engineered Mixtures for Concrete Pavements	Kansas City, MO
10/29/2019	OTEC	Performance-Engineered Mixtures	Columbus, OH
11/6/2019	PEM Training, NYSDOT	PEM Overview	Buffalo, NY
11/12/2019	NW Ohio Concrete Conference	Performance-Engineered Mixtures	Cleveland, OH
12/3/2019	ACPA Annual Meeting	Performance-Engineered Mixtures	New Orleans, LA
1/9/2020	NE RMCA	Performance-Engineered Mixtures	Lincoln, NE
2/13/202–2/14/2020	2020 Wisconsin Concrete Paving Workshop	Designing Concrete Mixture Proportions	Madison WI
9/22/2020	ACI UT	Various (PEM)	Webinar
12/11/2020	CP Tech Center Lunch and Learn	PEM and Reduced-Cement Paving Mixes in Iowa	Webinar
1/27/2021	Utah RMCA	Performance-Engineered Mixtures	Webinar
1/29/2021	Utah/ACPA Workshop	Performance-Engineered Mixtures	Salt Lake City, UT
2/27/2021	Virginia Concrete Conference	Performance-Engineered Mixtures	Richmond, VA
3/2/2021	IRMCA Annual Meeting	Performance-Engineered Mixtures	Iowa City, IA
3/12/2021	Con Expo 2020	Performance-Engineered Mixtures	Las Vegas, NV
3/23/2021	PCA	PEM/CP Tech Update	Webinar
5/25/2021	FHWA	Proportioning	Webinar

Date	Meeting	Presentation	Location
7/8/2021	ARDOT	Performance-Engineered Mixtures	Webinar
7/26/2021	SCA	PEM Report	Webinar
8/23/2021	TDOT	PEM Workshop	Nashville, TN
9/14/2021	CP Tech Center	Performance-Engineered Mixtures	Webinar
9/21/2021	South Africa Industry	Performance-Engineered Mixtures	Webinar
9/23/2021	CemenTech	Performance-Engineered Mixtures	Indianola, IA
9/27/2021–10/1/2021	International Conference on Concrete Pavements	Why Are Contractors Interested in PEM?	Webinar
10/7/2021–10/8/2021	Testing VKelly	Testing	Salem, SD
10/12/2021	NRMCA RES Committee	PEM and Partnership Update	Webinar
12/2/2021	ACPA Annual Mtg.	PEM: The Tech That Makes It Happen	Huntington Beach, CA
12/9/2021	Missouri AGC	Delivering Better Concrete Pavements with PEM	Lake of The Ozarks, MO
2/1/2022	SD Workshop	PEM 2022	Deadwood, SD
2/9/2022–2/10/2022	Illinois Chapter Annual Workshop	National Perspective on Concrete Pavement Research Efforts	Springfield IL
2/28/2022–3/3/2022	North Dakota Chapter Annual Workshop	Performance-Engineered Mixtures for Concrete Pavements	Bismarck, ND
2/11/2022	WI Workshop	PEM 2022	Peewaukee, WI
2/23/2022	MO Workshop	PEM 2022	Kansas City, MO
3/8/2021–3/9/2021	GDOT	PEM Workshop	Atlanta, GA
4/4/2022	NC^2	PEM Pooled Fund Update	Nashville, TN
4/28/2022	PEM TAC	Resistivity Testing: What Do I Need to Know? How Do I Use It?	Webinar
5/25/2022	Arkansas Transportation Research Committee	Performance-Engineered Mixtures	Webinar
8/16/2022	CP Tech Center Technology Tuesday	Linking PEM and Sustainability	Webinar
9/27/2022	NC^2	PEM Pooled Fund Update	Detroit, MI

APPENDIX B. REPORTS

MCTC Reports

Table 14 provides links to the reports published by the FHWA MCTC describing the shadow testing and open house activities.

Table 14. MCTC reports

State	Report Link
Iowa	https://intrans.iastate.edu/app/uploads/sites/7/2020/08/MCT_Iowa-Report.pdf
Kansas	https://intrans.iastate.edu/app/uploads/sites/7/2022/12/MCTC_KS1905-Final-Report.pdf
Minnesota	https://intrans.iastate.edu/app/uploads/sites/7/2020/08/MCT_Minnesota-Report.pdf
North Carolina	https://intrans.iastate.edu/app/uploads/sites/7/2020/09/MCTC-North-Carolina-Visit_Field-Report_9_18_20.pdf

State Reports to FHWA

A group of the pooled fund project member states received incentive money from FHWA to implement aspects of the PEM approach. As a requirement of the funding, each of the states submitted a report to FHWA detailing the use of the incentive funds. Table 15 lists the state agencies that received this funding and provides links to the reports submitted by each state.

Table 15. State reports to FHWA

State	Report Link
Iowa	https://intrans.iastate.edu/app/uploads/sites/7/2019/06/Iowa-PEM-Report_2019-06-20_Final.pdf
Minnesota	https://intrans.iastate.edu/app/uploads/sites/7/2021/05/MNDOT_I35W-Lake_PEM_AASHTO_PP84_Report.pdf https://intrans.iastate.edu/app/uploads/sites/7/2020/04/MNDOT_TH60_PEM_AASHTO_PP84_Report.pdf
New York	https://intrans.iastate.edu/app/uploads/sites/7/2020/09/PEM-Pavement-Report-NYSDOT-2020-002.pdf
North Carolina	https://intrans.iastate.edu/app/uploads/sites/7/2020/05/Post-Construction-Report-for-North-Carolina-DOT-Demonstration-Project-05-14-2020.pdf
Pennsylvania	https://intrans.iastate.edu/app/uploads/sites/7/2022/12/Pennsylvania-DOT-PEM-Demonstration-Project-Report.pdf
South Dakota	https://intrans.iastate.edu/app/uploads/sites/7/2019/10/South-Dakota-PEM-report-2019-08-30.pdf
Wisconsin	https://wisconsindot.gov/documents2/research/0092-17-07-final-report.pdf

APPENDIX C. DATA PLOTS

The following plots were prepared from the database developed for the PEM pooled fund project. Data were collected from state agencies as well as the MCTC. These data are available in spreadsheet format at the following link: https://intrans.iastate.edu/app/uploads/sites/7/2022/12/MCTC_PEM_Data.xlsx.

The data are organized into fresh properties and hardened properties, as reflected in the plots. In addition to the figures provided in this appendix, the plots and data are available for viewing on the CP Tech Center's PEM website, https://cptechcenter.org/performance-engineered-mixtures-pem/.

Fresh Properties – Unit Weight Plots

Figure 35 shows scatter plots of unit weight test results versus date for bridge and pavement projects. While it is difficult to see correlation or trends, the scatter plot provides a glimpse of the number of total tests taken.

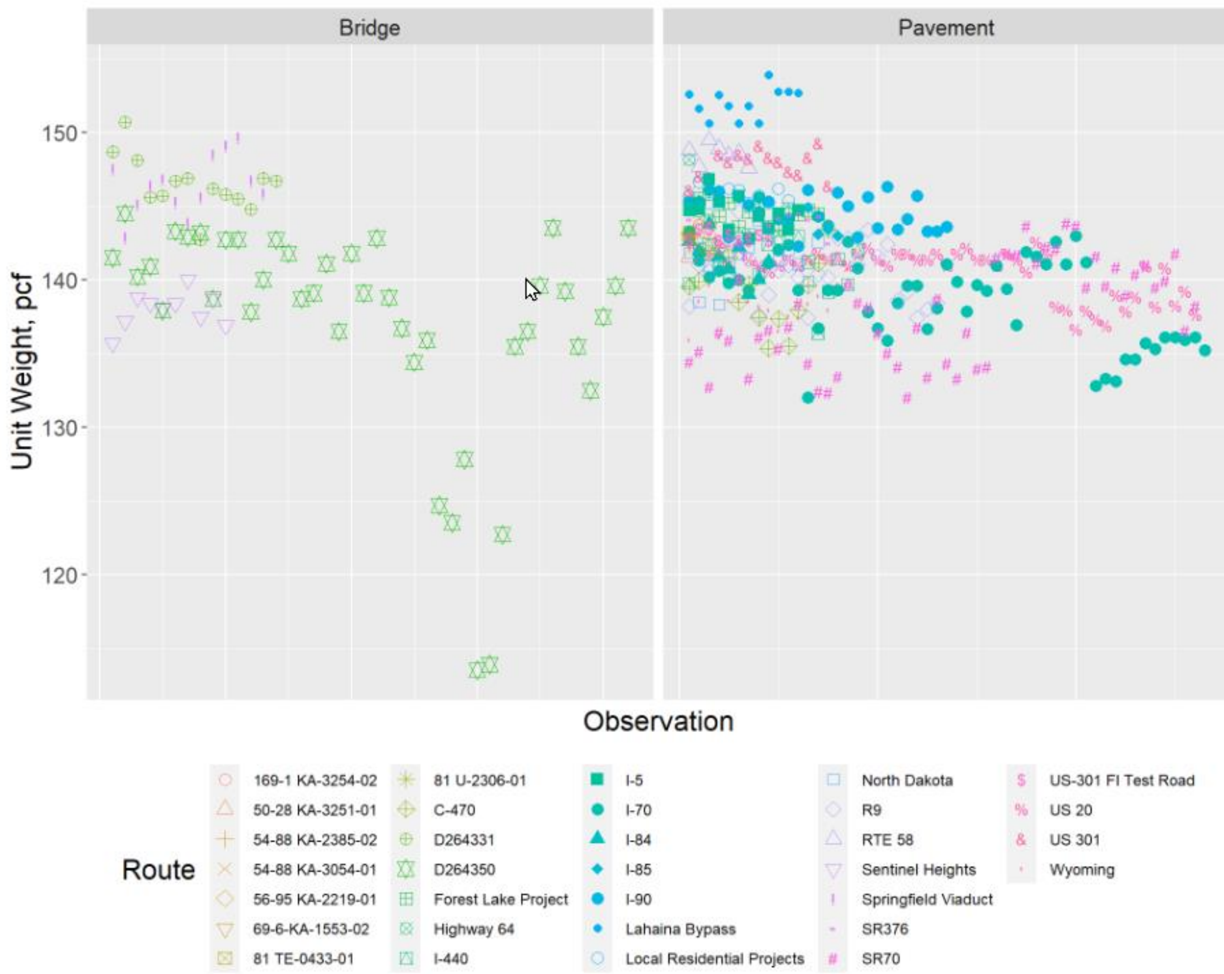

Figure 35. Unit weight scatter data for bridges and pavements

Figure 36 shows the unit weight test results over time. Data plots that result in a horizontal line indicate a consistent and uniform mixture based on consistent weights.

Figure 36. Unit weight data from various locations

Figure 37 is a box and whisker plot showing unit weights for all pavements. This figure allows for comparison between different projects. The box and whisker plot is a way of showing data that provides the lower and upper quartiles, the interquartile (where 50% of the data are found), and the median value.

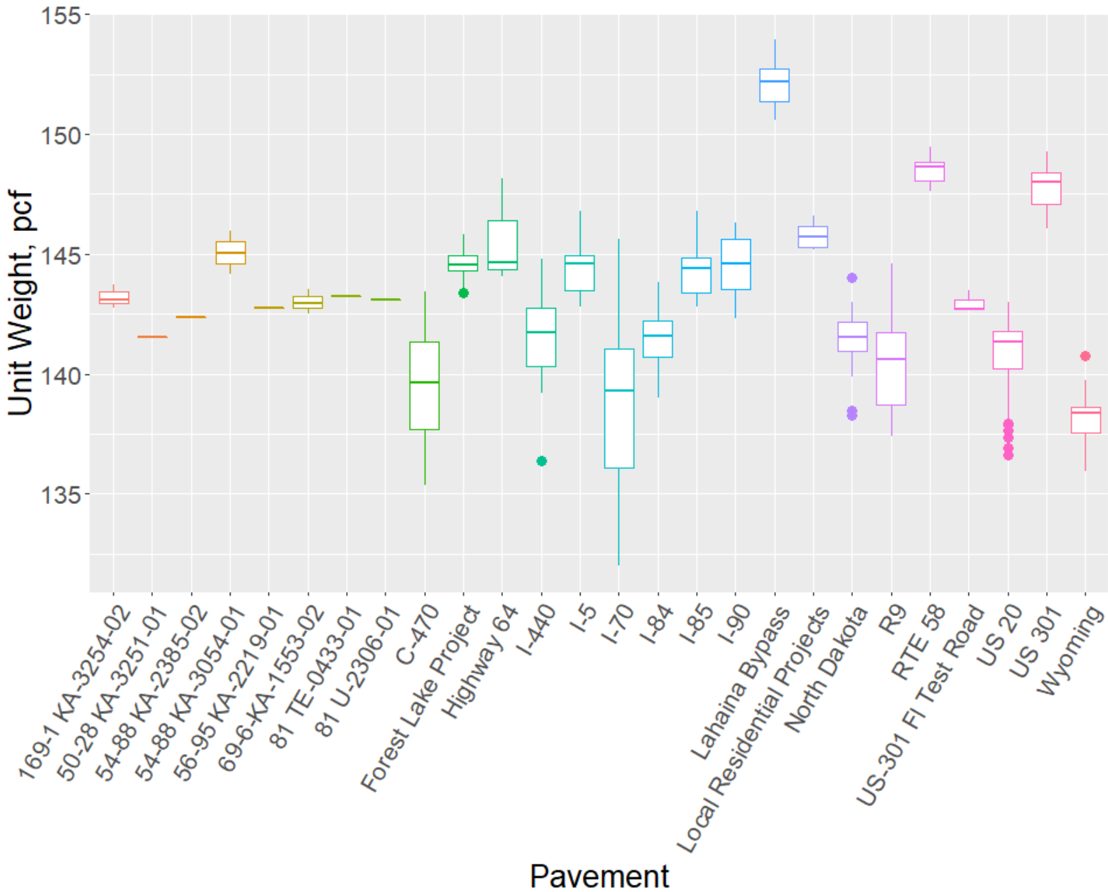

Figure 37. Unit weight box and whisker data for pavements

Figure 38 shows the box and whisker plots for unit weight versus date on bridge projects.

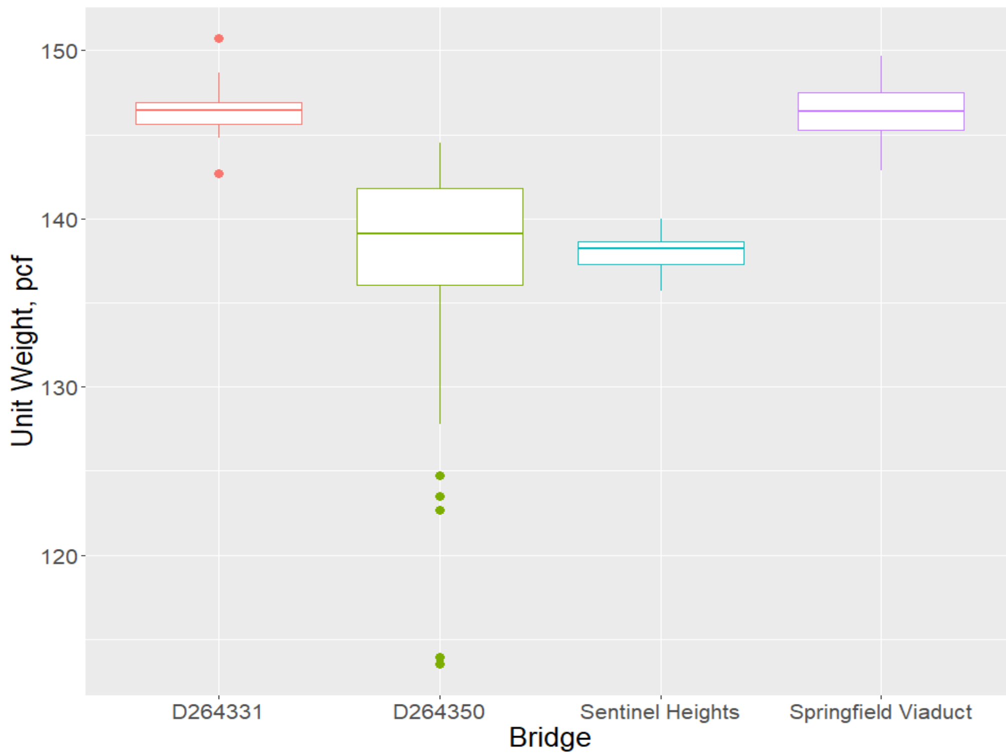

Figure 38. Unit weight box and whisker data for bridges

Fresh Properties – SAM and Air Content Plots

The following figures represent SAM test results and air content testing. SAM_Air represents air content determined by the SAM. Air_Content represent air content determined by the Type B meter.

Figure 39 is a box and whisker plot showing SAM numbers for pavement projects, while Figure 40 is a box and whisker plot showing SAM numbers for bridge projects. The horizontal lines indicate a SAM value of 0.3 and a value of 0.2. This figure allows for SAM number to be compared among several projects, with some projects having more variability than others.

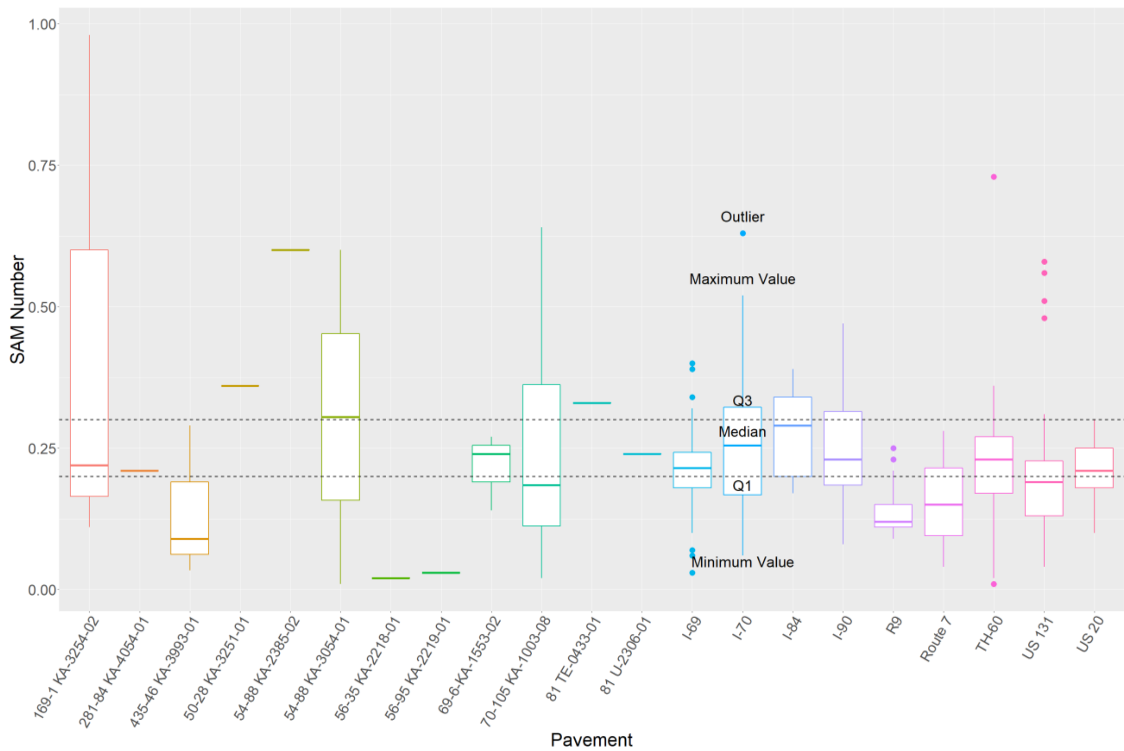

Figure 39. SAM box and whisker data for pavements

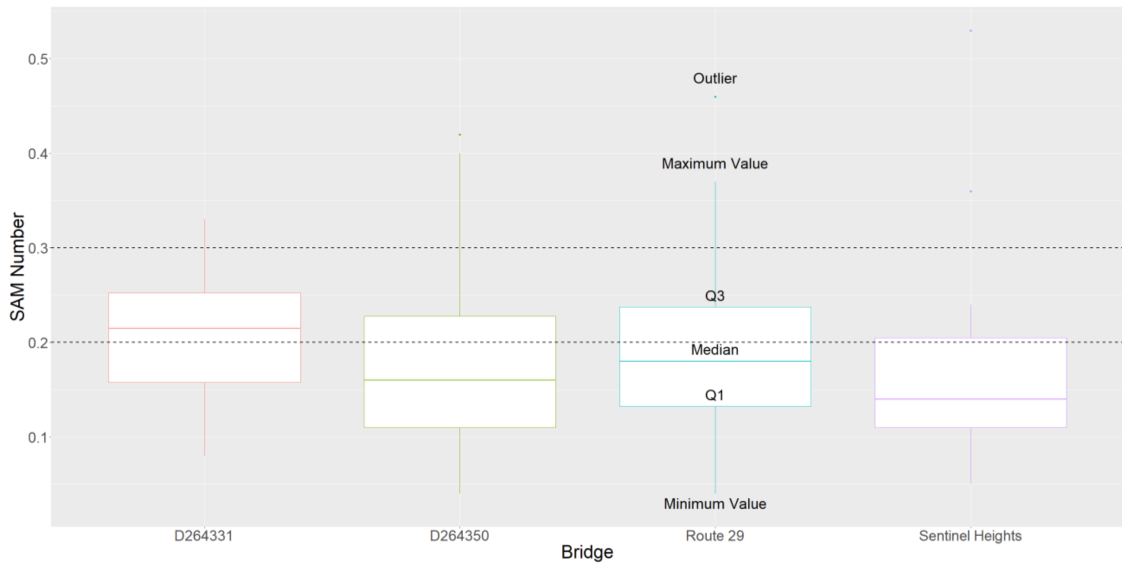

Figure 40. SAM box and whisker data for bridges

Figures 41 and 42 show SAM numbers versus date for various projects. Separating the data into individual projects allows the data to be compared between projects, and the outlier data, or any data not found on a horizontal line, can be observed. Variability in the results may warrant further investigation.

Figure 41. SAM data for various locations

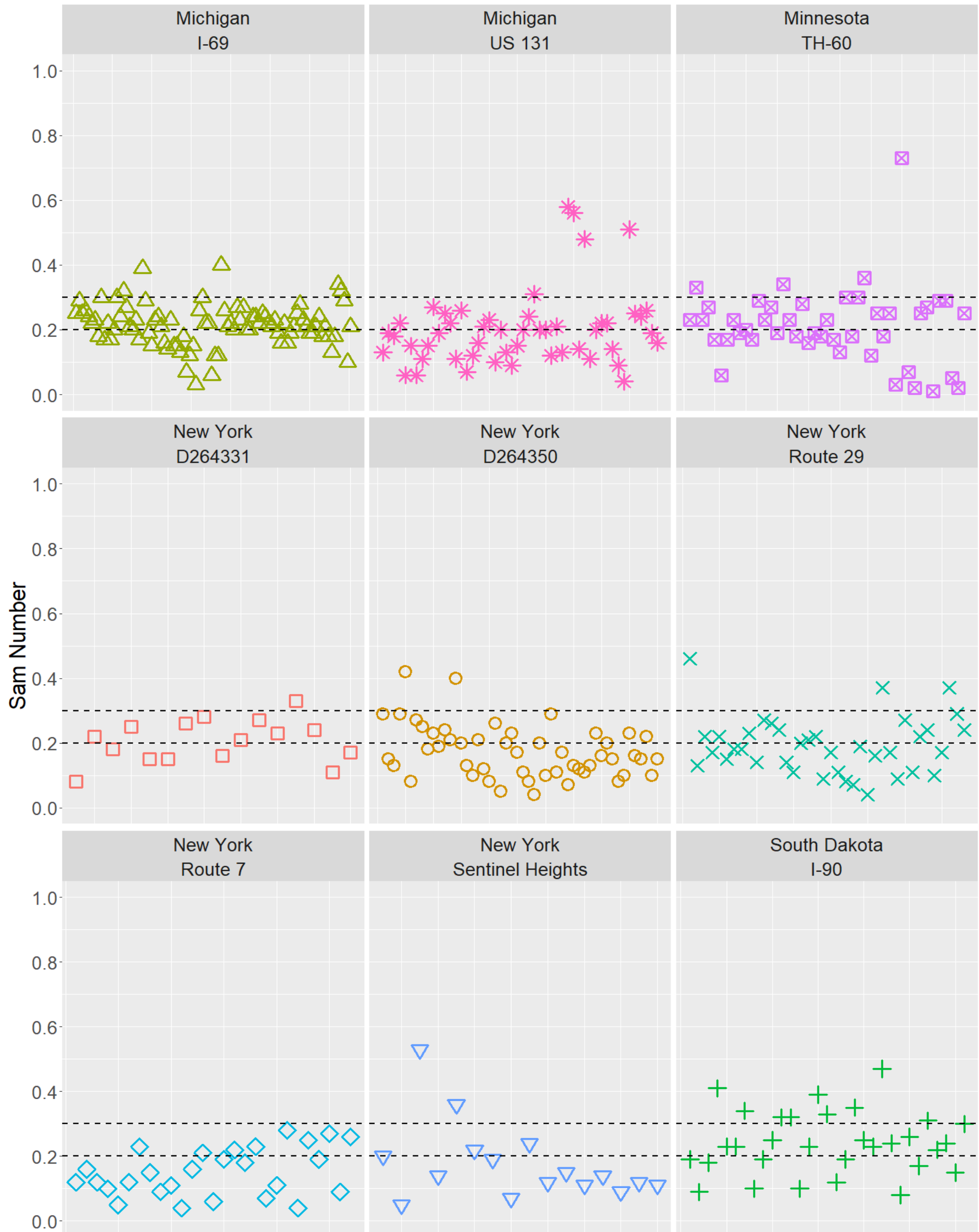

Figure 42. SAM data for various locations (continued)

Figure 43 is a SAM scatter plot for all pavement projects, and Figure 44 is a SAM scatter plot for all bridge projects. While it is difficult to see correlations or trends, the scatter plots provide a glimpse of the total number of tests taken.

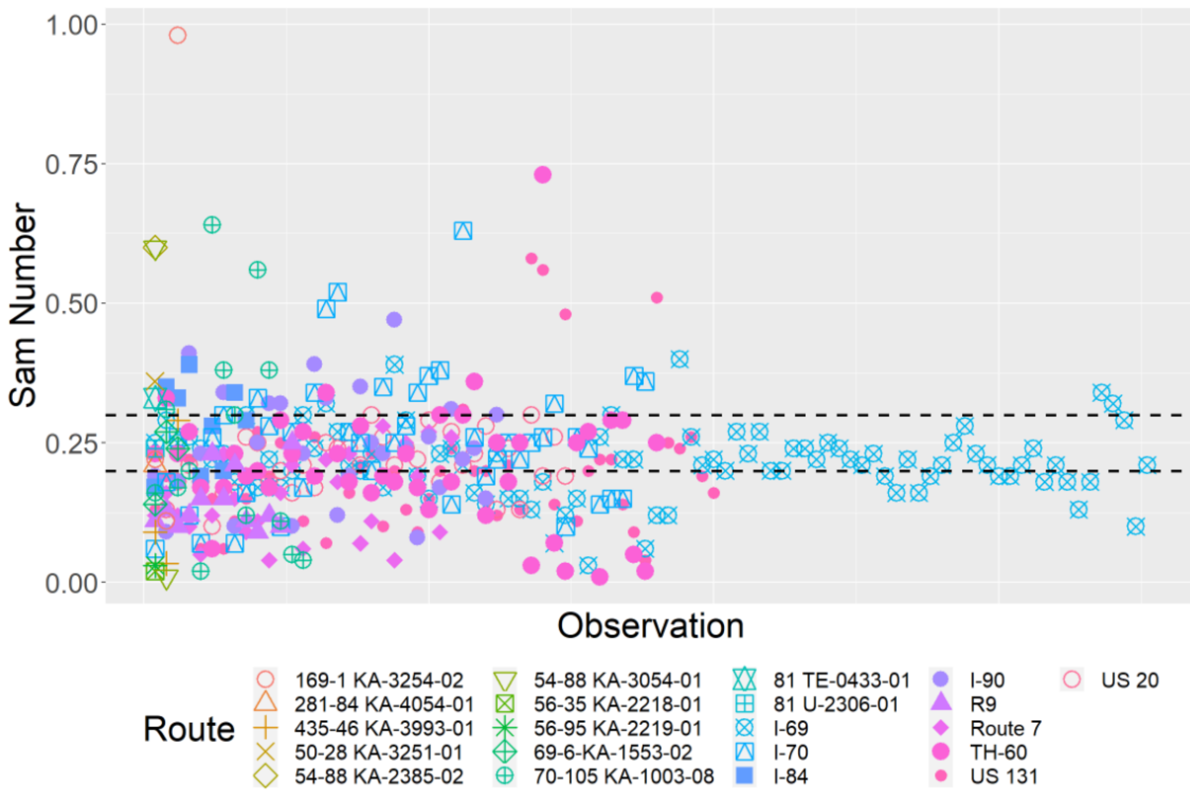

Figure 43. SAM scatter data for pavements

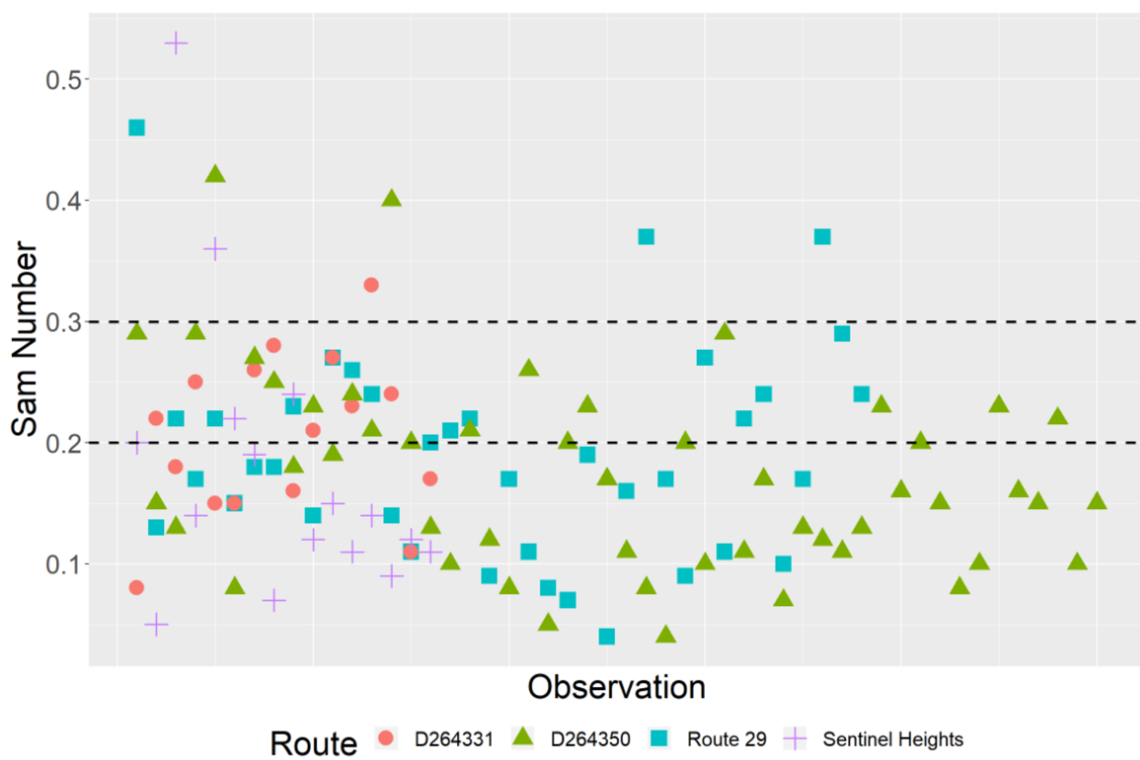

Figure 44. SAM scatter data for bridges

Figure 45 is a box and whisker plot of air content taken by the Type B meter for all pavement projects, and Figure 46 is a box and whisker plot of air content taken by the Type B meter for all bridge projects.

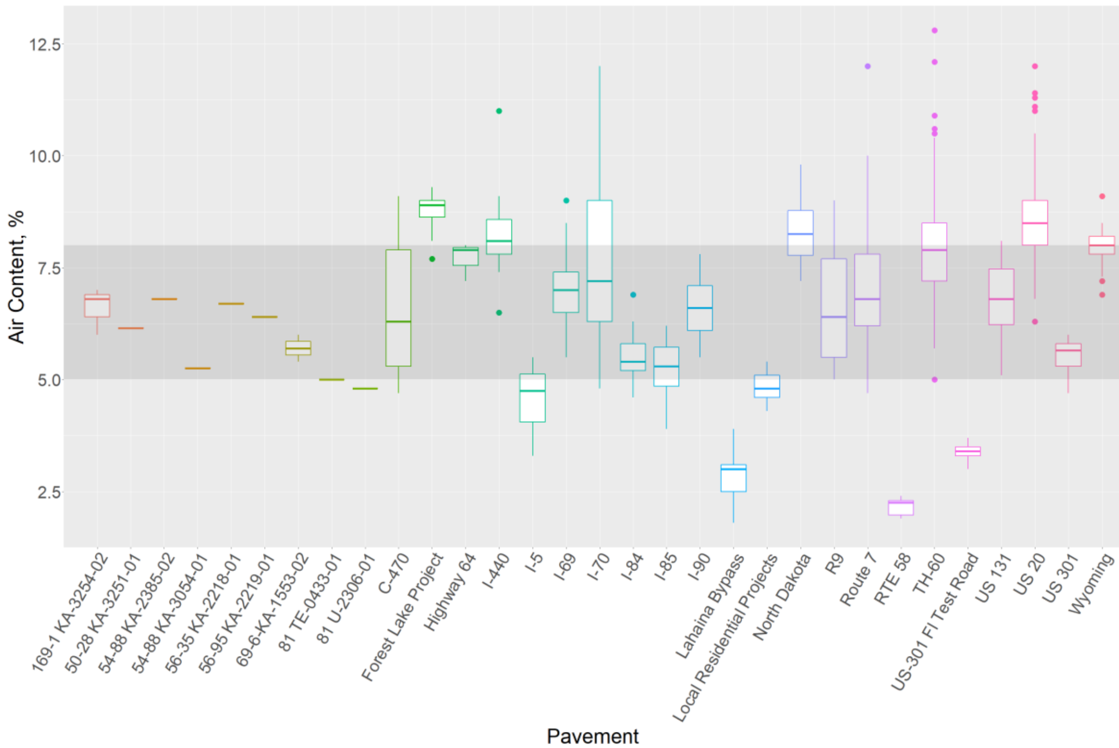

Figure 45. Air content box and whisker for pavements

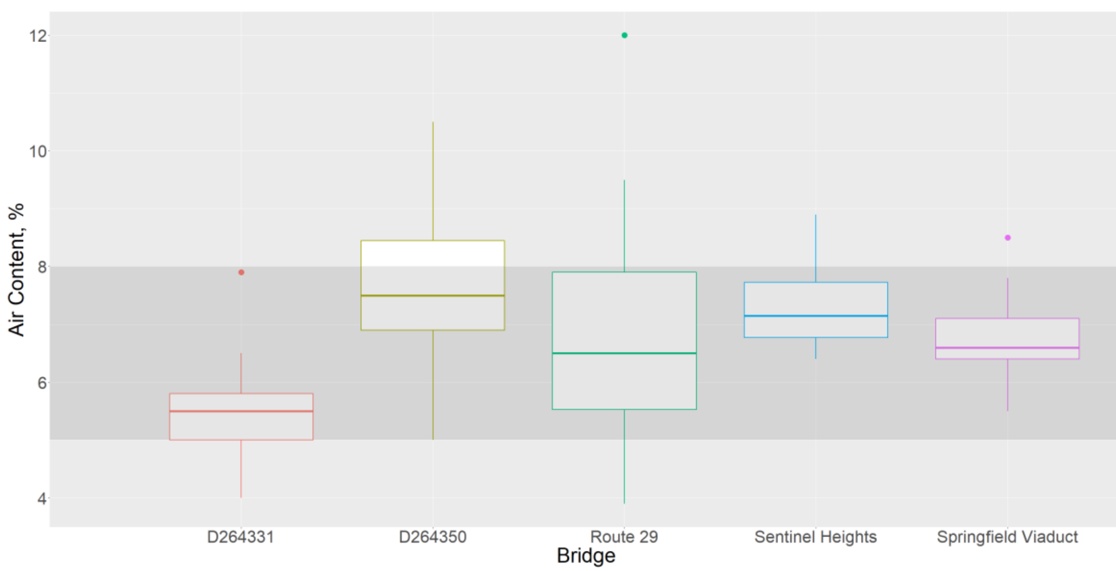

Figure 46. Air content box and whisker for bridges

Figure 47 shows air content as determined by the Type B meter versus date in scatter plots for bridge projects (left) and pavements (right). The shaded region between 5% and 8% represents the range of acceptable air content per AASHTO R 101.

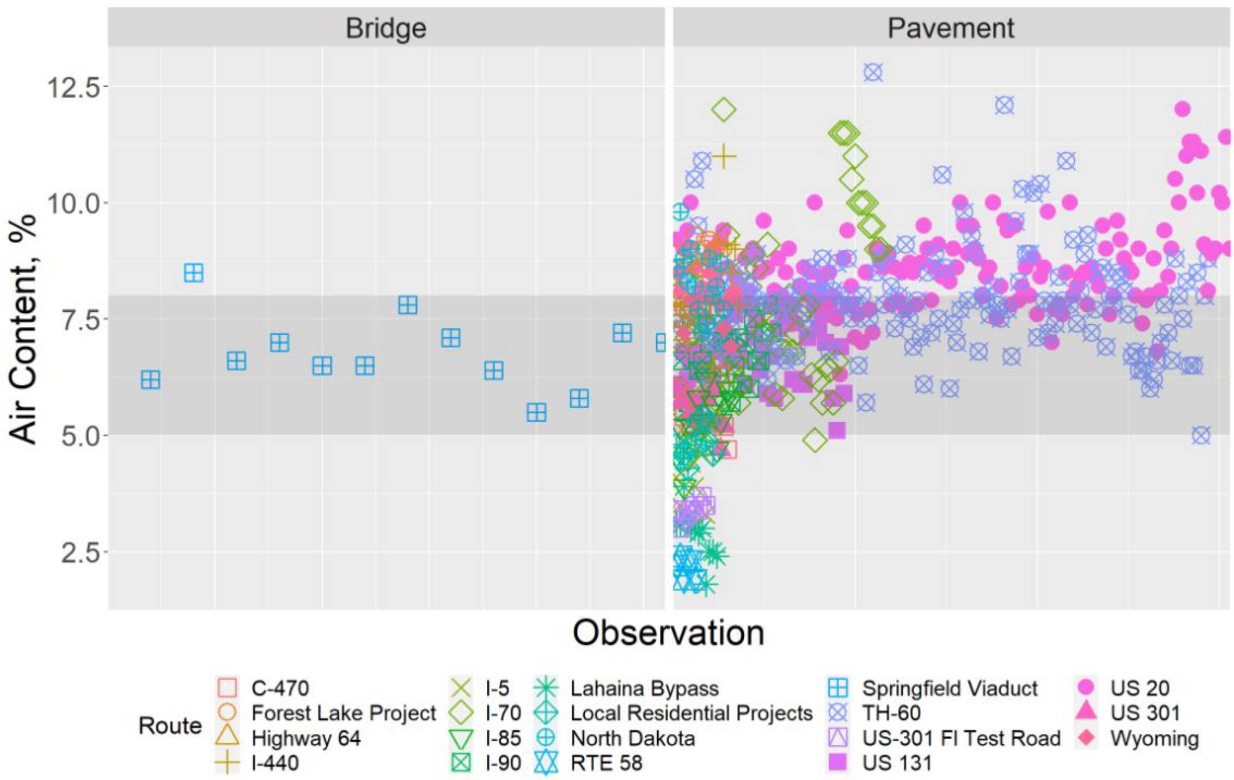

Figure 47. Air content scatter data for bridges (left) and pavements (right)

Figure 48 shows the air content determined by the Type B meter (Air_Content) and the air content determined by the SAM (SAM_Air) for various projects. The y-axis is the air content, and the x-axis is the observations. The expected standard deviation based on ASTM standards for the air content determined by the Type B meter and the air content determined by the SAM is 0.29%. This means that expected variation, within a 95% confidence interval, can vary by 0.58% for laboratory measurements. Variability between the two results can be caused by many factors, including differences in the location of the air test (at the batch plant versus at the paver), calibration of equipment, and other factors.

Figure 49 shows air content determined by the Type B meter for various projects. The y-axis is the air content, and the x-axis is the observations. Some locations with low air content values (Hawaii and Florida) are representative of mixtures that do not require a specified air content for freeze-thaw durability.

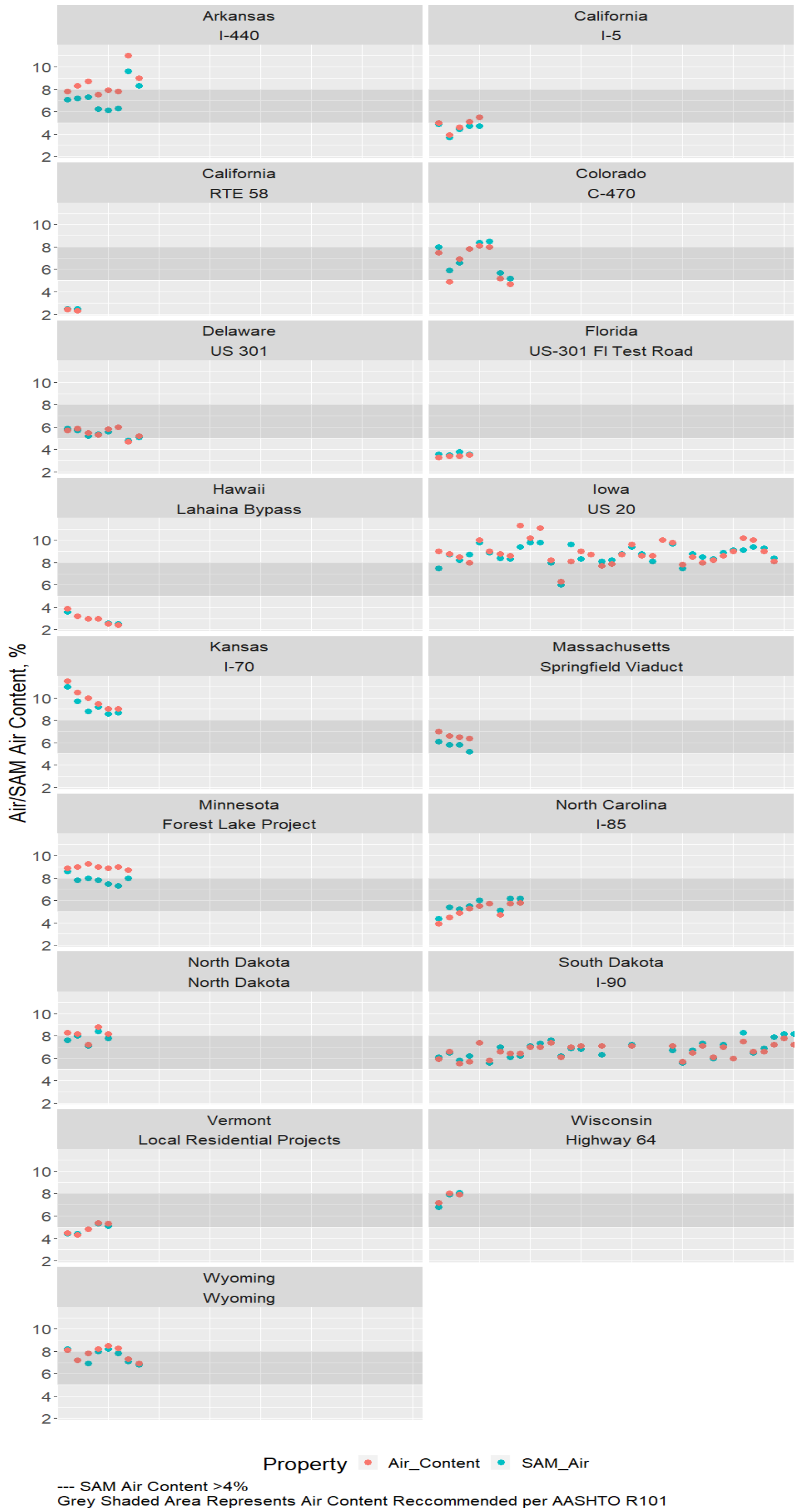

Figure 48. Air content measured by Type B meter (Air_Content) and SAM (SAM_Air) for various locations

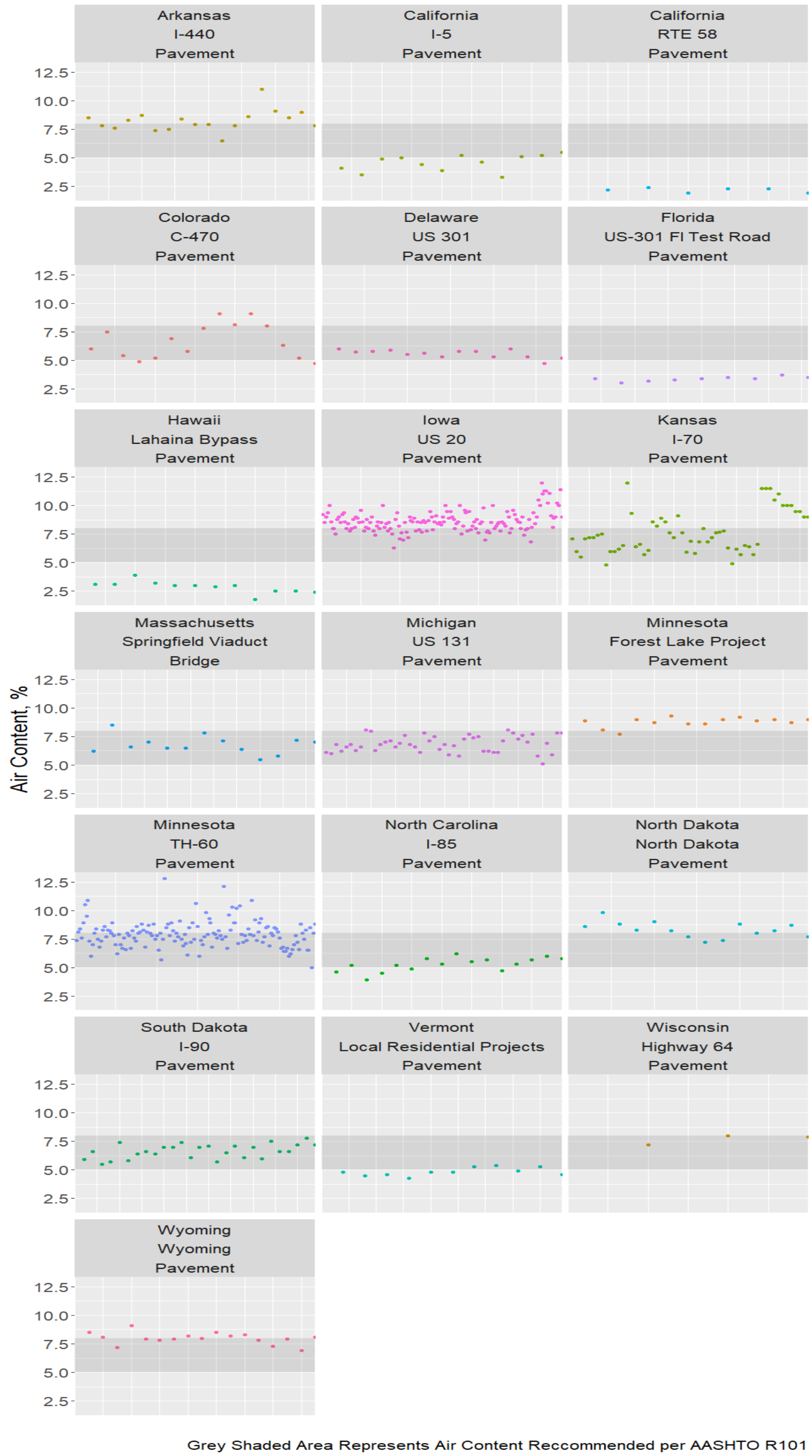

Figure 49. Air content measured by Type B meter (Air_Content) for various locations

Figure 50 illustrates a histogram of all of the SAM data gathered in this pooled fund project. The suggested limits of 0.20 and 0.30 are shown by two black vertical lines. A normal distribution curve is shown to highlight how the data are distributed. Since the data are normally distributed, it is appropriate to calculate an average and standard deviation.

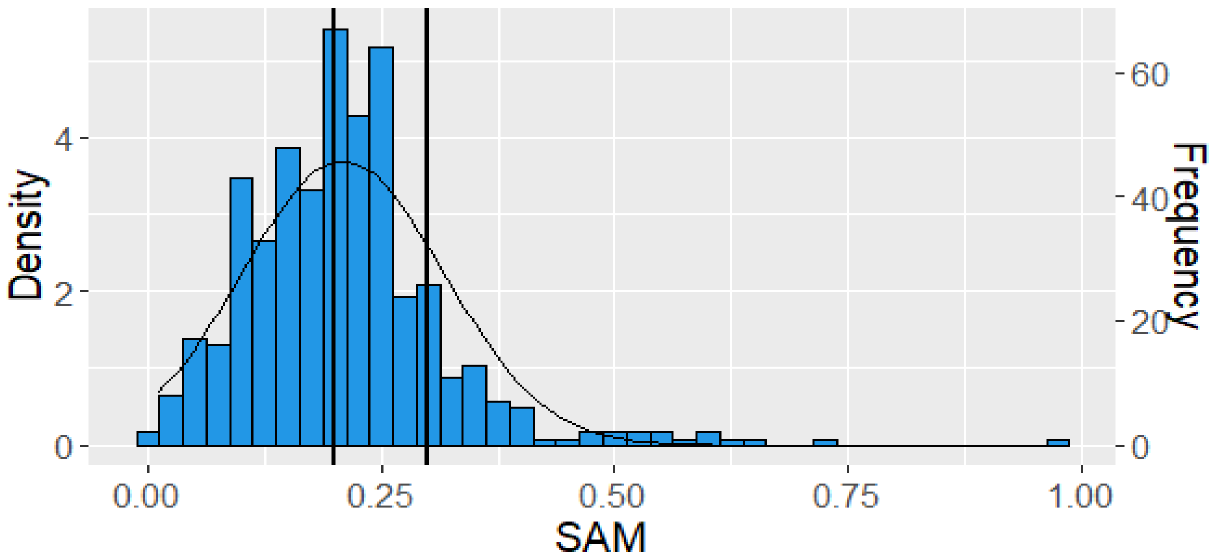

Figure 50. SAM histogram for all projects

The results show the following:

- The average SAM number was 0.21.
- Approximately 50% of the data were above the recommended 0.20 limit.
- Approximately 14% of the data were above 0.30.

The 0.30 limit is the recommended limit for freeze-thaw durability. This means that roughly one out of every six measurements made had a SAM number above this limit, and therefore freeze-thaw durability is a concern for these mixtures; that is, if this concrete becomes saturated and freezes, freeze-thaw damage is expected.

One reason for the higher SAM numbers in Figure 50 is that these were measurements made in the field based on existing specifications. These projects did not require a target SAM number in the mixture design stage. For example, the current AASHTO R 101 document requires the SAM number to be less than 0.20 in the mixture design stage and then sets a limit of 0.30 for the field. The data set from NYSDOT is unique in that the SAM was required to be less than 0.20 in the mixture design stage. These data are shown in Figure 51.

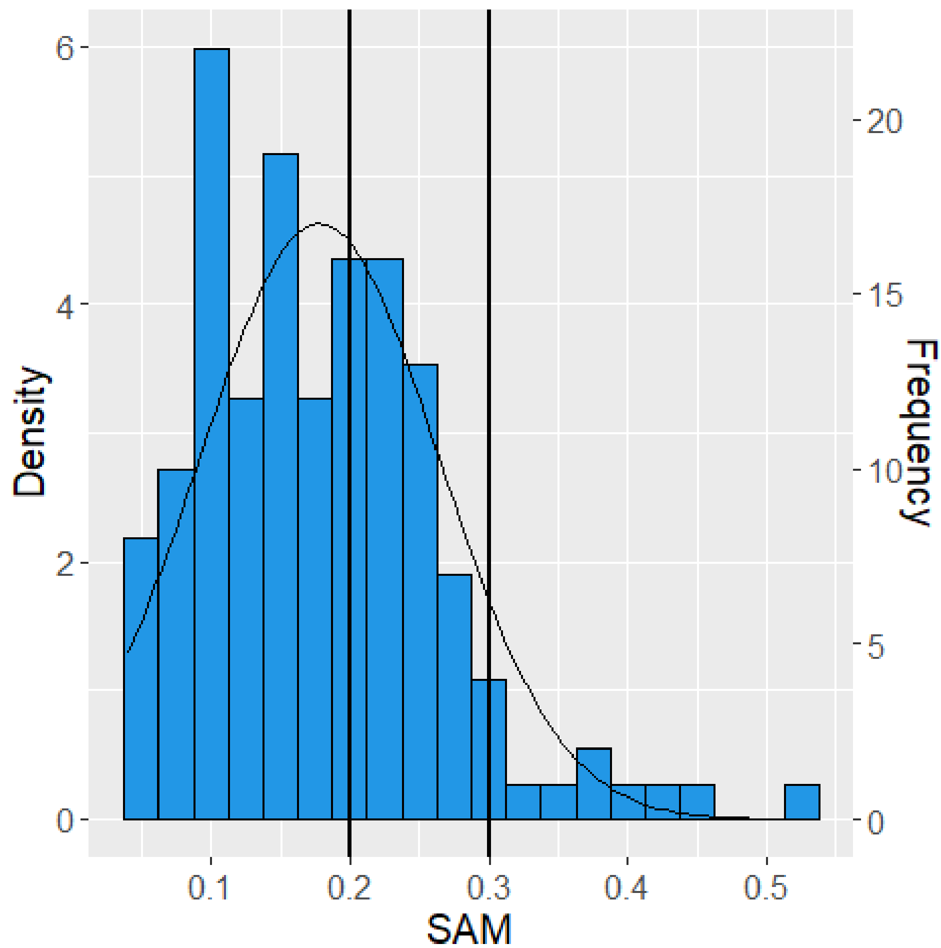

Figure 51. SAM histogram for all New York projects

When comparing the histograms in Figures 50 and 51, the values in Figure 51 are located more to the left, indicating lower SAM numbers. The average SAM number in Figure 51 is 0.18, and it was required that mixtures be designed to have a SAM number less than 0.20 on average. This is important because only 5% of the data in Figure 51 have SAM numbers above 0.30.

Figure 52 shows the difference in the air content as determined by the Type B air meter and the SAM. The difference between the air content from the Type B air meter and the SAM was on average 0.1%, with a standard deviation of 0.58%. The published standard deviation between the two is 0.29%. The reasons for the higher standard deviation in these measurements could be differences in calibration between the meters or the fact that the tests were performed in different locations. Previous laboratory and field studies have shown that the Type B meter and the SAM give nearly equivalent air contents and lower standard deviations than what is shown in this work.

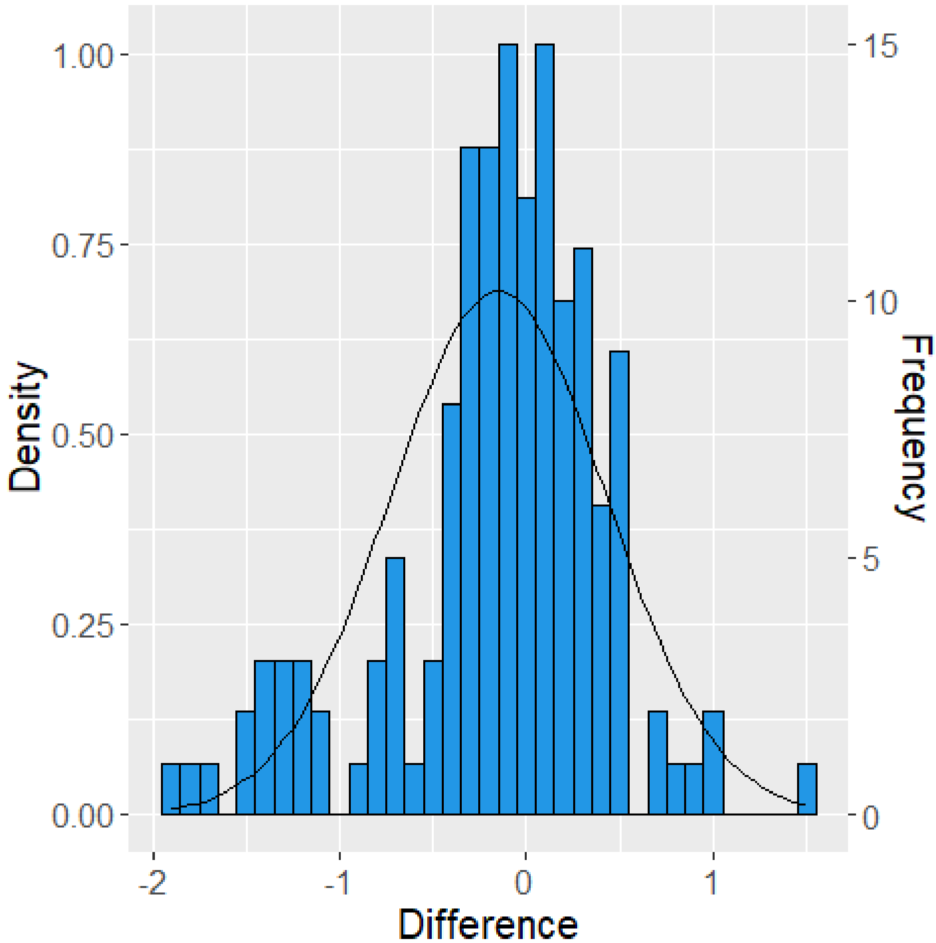

Figure 52. Difference between SAM_Air and Air_Content measured with Type B meter

Hardened Properties – Hardened Air Relationships

The following figures represent data from hardened concrete testing. Figure 53 shows relationships between air content as determined from hardened testing (Hard_Air), the Type B meter (Fresh_Air), and the SAM (SAM_Air). Figure 54 shows the relationship between Fresh_Air and Hard_Air. The y-axis in Figures 53 and 54 is air content, while the x-axis is the observations.

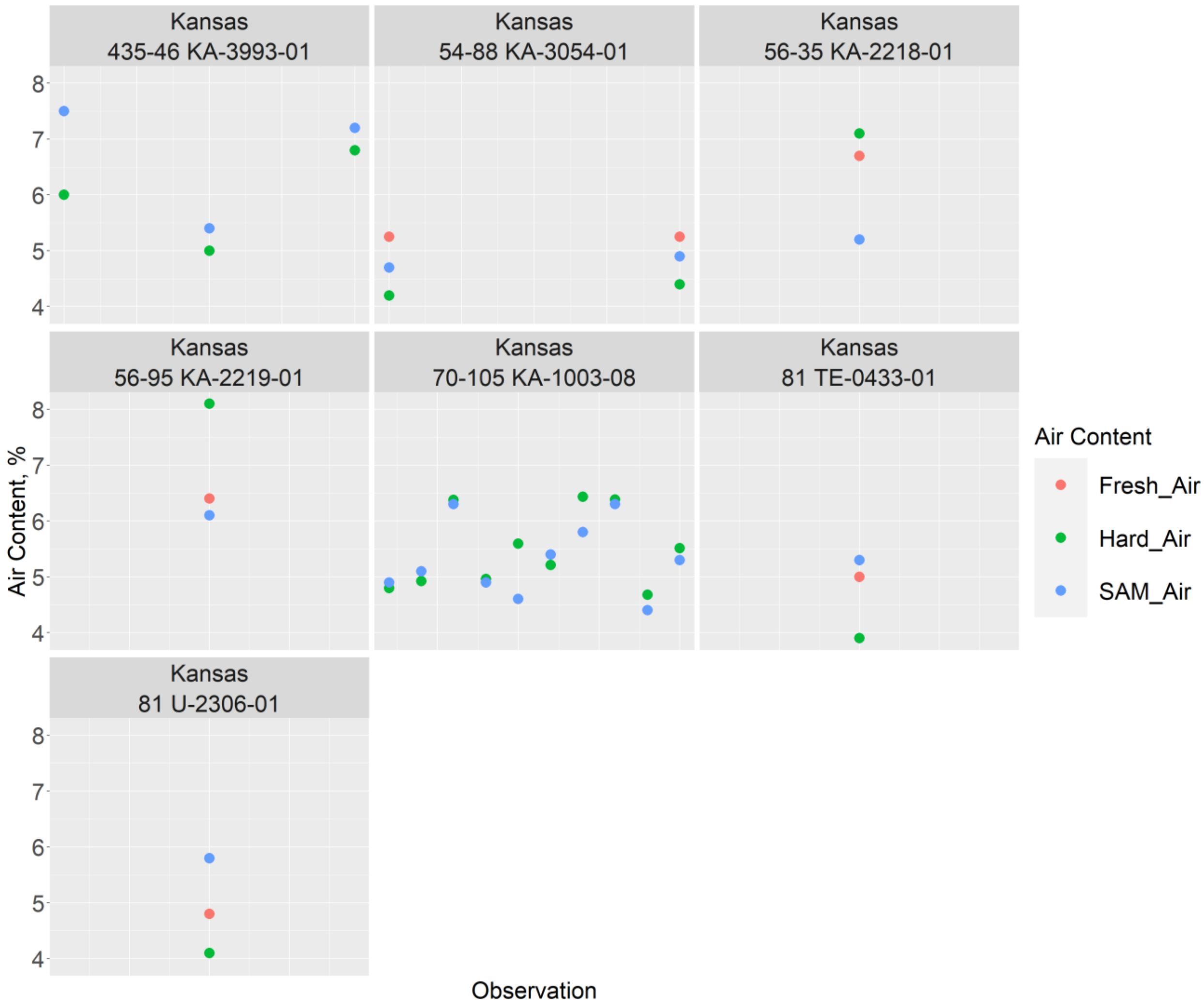

Figure 53. Fresh air, hardened air, and SAM air

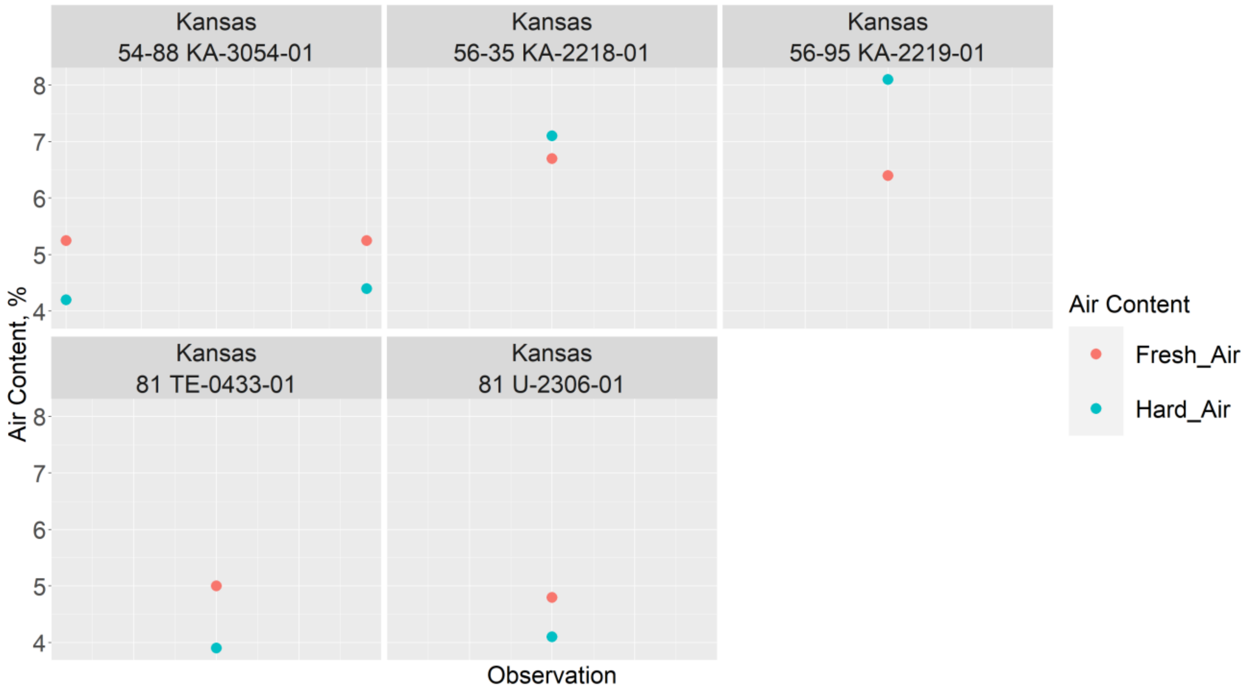

Figure 51. Fresh and hardened air content

One finding from the data review process was that if more data were provided, more plots could be developed with relationships similar to those in Figure 53.

Figure 55 shows the relationship between the SAM and hardened air, with the y-axis showing SAM number.

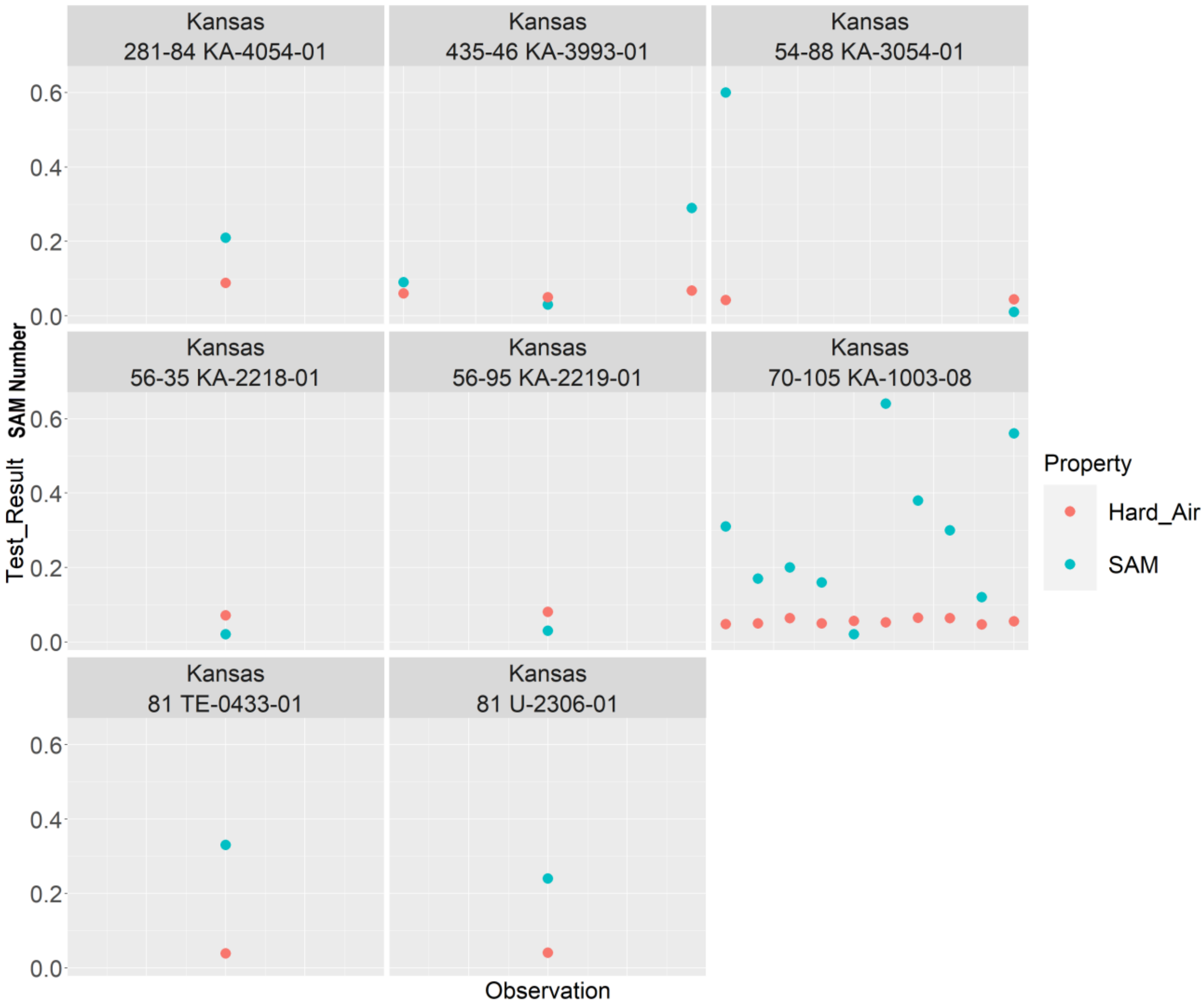

Figure 55. Hardened air and SAM

Figure 56 shows the relationship between the SAM and hardened air, with the y-axis showing units of inches.

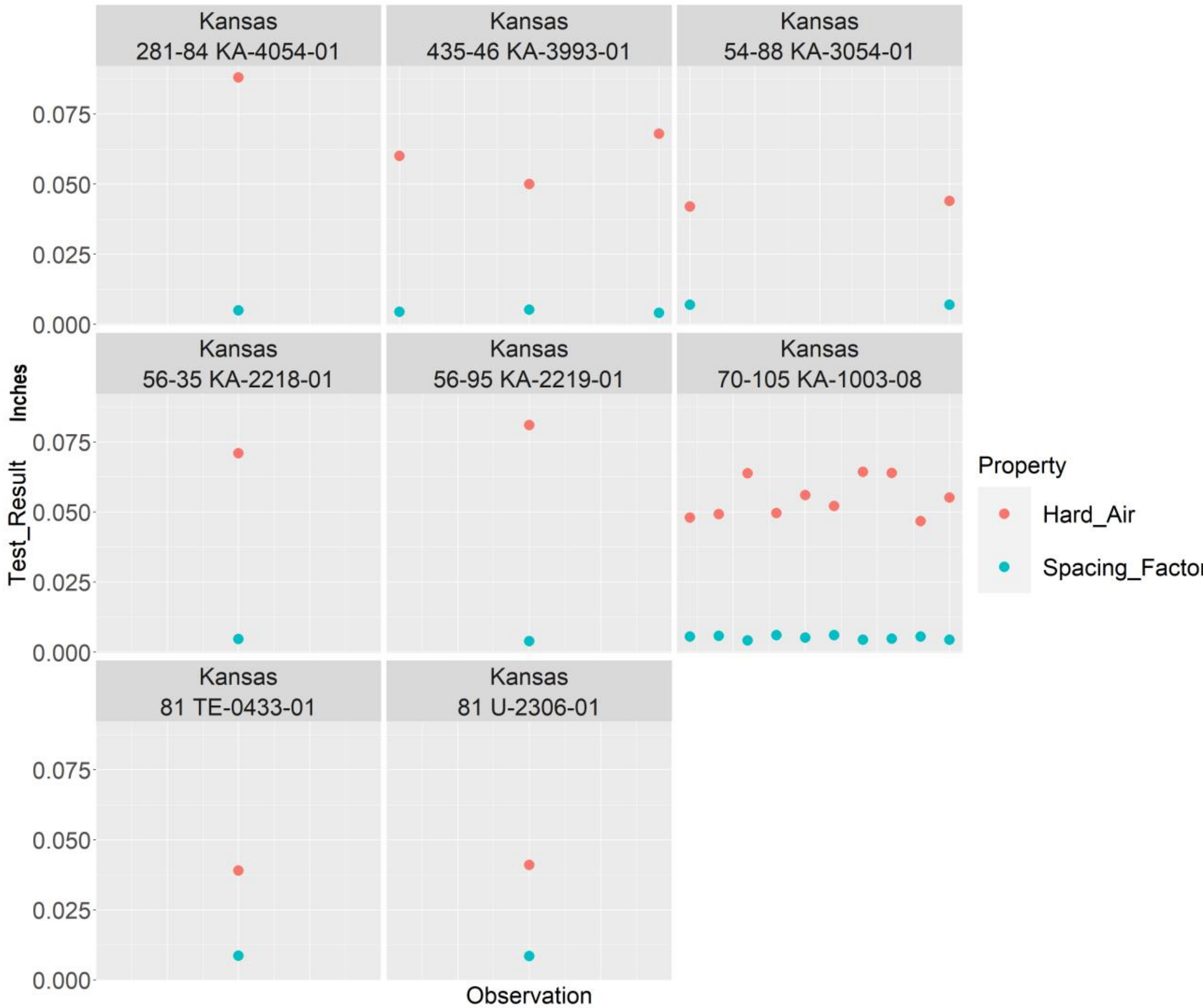

Figure 56. Hardened air and spacing factor

Figure 57 shows a scatter plot of hardened air results, and Figure 58 shows hardened air results based on various projects.

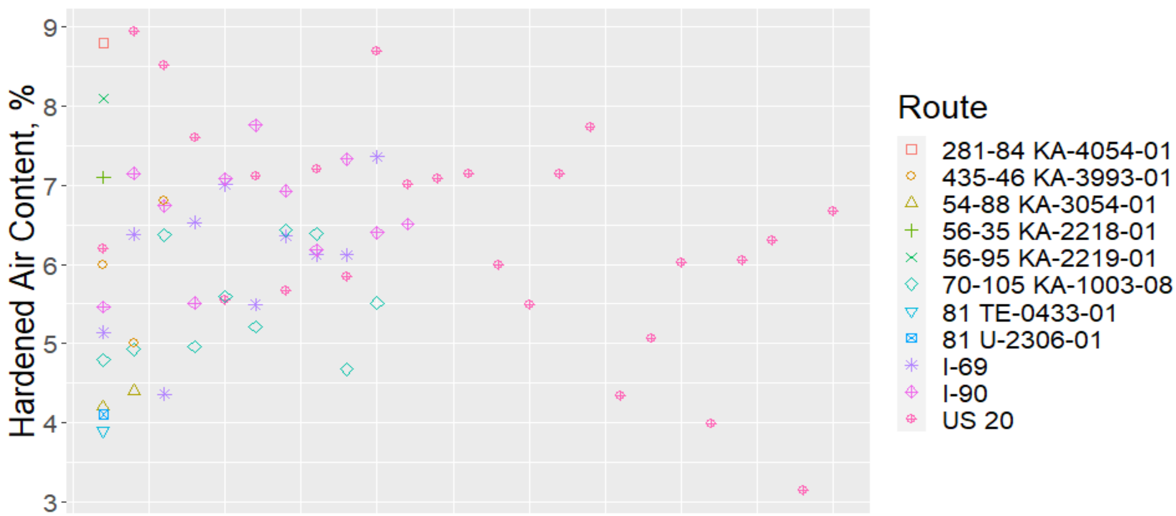

Figure 57. Scatter data for hardened air content

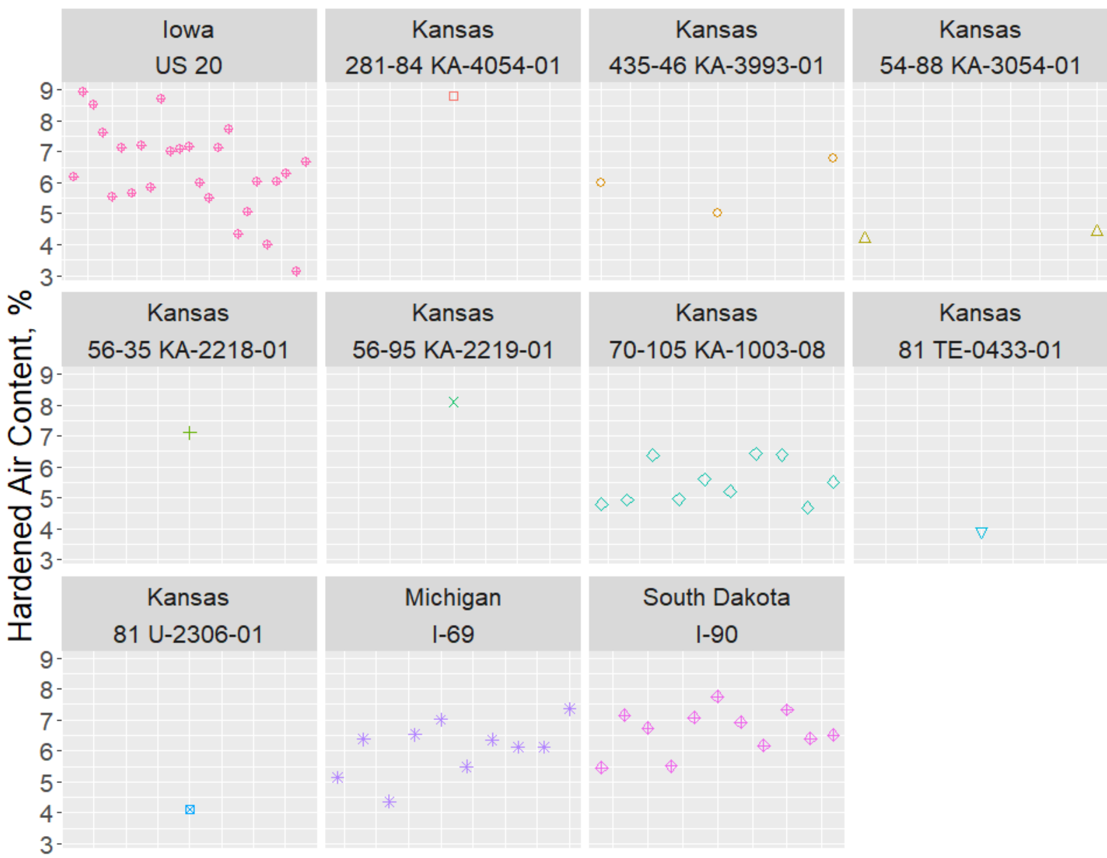

Figure 58. Hardened air content for various locations

Figure 59 shows box and whisker plots for hardened air on various projects.

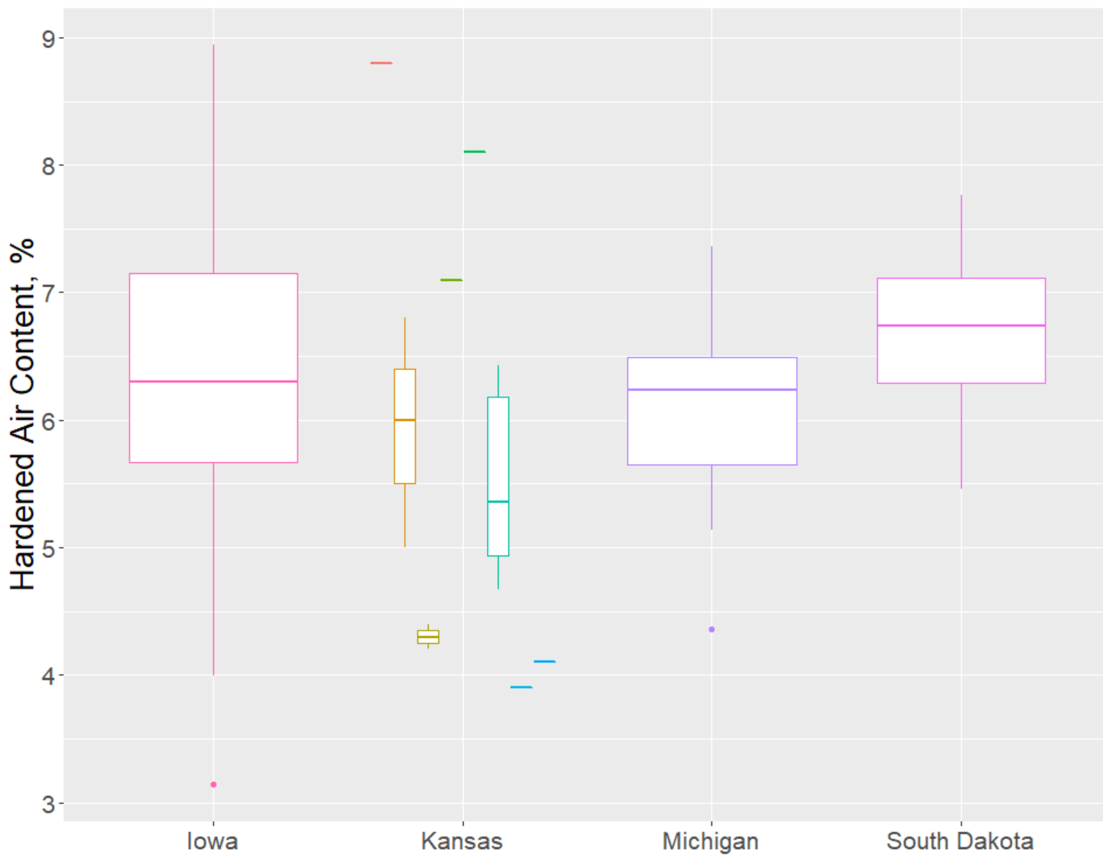

Figure 59. Box and whisker data for hardened air for various locations

Hardened Properties – Compressive and Flexural Strength Plots

Figure 60 shows 7-day, 28-day, and 56-day compressive strength results for various locations. The x-axis is the casting date.

Figure 60. Compressive strength for various locations

Figure 61 shows 28-day flexural strength values for a few projects, while Figure 62 shows a scatter plot of compressive strength values at various days for bridge projects (left) and pavement projects (right). Figure 63 shows the same data separated for various projects.

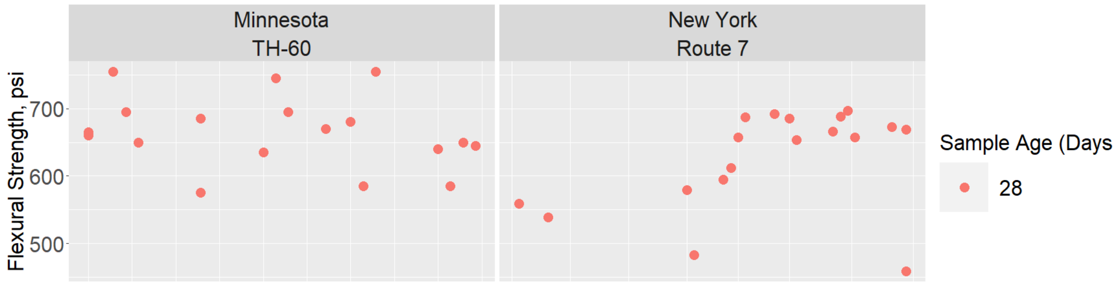

Figure 61. Flexural strength for various locations

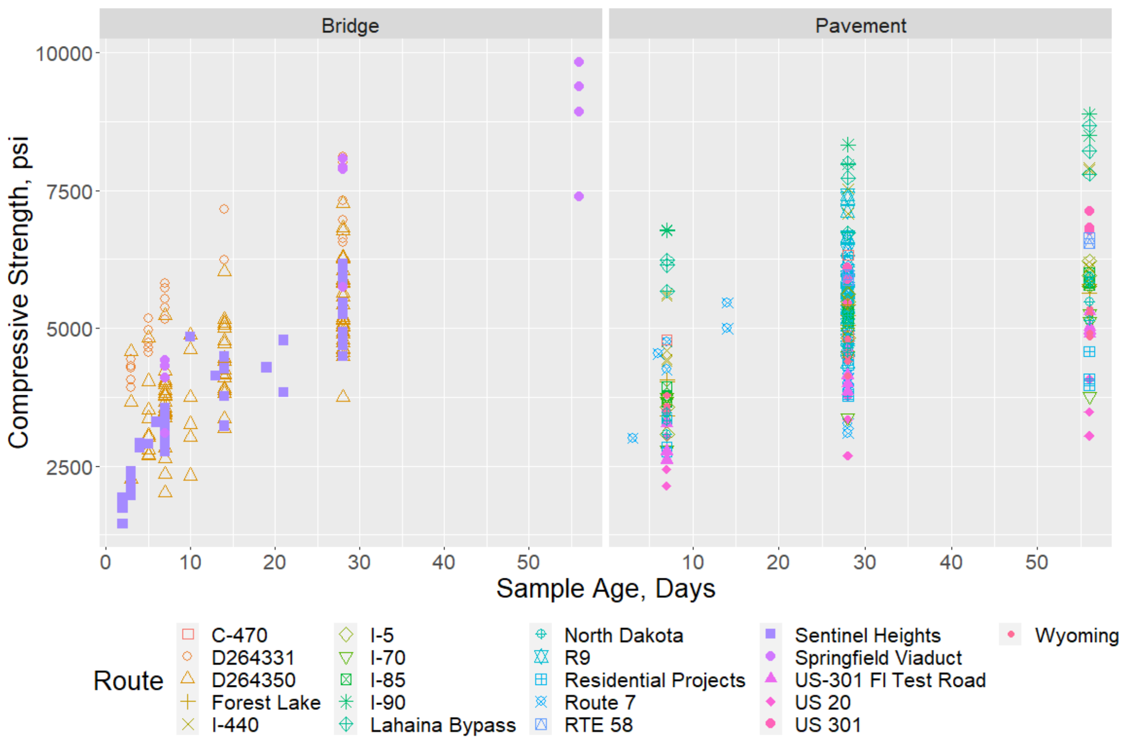

Figure 62. Scatter data for compressive strength for bridges (left) and pavements (right)

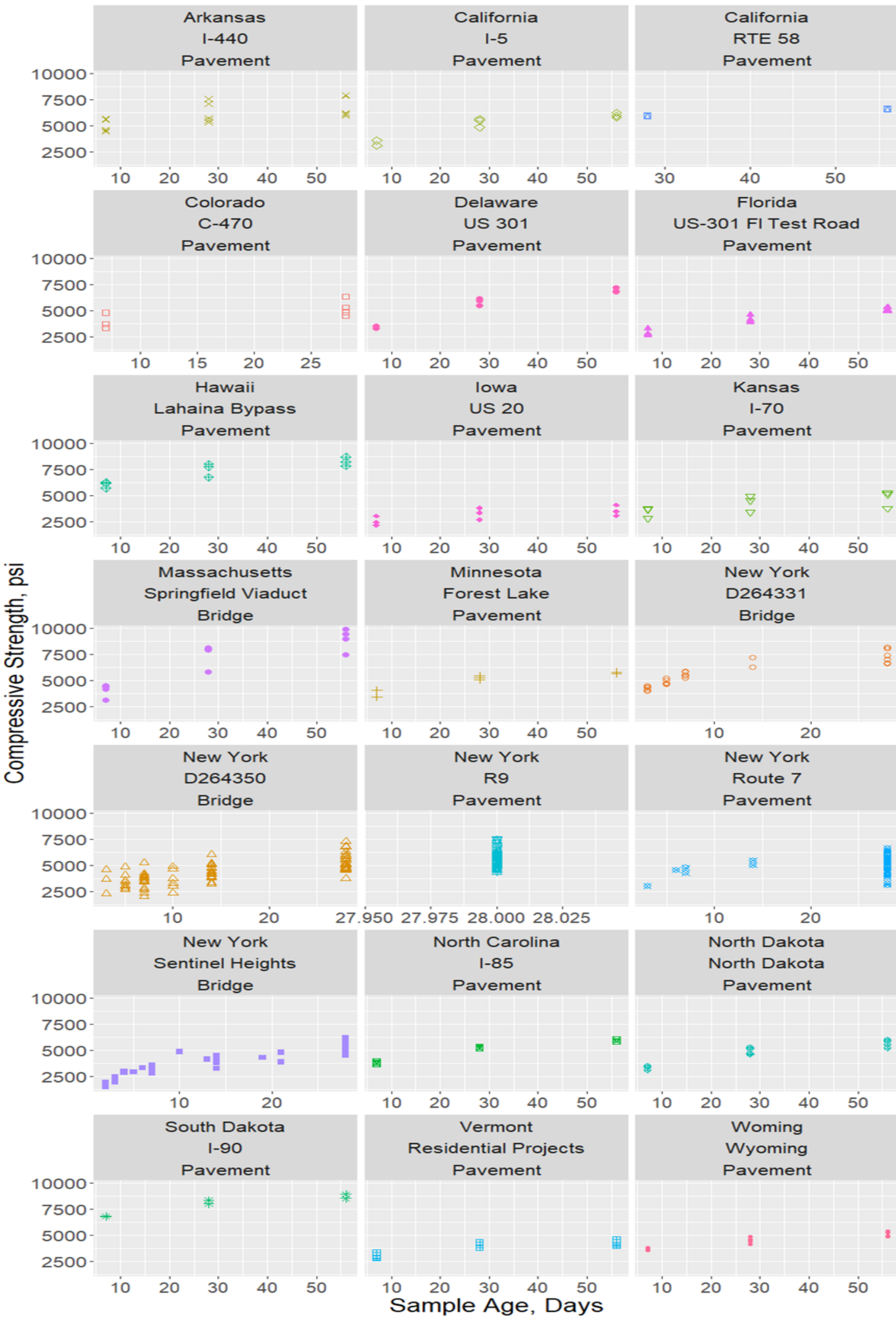

Figure 63. Compressive strength data for pavements at various locations

Figure 64 shows flexural strength scatter data versus sample age in days for a few projects, while Figure 65 shows the same data separated into two graphs.

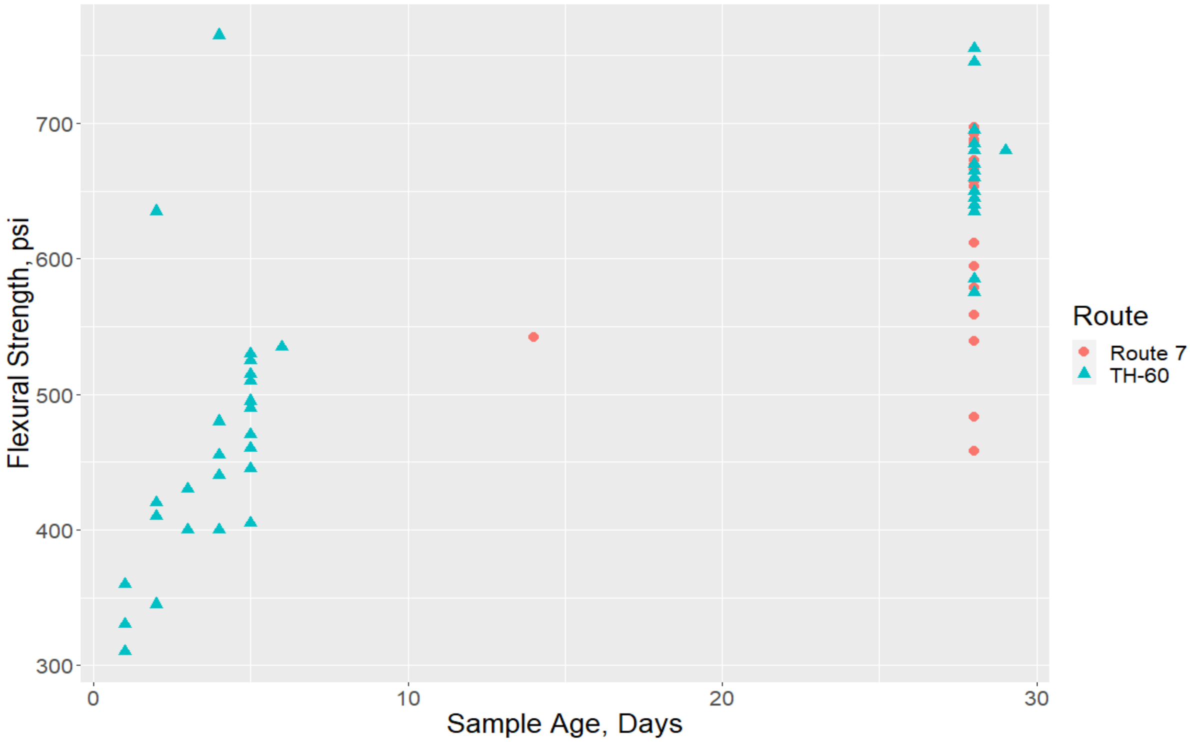

Figure 64. Flexural strength data for pavements

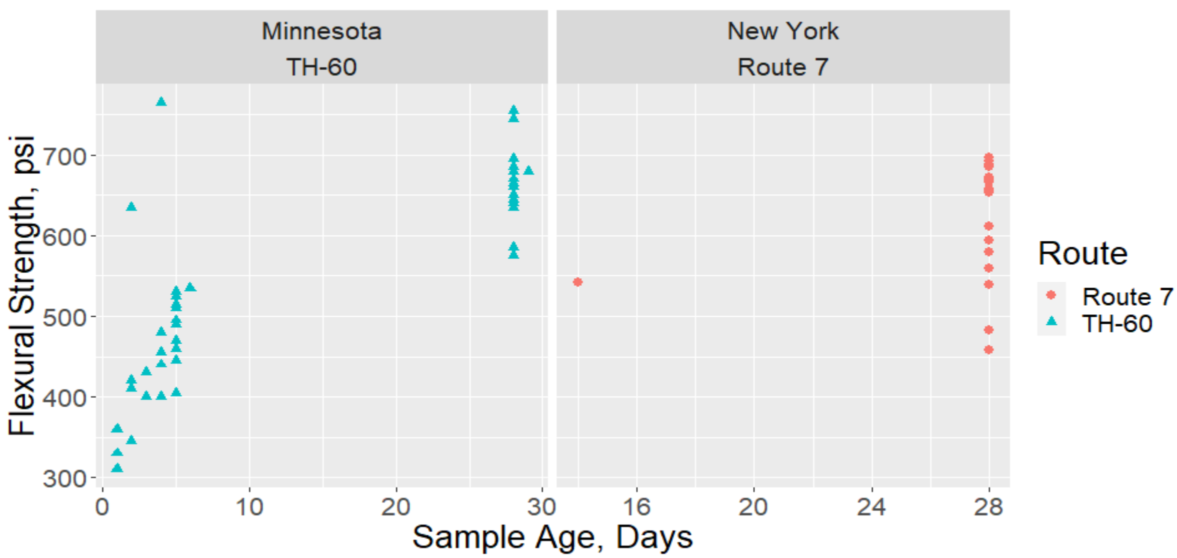

Figure 65. Flexural strength data for pavements at various locations

Figure 66 shows scatter data for resistivity versus compressive strength, with the y-axis having units of kOhm-cm. While one would expect that higher strength is consistent with higher resistivity, adding cement to a mixture does not inherently increase durability, and in many instances doing so may have the opposite result.

Figure 66. Scatter data for surface resistivity versus compressive strength

Hardened Properties – Formation Factor and Surface Resistivity Plots

Figure 67 shows the formation factor versus sample age in days. Although the data show a general increase in formation factor from left to right over time, the last three data points indicate potential erroneous test results.

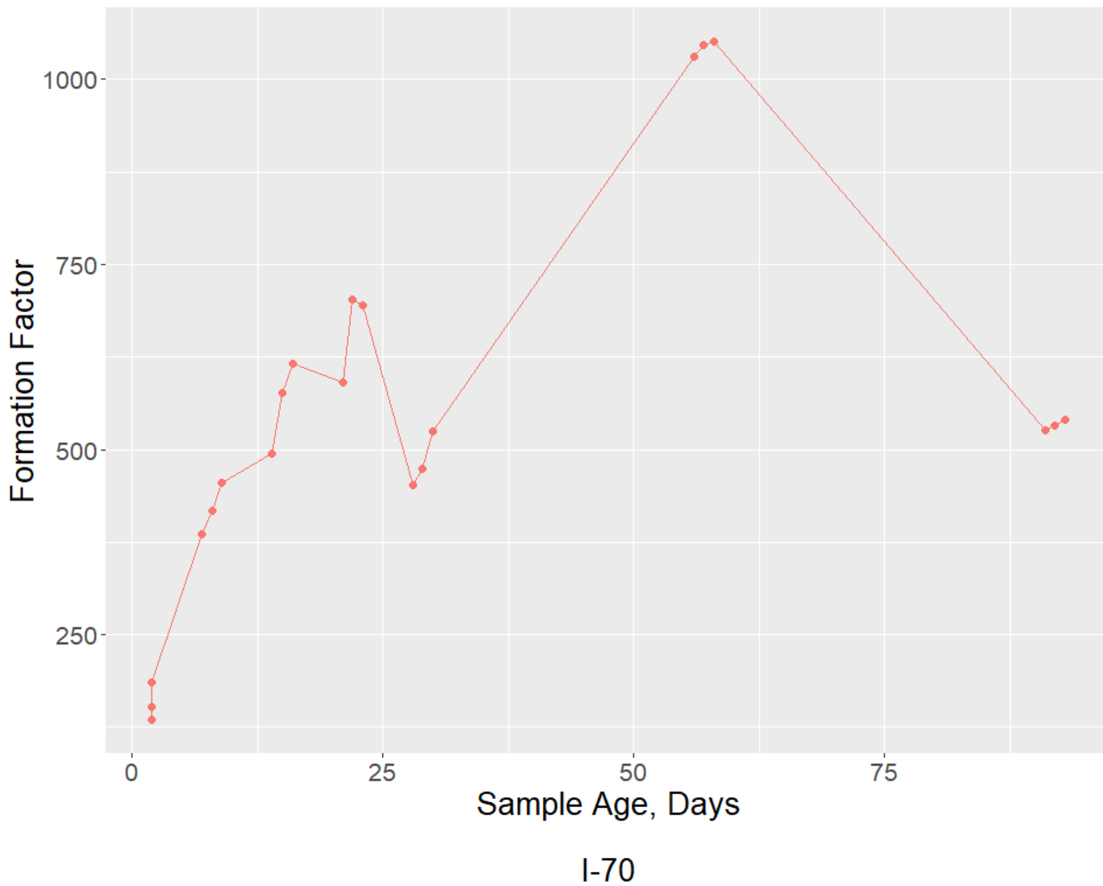

Figure 67. Formation factor versus age

Figure 68 shows the same data as Figure 66 separated into various projects. One conclusion that can be drawn is that the data from samples that underwent lime water conditioning exhibit higher variability than data from samples conditioned by other methods.

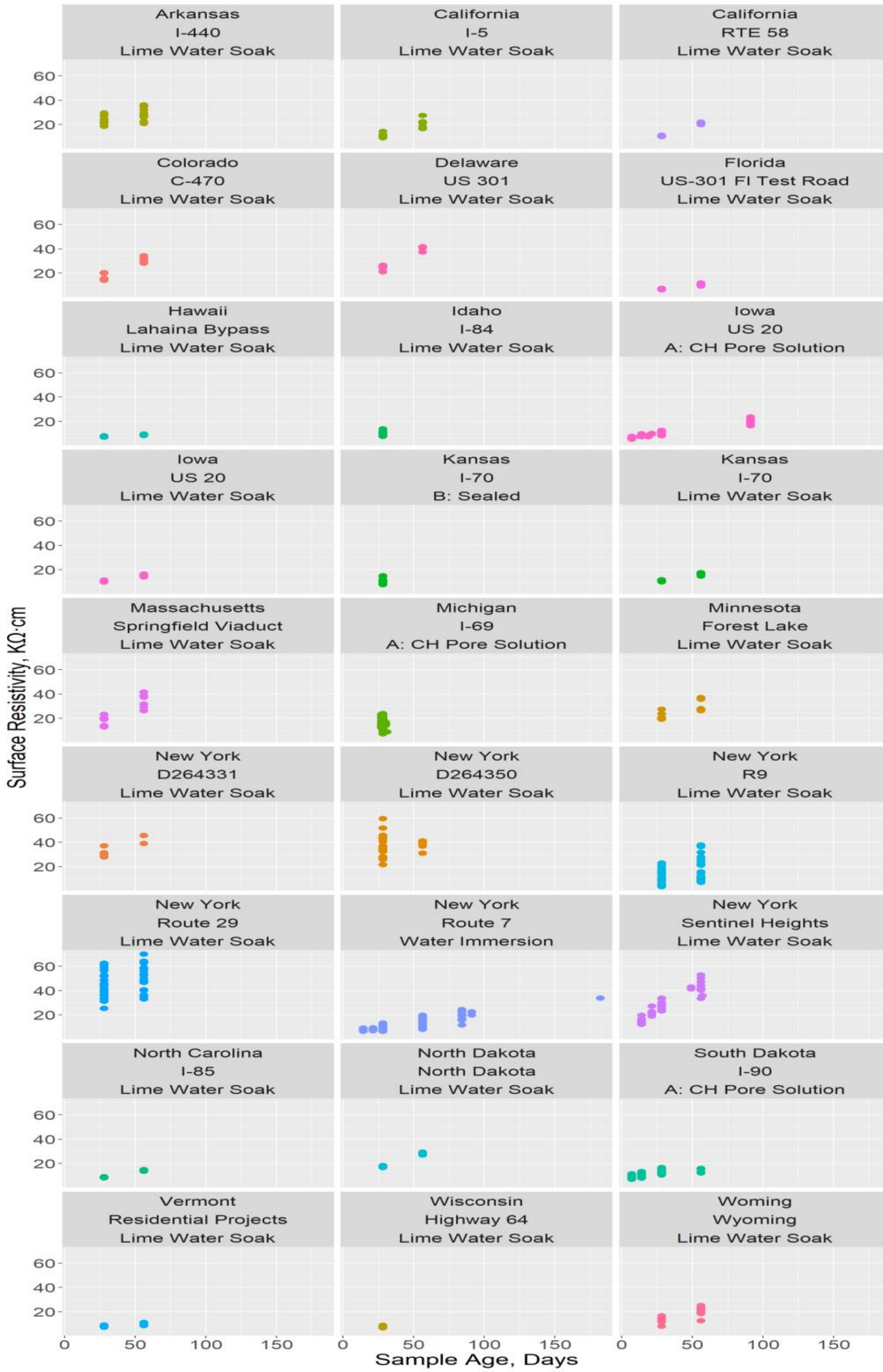

Figure 68. Surface resistivity versus age for various locations

Figure 69 shows resistivity data based on various conditioning methods. Again, it is evident that samples conditioned with lime water show a higher variability in the resistivity results.

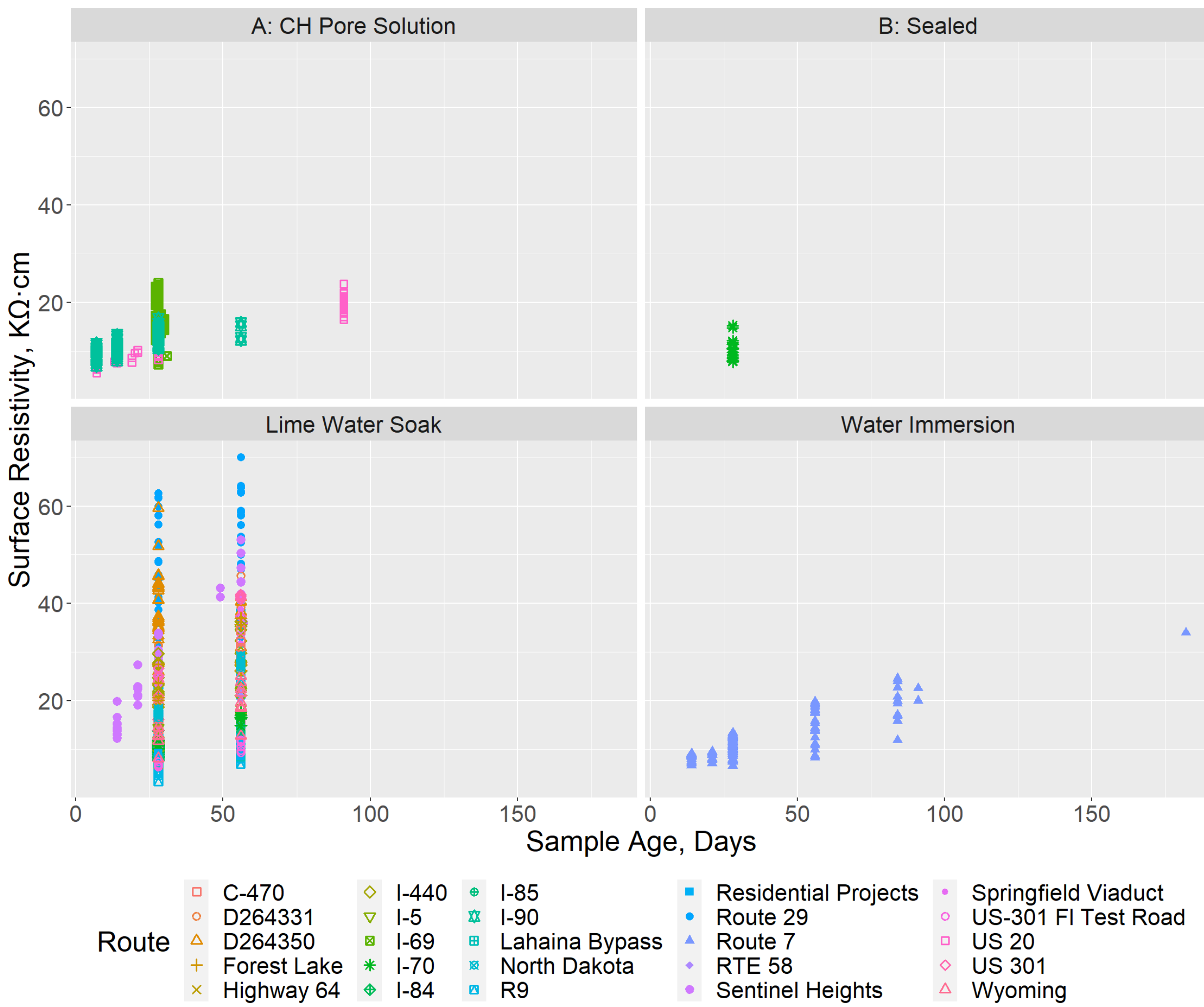

Figure 69. Surface resistivity versus age by various conditioning methods

Figure 70 shows box and whisker plots for the resistivity of samples conditioned by various methods.

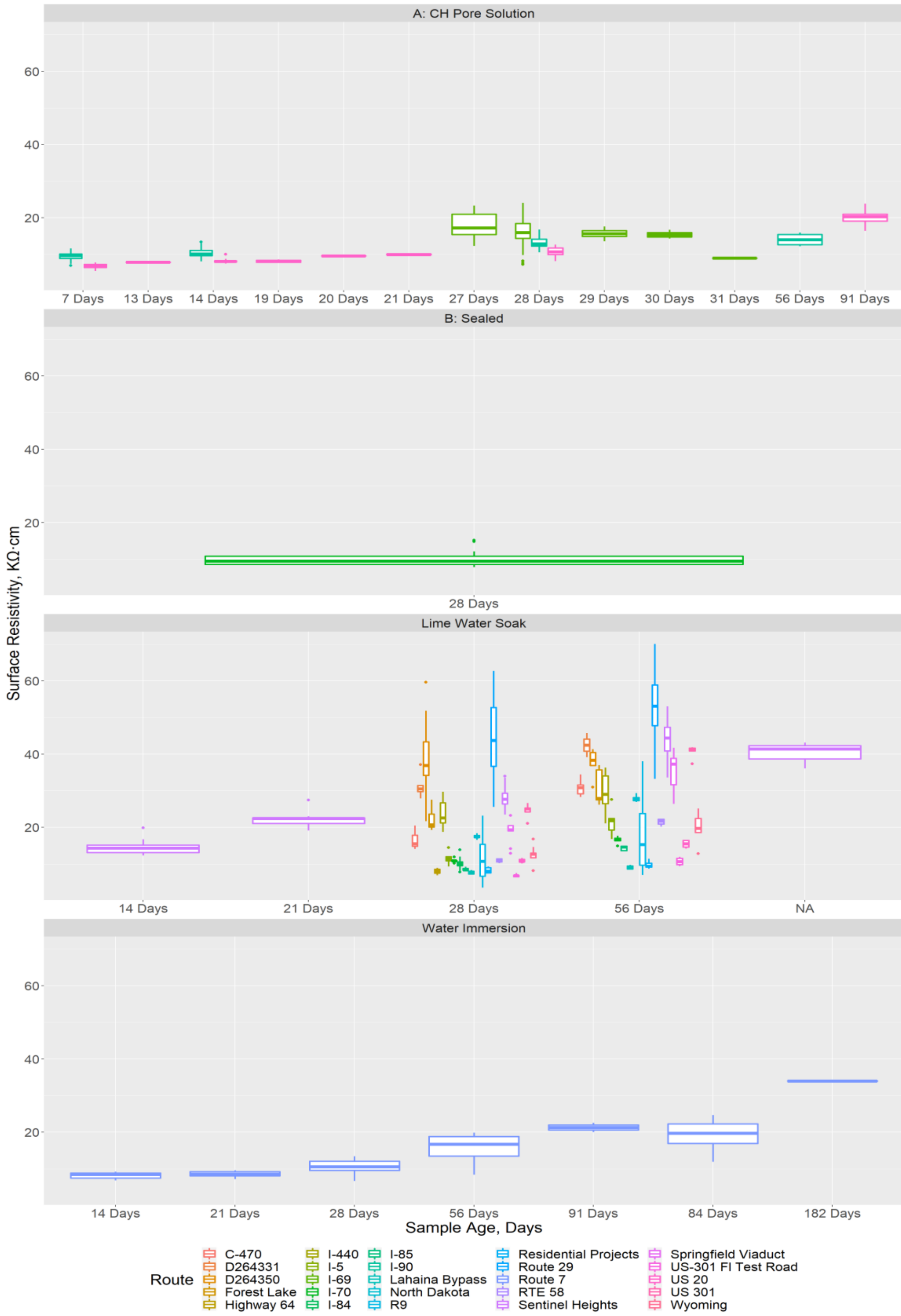

Figure 70. Box and whisker data for surface resistivity versus age for various conditioning methods

Figure 71 shows box and whisker plots for the resistivity of samples conditioned by various methods for various projects.

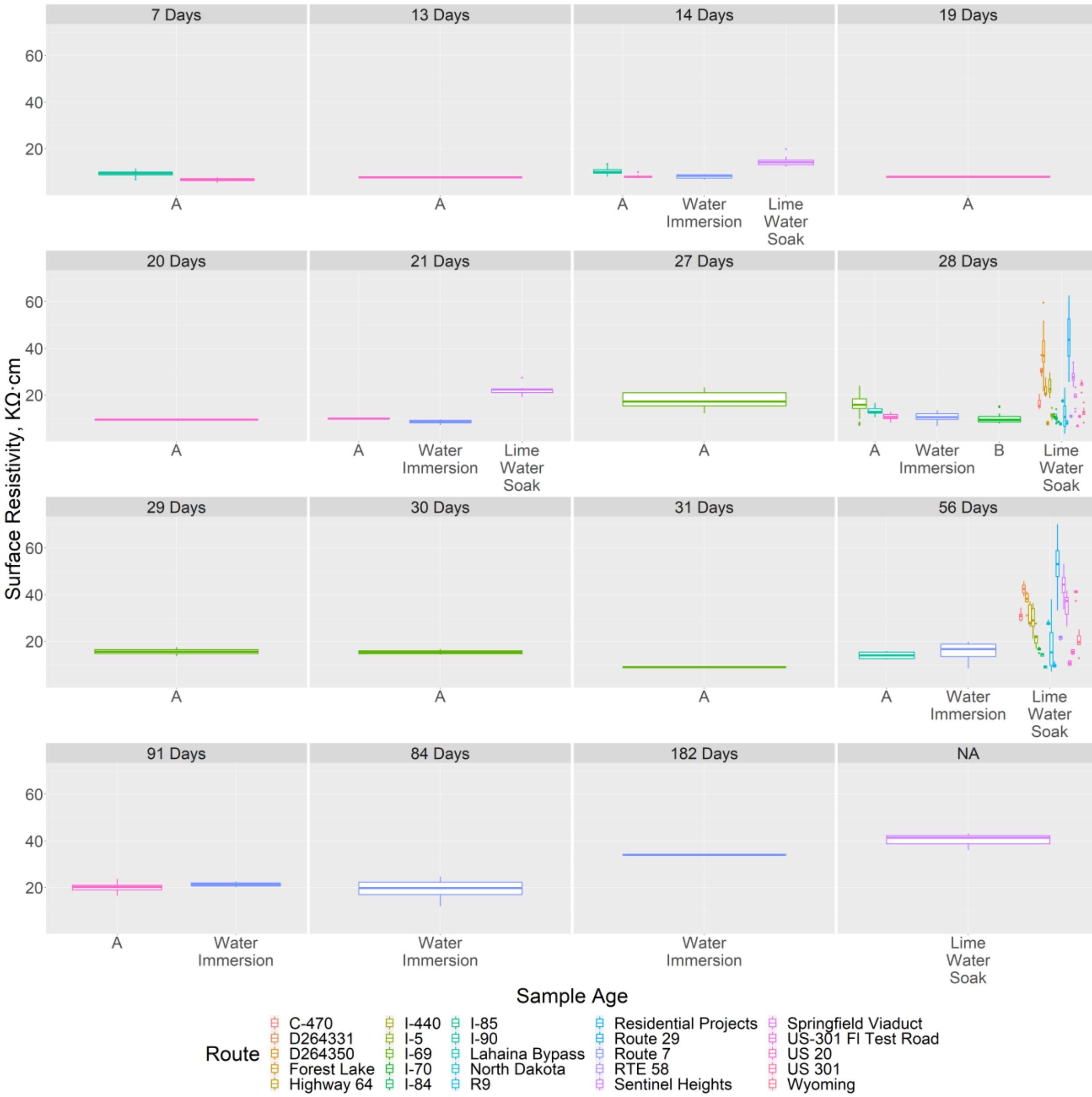

Figure 71. Box and whisker data for surface resistivity versus conditioning method at various ages

Figure 72 shows line plots for resistivity based on various conditioning methods. The data for the samples conditioned in lime water show high variability.

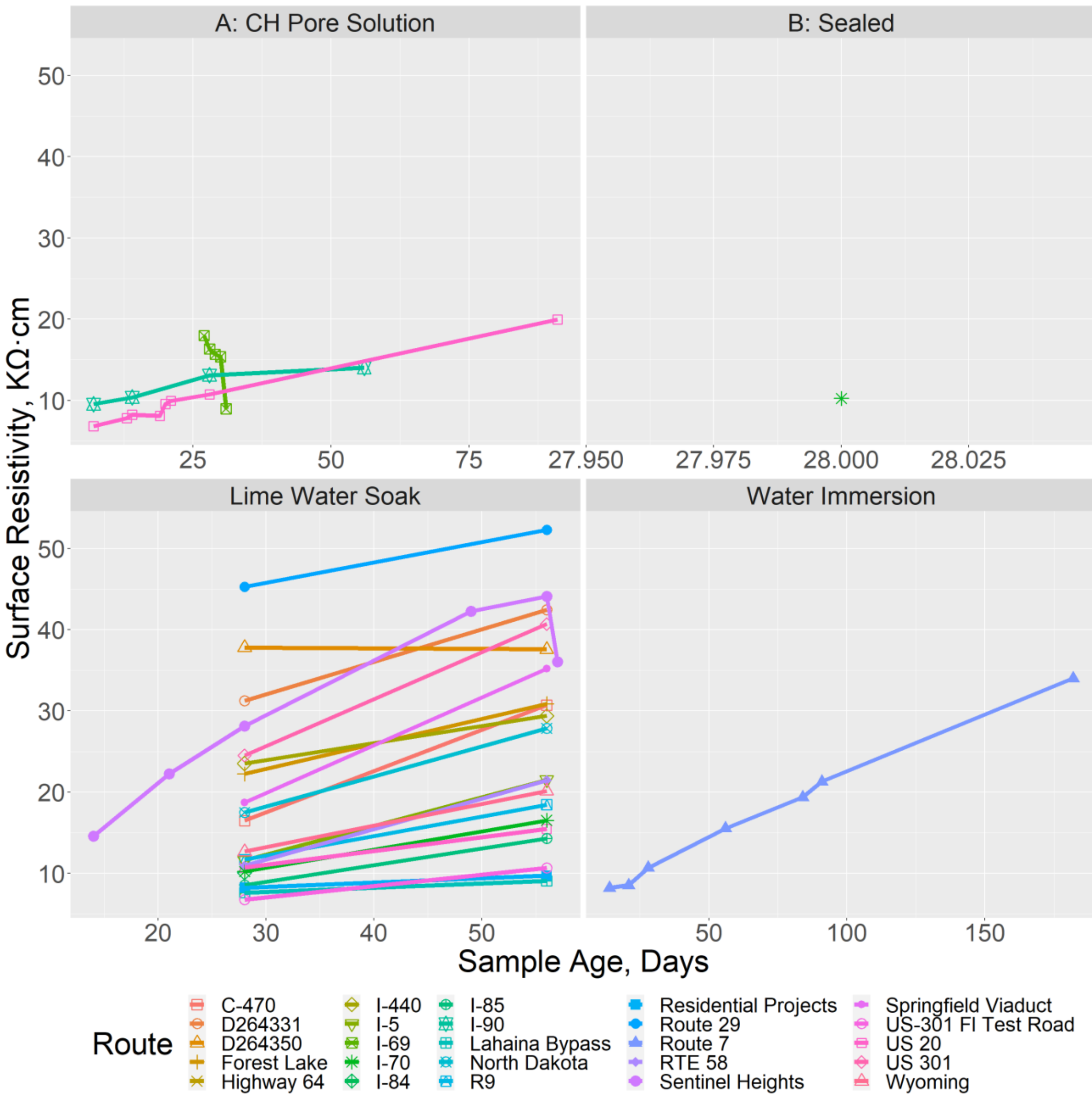

Figure 72. Surface resistivity versus age line data for various conditioning methods

Figure 73 shows the relationship between 56-day resistivity and w/cm ratio. The trendline shows that as the w/cm increases, the resistivity decreases.

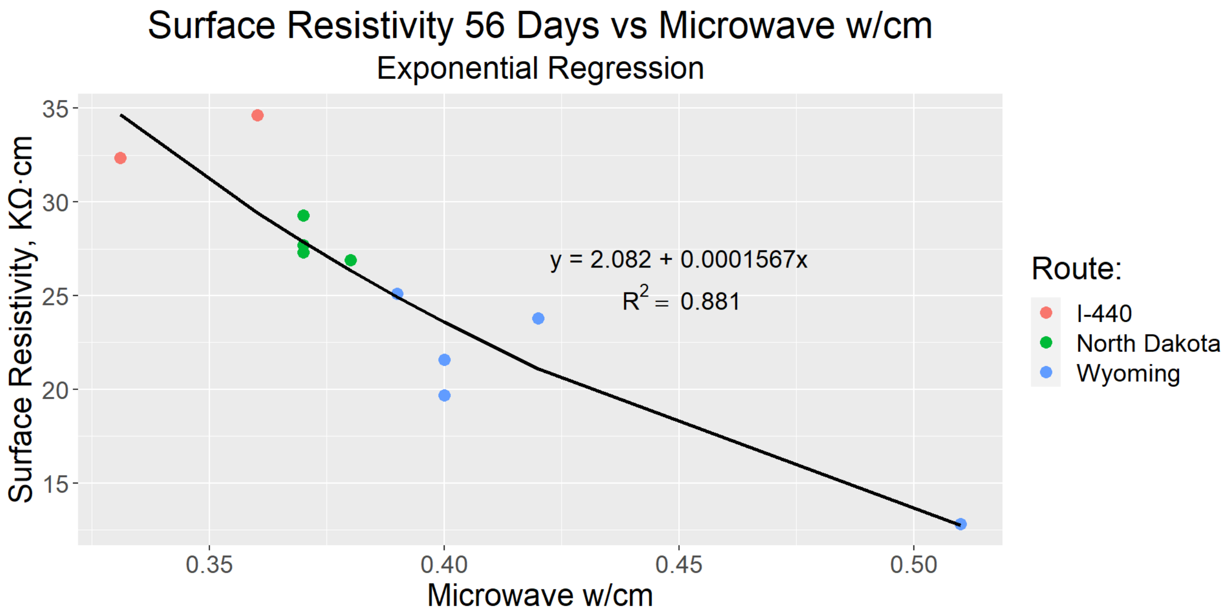

Figure 73. Surface resistivity versus microwave w/cm ratio

Table 16. Fresh properties test count

Number of Projects	40
Air content	37
AVA spacing factor	15
AVA specific surface	11
Box Test	2
Concrete temperature	34
Microwave w/cm ratio	6
Phoenix w/cm ratio	1
SAM	40
SAM air content	32
Slump	35
Unit weight	31
VKelly	2

Table 17. Hardened properties test count

Number of Projects	27
Coefficient of thermal expansion	9
Compressive strength	21
Flexural strength	2
Formation factor	1
F-T durability	1
Hardened air content	1
Maturity meter	1
Resist chloride ion penetration (RCP)	4
Spacing factor	2
Specific surface	1
SR at RCPT age	3
SR sample prep Option A	3
SR sample prep Option B	1
SR sample prep water immersion	2
SR sample prep lime water soak	22

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