Regional Rollout of the Super Air Meter (SAM) and Surface Resistivity (SR) for Performance Engineered Mixture Initiatives

RES2023-27

Final Report from the Materials Control Team | Tyler Lacy, PE and M. Jason Mellons, PE | December 31, 2024

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DISCLAIMER

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16. Abstract

Performance Engineered Mixtures (PEMs) have been the primary focus of concrete mixture research on a national level for years. Tennessee has facilitated several projects over the years to move facets of PEM forward, including *Enhancing Freeze-Thaw Resistance of Tennessee Concrete Mixes through Improved Air Void Testing (RES2020-09) and Determining Concrete Chloride Permeability Rapidly and Effectively (RES2013-41).* Both research projects proved the viability of the Super Air Meter (SAM) and Surface Resistivity (SR) devices to some degree. This project served as a continuation of the data collection to attain a broader understanding of concrete mixtures utilized in Tennessee statewide. The resulting dataset has assisted TDOT's Materials Control team in making determinations about where these devices the respective methods will fit in the sampling and testing program. This research project also served as an opportunity to develop and implement hands-on training with our Independent Assurance (IA) team members.

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Executive Summary

The following were the primary objectives of the research project:

- Develop/Provide training for all Regional Independent Assurance (IA) staff
- Collect dataset and evaluate SAM number and the resistivity measurement from concrete mixtures statewide
- Develop an acceptance program for Performance Engineered Mixtures (PEMs)
- Develop TDOT specifications and procedures to incorporate into the concrete and aggregate programs

Key Findings

The following were key findings determined during this research project:

- Training multiple individuals
    - Scaling up training with hands-on demonstration utilizing the developed course material is possible.
    - Data collection was diverse, covering a range of concrete mixtures and constituent materials. Targeted training gave each team the tools to accomplish this objective.
        - Materials Control (Statewide) reported 22 samples collected.
        - Field Services – Knoxville (Region 1) reported 26 samples collected.
        - Field Services – Chattanooga (Region 2) reported 22 samples collected.
        - Field Services – Nashville (Region 3) reported 31 samples collected.
        - Field Services – Jackson (Region 4) reported 9 samples collected.
    - Annual industry meeting agenda will provide the information and direction of TDOT projects that have concrete bridge decks.
- Acceptance via a performance basis is applicable, primarily for resistivity testing
    - Class D concrete, Class DS concrete, Class PEM concrete, and Class L concrete mixtures could share the same case-by-case designations. Class PEM concrete and Class L concrete mixture criteria can be discussed and established as the project designates. Class D concrete and Class DS concrete for use on concrete bridge deck application will require resistivity testing for TDOT's Acceptance Program.
- Verification testing for all concrete mixtures, with notable exceptions (SAM for lightweight, non-structural, etc.)
    - SAM (exception Class L) and resistivity testing results will be performed during the trial batching and submitted with the Concrete Mixture Design Template for approval and documentation.
    - On-going systematic data collection. We will continue adding data into our records.
- Visual trial batching tools can be developed
    - Concrete Mixture Design Template tools will serve as a visual for designers.
    - Develop an area within the trial batch data for testing results for SAM and resistivity results.

Key Recommendations

A short summary with potential benefits of the recommended course of action:

- Trial batches for Class D concrete, Class DS concrete, Class PEM concrete, and Class L concrete should be accompanied with SAM data (exception for Class L) and resistivity data for the resulting cylinder set(s).
    - Continual trial batching and project verification of the concrete mixture(s) will provide confidence in the ability to produce in a consistent fashion to meet project requirements and specifications.
- Resistivity testing should be conducted on Class D concrete, Class DS concrete, Class PEM concrete, and Class L concrete as acceptance criteria, where applicable.
    - Introduction into the Quality Acceptance Program will allow for a measurable method of proving a less permeable and more durable concrete mixture for use on TDOT's projects.
- The SAM method should not be listed as an acceptance test at this time.
    - Due to the inconsistency of results in comparison to national research studies, it was determined that an acceptance test criterion could affect production efforts with little guidance for correction. Field experience revealed equipment operation challenges that could be addressed with more widespread training efforts.
    - Corrective actions would have to be developed to guide a concrete producer of how-to bring SAM numbers within a range that was acceptable.
- Quality Assurance Program should be modified to ensure resistivity is checked on a regular frequency.
    - Introduction of smaller frequencies will provide the confidence of the concrete mixture(s) to consistently meet project requirements and specifications. Once confidence in the process is established longer frequencies can be specified.

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Chapter 1 Introduction

PEM initiatives have been the primary focus of concrete research for some time. To date, PEM has targeted projects that further the use of concrete pavements, which does not have a direct impact on the Tennessee Department of Transportation's (TDOT) concrete program. TDOT has partnered with multiple state universities over the past ten (10) years to build knowledge on the use and implementation of emerging PEM testing requirements. Two (2) research projects concluded over the years support the use of emerging technologies in the field of concrete mixture performance.

RES2020-09 titled *Enhancing Freeze-Thaw Resistance of Tennessee Concrete Mixes through Improved Air Void Testing* [(1)] conducted by the University of Tennessee – Knoxville (UTK). RES2020-09 investigated the use of the sequential pressure method, using the super air meter (SAM), described in AASHTO T 395 [(2)] on Tennessee concrete mixtures. This research project introduced an understanding of the use of the SAM on concrete mixtures within Tennessee utilizing a laboratory approach. A challenge of a limited dataset versus the initial proposed target made implementation of a statewide program difficult. Timing of this research project led to a biased focus on the eastern regions of Tennessee. Therefore, RES2023-27 focused efforts into data collection statewide on the field sampling and testing opportunities.

RES2013-41 titled *Determining Concrete Chloride Permeability Rapidly and Effectively* [(3)] conducted by Tennessee Technological University (TTU). RES2013-41 investigated hardened concrete permeability. Rapid Chloride Penetration Testing (RCPT) [(4)] is an accepted method for determining permeability susceptibility. However, it is costly and highly variable upon repeat attempts. During this study, the surface resistivity (SR) test method detailed in AASHTO T 358 [(5)] was determined to have similar results to the RCPT for a fraction of the time and cost. This test allows TDOT to quickly test the resistance as a means of determining permeability of the concrete structure. More data is necessary for concrete mixtures statewide to determine acceptance values for recommended resistivity values in combination with the results of RES2013-41.

TDOT's partnership with internal and external customers (departmental, contractors, materials producers, the public, etc.) is built on good stewardship and transparency. The "data driven" results ensure good decisions and sound operational direction for the transportation system. TDOT's Strategic Direction [(6)] outlines the mission to provide a safe and reliable transportation system that supports economic growth and quality of life. With the vision stating the commitment to excellence in managing and improving the state's transportation system, TDOT is committed to the task of investigating and implementing innovation that can serve our customers while providing a safe roadway. These previous research efforts gave TDOT valuable information; however, these datasets were limited in scope and not a conclusive basis for launching programmatic changes. These efforts did conclude that the SAM and SR devices would be an integral part of ensuring a performance-based specification was achievable. Due diligence in the way of further investigation was a vital part of setting realistic criteria for each of these methods.

RES2023-27 was necessitated by the wide array of different constituent materials available to concrete producers statewide. No research project at the time of the kickoff had endeavored the capture of a full system investigation into TDOT's concrete program. Facilitating the growth of the statewide fresh and hardened property dataset including detailed analysis was a critical component to incorporating these performance-based test methods into TDOT's acceptance and verification programs.

In 2024, the concrete industry is on the verge of its next frontier. The state of the practice is changing rapidly for all facets of the concrete industry. Many producers are currently investigating the use of alternative materials – ranging from new recycling sources to alternative cementitious materials targeting carbon neutrality. The cement industry has one of the most ambitious climate goals in domestic market with a target of net zero carbon emissions by the year 2050 [(7).] The shift will likely require changes to the TDOT Standard Specifications [(8)] [(9)] for concrete to make acceptance and verification feasible while continuing to satisfy the requirements of Title 23, Part 637 of the Code of Federal Regulations [(10)]. Changes will likely specifically target replacing the traditional prescriptive methods with performance-based methods.

Chapter 2 Literature Review

This section reviews the theory behind the PEM for estimating the durability of concrete. The primary focus of this chapter will be on the SAM and SR test methods, to establish a performance-based acceptance and/or verification procedure monitoring the durability of concrete for TDOT.

2.1 Performance of Tennessee Concrete Mixtures

As pooled-fund members of *Performance Engineered Concrete Paving Mixtures (TPF-5(368))* [11]. TDOT has been actively involved in reviewing national research efforts made in the areas of PEM. One trend that has stifled the progress in implementing PEM into TDOT's concrete program is that the national efforts focus primarily on concrete pavement and the refinement of pavement practices. While indirect benefits such as the standardized test methods are developed in this process, TDOT does not achieve data driven recommendations that directly apply to the TDOT Concrete Program. To make data driven decisions, an increased effort was needed to examine structural concrete within TDOT's program. This research project applied the standards used by academia, industry, and other state DOTs to form a TDOT program based on structural concrete mixtures statewide.

The SAM number, which is captured during the fresh property state, is a key component in understanding the performance of the hardened concrete. RES2020-09 led to recommendations regarding an acceptable SAM number for TDOT's concrete mixture classifications observed. While helpful, these recommendations were limited in scope. Without further data collection it would prove difficult to determine if all concrete mixtures statewide were capable of consistently meeting the recommendations. This is due in large part to questions regarding localized geological formations causing a wide diversity of aggregate availability.

RES2013-41 concluded that the SR is a viable alternative to RCPT in a laboratory setting. Additional data collection was necessary to determine if the recommendations TTU provided are reflective of the concrete program statewide, with a primary focus of ensuring the resistivity data trends transfer to field collected cylinders.

2.2 Tennessee's Dataset Considerations

A comprehensive investigation was initiated to understand the basic goals of this research project. Tennessee's geology differs drastically across the state. Regional availability of aggregates was one of the single largest factors that differentiates the constituent material selection. The western region of Tennessee between the Mississippi River and Tennessee River is composed predominantly of alluvial deposits containing gravel. The central region spanning from the Tennessee River to the Appalachian Mountains is predominantly limestone. The eastern region along the Appalachian Mountains, between Bristol and Chattanooga, has many granite sources available. Further adding to the complexity, two (2) distinct fine aggregate sources are utilized in Tennessee, natural and manufactured sand. TDOT requirements for natural sand to be used in wearing surfaces ensures an adequate amount of silicious material is present for frictional characteristics, whereas manufactured sand is utilized in many designs to achieve higher compression values. To ensure statewide applicability of the standards, many designs were collected to ensure that these variant materials were adequately represented.

Cement was another focus of initial investigation. Domestic and foreign cement mills have been transitioning from the Type I cement designation in AASHTO M 85 (12) to ensure that they are on track to meet 2050 carbon neutrality goals. As of 2024, the transition to the Type IL cement designation in AASHTO M 240 (13) has been completed for all Tennessee mills and terminals. The net impact nationally has resulted in approximately an 7-9% reduction in carbon emissions in the cement industry (14). This is a notable impact since the cement industry is one of the largest carbon emitting entities in the United States, mainly attributed to the scale of production. (15) At the kickoff of this research project, Type I cement was still widely available and has been captured in the dataset. To present, Type III cement remains the predominant choice for many prestressed applications, which were also collected into the dataset.

Another investigation focused on the use of supplementary cementitious materials (SCMs), including regional availability. Both Class C fly ash and Class F fly ash remain largely available in the Tennessee market. The use of these constituent materials versus cement only designs was to be closely monitored. This was necessary since both concrete mixture variants were widely selected regardless of concrete mixture classification and use cases in the database.

Admixtures were to be tracked during the collection of the concrete mixture design files (indicating potential use) to the batch tickets (indicating the selected dosage) over the course of the research project. TDOT allows approves designs on an annual basis, which results in concrete mixture designers listing all possible admixture combinations. Batch ticket information was deemed critical for use in validation of the mixtures, coupled with the tolerances on all other constituent materials.

Chapter 3 Methodology

3.1 Overview of Goals

The goal of this research is to develop knowledge, procedures, and specifications that allow TDOT to ensure concrete mixtures are providing equal or better performance while increasing the benefit in a measurable way. There is a potential cost benefit to contractors and producers actively utilizing available constituent materials in a more efficient way. With a focus on efficient design practices, resulting concrete mixtures may achieve all design targets while experiencing an overall reduction in cement paste, creating a more economic concrete mixture in the process. With paste reduction there is also the environmental incentive of reducing carbon emissions overall as cement manufacturing is a major carbon contributor [(15)] due to production volumes.

With PEM concrete designs becoming prevalent nationwide, TDOT's need to enhance understanding of emerging test methods along with regional capabilities in the way of monitoring the properties and performance of concrete mixtures is critical. This research project allowed TDOT to acquire both the required tools and develop the guidance, to enhance the monitoring of production concrete mixture performance.

Special attention was needed to ensure that the coverage of constituent materials across the state were tested. To achieve this, eight (8) of TDOT's concrete mixture classifications were utilized during the data collection phase. Due to the variety in concrete mixture classifications and the designed intended use, there were a variety of constituent materials captured in this research. Multiple aggregate sources included: limestone, gravel, and granite for coarse aggregates as well as natural sand and manufactured sand for fine aggregates. Multiple cement types included: Type I cement, Type IL cement, and Type III cement. Several concrete mixtures were designed using cement only while other designs utilized SCMs – mainly Class C fly ash and Class F fly ash. A limited number of concrete mix designs utilized Slag 100 as the SCM were also captured in this dataset.

3.2 Training Program

A training program was developed to satisfy two goals: 1) To develop a capable workforce to engage in data collection activities, 2) To have a baseline presentation for a future training and development opportunity for the rollout of the field acceptance and verification program.

To achieve the first goal, TDOT's Materials Control team developed a step-by-step presentation detailing the SAM and the SR test methods. Using the AASHTO T 395 [(2)] and AASHTO T 358 [(5)] documents respectively, the steps were described in order with photos to assist in the visual learning of each of the test methods – see Appendix A. Following each AASHTO test method lecture in the slides, TDOT's Field Services personnel were instructed to interact through hands-on training by conducting tests on each device. This hands-on demonstration required surrogate cylinders as test specimens for the SR testing, while still in the classroom setting. Following completion of the SR trials, bagged concrete was mixed to simulate field conditions and allow personnel to trial the SAM method by sampling and testing in accordance with the presented course material.

The course material was administered four (4) times – once per regional Field Services Materials and Tests office. This course used a "Train-the-Trainer" approach, presenting the material to the Field Services Team Lead as well as three (3) senior staff members per region. This also resulted in a knowledge base at the supervision level to ensure the data collection for the research project was completed accurately.

3.3 Data Collection

To keep data formatted in a similar fashion, the decision was made to utilize Microsoft Forms, which was covered during the local training event at each region. Two (2) QR codes – shown in Appendix B – were created and distributed: the first QR code directed the individual to the fresh property collection form for the SAM number and other fresh property entries; the second QR code directed them to the hardened property collection form for resistivity data as well as compression data for each pair of cylinders. The latter QR code was accompanied by a compass to assist in marking the 90-degree locations for completion of the SR testing. Once all four (4) Field Service locations received the applicable training, those offices were instructed to begin data collection on June 1st, 2023. Data collection was concluded on September 30th, 2024.

Following a fresh property data entry, TDOT's Materials Control team would save a copy of the applicable concrete mixture design spreadsheet originally submitted by the producer as well as transfer the applicable data into the master data sheet for analysis. The Field Services team member would also upload a copy of the batch ticket, if applicable. These tickets were used to transfer material usage into the master data sheet for validation purposes.

3.4 Data Analysis

The data analysis was all completed from the master data sheet. It was necessary to split the data into a few categories to complete this step. A master dataset was filtered via dropdown columns to determining the occurrence of trends. There was a large amount of raw data coupled with a wide variety of concrete mixture classifications, constituent materials, the variability of volumetrics, and the regional specific design parameters. The use of data filters, hypothesized impactful graphs, and trial checks were used to determine trends.

Aggregate data was handled separately. It was collected from all concrete mixture design spreadsheets that were collected over the course of the research project. This data was processed using both the Tarantula curve method (16) and the revised Shilstone chart (17) (18) which requires the use of the coarseness factor and workability factor. Both methods have their merit. The Tarantula assists the designer with a visual that can be used to address individual sieve sizes. The revised Shilstone chart showcases the workability of the concrete mixture and indicates which adjustments may be necessary if the concrete mixture is not optimized.

For the Shilstone method, aggregate data plotted on the revised Shilstone chart was characterized using zones, defined via the following criteria:

- Zone I denotes a gap-graded concrete mixture
- Zone II denotes an optimal concrete mixture
- Zone III denotes an optimal SCC mixture [1/2" (12.5 mm) aggregate and smaller]

- Zone IV denotes a concrete mixture that it too fine
- Zone V denotes a concrete mixture that is too coarse

To determine the location of each data point and to analyze the grading of each concrete mixture, the following equations were utilized:

Equation 1 $$\boldsymbol{Coarseness\ Factor\ (CF) = \left(\frac{R}{X}\right) \times 100}$$

Equation 2 $$\boldsymbol{Workability\ Factor\ (WF) = P + 2.5\left(\frac{(C-564)}{94}\right)}$$

where R = Cumulative percent retained on the 3/8" (9.5 mm) sieve

X = Cumulative percent retained on the #8 (2.36 mm) sieve

P = Percent passing the #8 (2.36 mm) sieve

C = Total cementitious content (hydraulic cement plus SCMs)

Data entered in Equation 1 determines the coarseness factor is expressed as a percentage of the ratio acquired by comparing the cumulative percent retained on the 3/8" (9.5 mm) sieve to the cumulative percent retained on the #8 (2.36 mm) sieve. The data entered in

Equation 2 determines the workability factor is controlled by the percentage of fine particulates passing the #8 (2.36 mm) sieve in the aggregate blend as well as the total cementitious content of the concrete mixture.

Chapter 4 Results and Discussion

The data analysis described in the methodology was categorized into the following format: that pertaining to aggregate materials, data pertaining to the SAM numbers, data pertaining to the resistivity values, and additionally data validation checks to ensure batched material was accurately depicted by previously shown figures. The results were categorized like this to show how each of the topics result in specification updates.

4.1 Aggregates

The aggregate blend for all concrete mixtures collected in this study were compared to both the Tarantula curve and the revised Shilstone chart comparing the concrete mixture coarseness and workability. These methods assist concrete mixture designers with creating an aggregate blend that is workable for field production. These also serve as a basis for quality control practices.

4.1.1 Tarantula Curve

Regarding the Tarantula curve, the average trends for each concrete mixture design classification were plotted on metric, 0.45 power chart. In Figure 4-1, the trends indicated that the average Class A concrete, Class AS concrete, Class D concrete, and Class DS concrete mixtures statewide would all fail to meet Tarantula curve requirements. Utilizing a two-aggregate system consisting of one (1) coarse aggregate and one (1) fine aggregate, each concrete mixture would miss the Tarantula curve requirements for the ½" (12.5 mm) sieve [denoted by 3.116] with a certainty. These concrete mixtures represent most of the dataset, with ninety-two (92) of the one-hundred and ten (110) entries representing one of these four concrete mixture classifications.

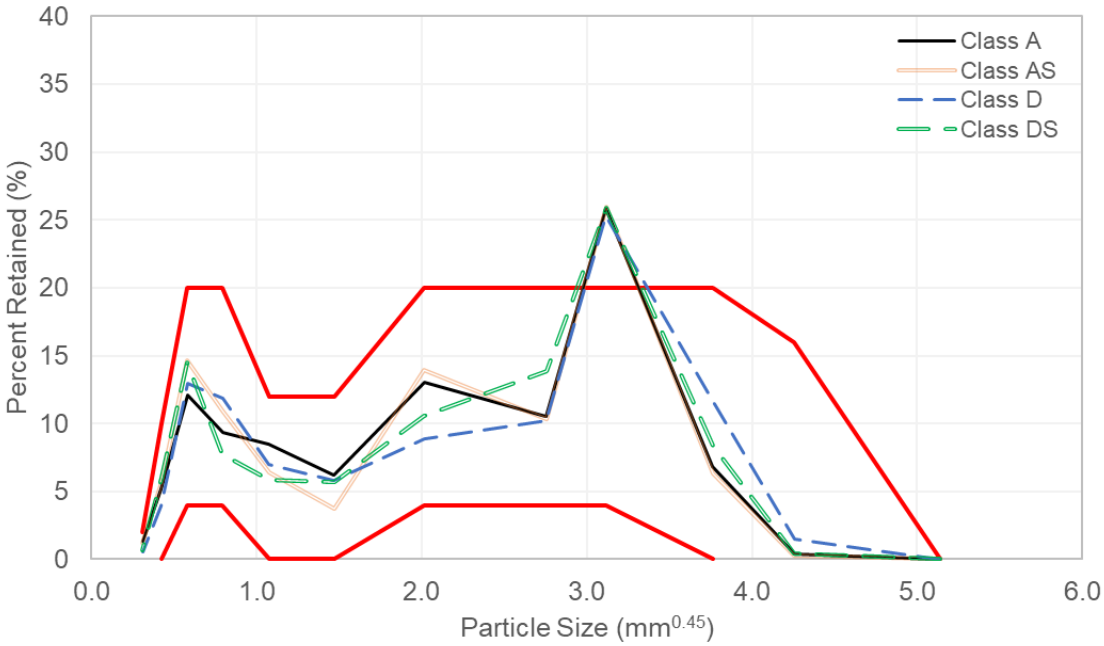

Figure 4-1 details the average Tarantula curve plot for Class A, AS, D, DS concrete mixtures

Mixture gradation trends in Figure 4-2 also suggest that Class A concrete combinations were close to the limit or missing on the #16 (1.18 mm) sieve [denoted by 1.077] under certain conditions as well. This is true in cases where manufactured sand was utilized as the fine aggregate. These trends were duplicated in the RES2023-16 optimized gradation research project [(19)], which also indicated that available stockpiles in Tennessee would result in the ½" (12.5 mm) and #16 (1.18 mm) sieves missing the Tarantula curve requirements, in agreeance with both Figure 4-1 and Figure 4-2.

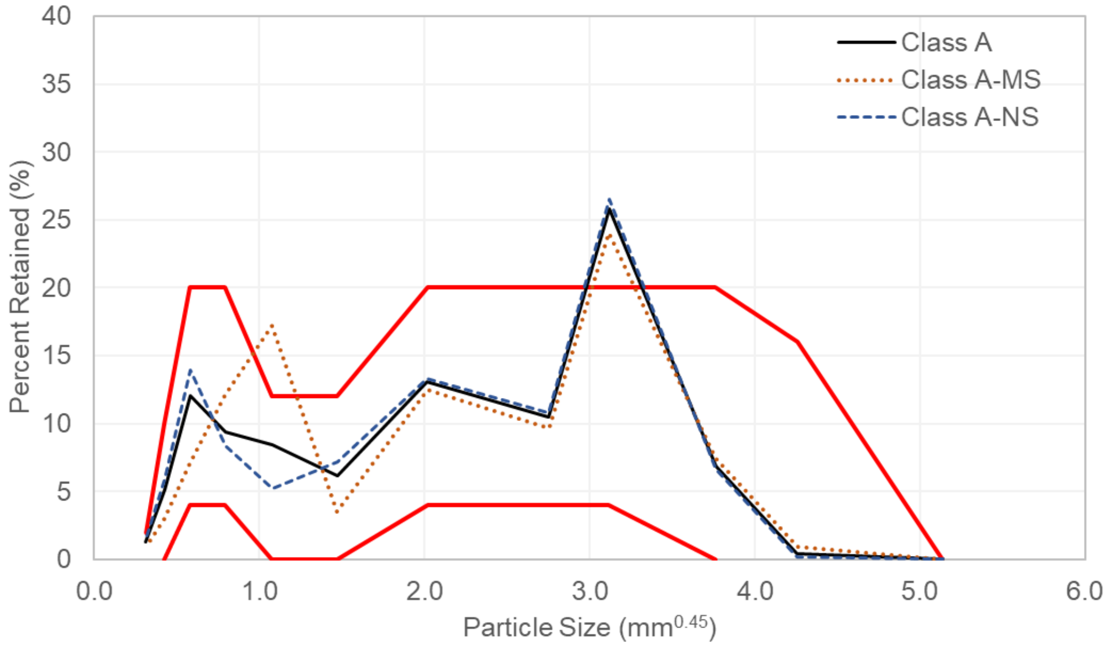

Figure 4-2 details the differences between Class A mixtures with natural sand and manufactured sand

Additional gradation details were captured for the other concrete classifications in this project. Class P concrete, Class SCC concrete, Class SH-SCC concrete, and Class X concrete all had limited entries. Figure 4-3 details the average Tarantula curve for each of these concrete mixture classifications. Although the data was limited, Class P concrete and Class X concrete were both in line with the trends from Figure 4-1, although Class P concrete was close to meeting the coarse aggregate requirements of the Tarantula curve. Class SCC concrete and Class SH-SCC concrete were averaged together given the limited data and similar specification for each. Due to the maximum coarse aggregate size of #67 sized aggregate denoted in TDOT Standard Specifications, Section 604.03.A.1.b. [(8)] coupled with the increased use of fine aggregate, the sieve size missing the Tarantula curve shifted down from the ½" (12.5 mm) sizing to the #4 (4.75 mm) sizing for Class SCC concrete mixtures.

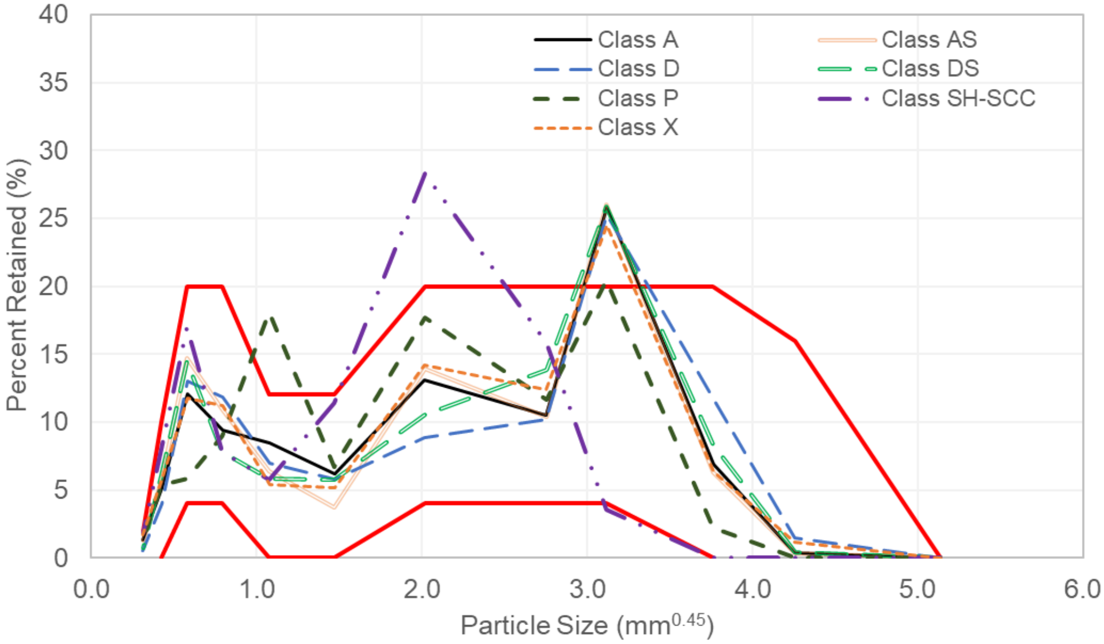

Figure 4-3 details the average Tarantula curve plot for Class P, SCC/SH-SCC, and X concrete mixtures

Per TDOT Standard Specifications, concrete mixtures typically utilize a blend of a #57 sized aggregate with either a natural sand or a manufactured sand. Regional exceptions due to locally available aggregates occasionally result in replacement of the #57 with a #67 sized aggregate. Due to the current use of these sizes, it is likely any two-aggregate system will continue to trend outside of the Tarantula specification on the #1/2 (12.5 mm) sieve regardless of adjustments. Another limiting variable relates to TDOT's limits on fine aggregate in the blend. RES2023-16 was able to address the issue with the ½" (12.5 mm) sieve by utilizing a third stockpile sized at either #7 or #89 sized aggregate as described in AASHTO M 43 [20]. The #16 (1.18 mm) sieve was notably still missing on a couple optimized designs. Those designs were permitted for the purpose of this research since they were close to the Tarantula curve limit. Notably, those designs missing on the #16 sieve (1.18 mm) still experienced improvement versus the non-optimized designs that served as the control.

4.1.2 Shilstone Coarseness Chart

In addition to the Tarantula curve, concrete mixture designs were examined on the revised Shilstone chart. Since many different concrete mixture classifications were captured during this research project, this chart was deemed appropriate to showcase results and target specific questions regarding TDOT's aggregate specifications. Equation 1 regarding the coarseness factor and

Equation 2 regarding the workability factor were used to determine where each concrete mixture was located on the revised Shilstone chart. Both equations used the provided aggregate gradations in the concrete mixture design submittal. These coarse aggregate and fine aggregate gradations were combined based on the listed concrete mixture design proportions to achieve the blended gradation.

Equation 2 also required the cementitious content utilized in each concrete mixture to adjust for the fine particle effects on workability more accurately. Figure 4-4 illustrates both the coarseness factor and workability factor for each of the concrete mixtures captured in this research.

The investigation shows that the average Class A concrete designs are primarily in Zone II near the border of Zones I and IV. While the average is optimal, this suggests that several of the Class A concrete designs are near gap-graded while some are considered too fine. Class D concrete and Class DS concrete mixtures are also around Zones I, II, and IV, though these designs captured in this research are shifted toward Zone I primarily, indicating a gap-graded aggregate blend. While some of the concrete mixtures captured are have cementitious contents above the minimum allowable per TDOT Standard Specifications [(8)], the trend persists for concrete designs at the minimum allowable cementitious material limit. This fact suggests that coarseness and workability adjustments must either be made by optimizing the aggregate blend and/or utilizing the Class PEM concrete procedure to reduce the necessary cementitious content.

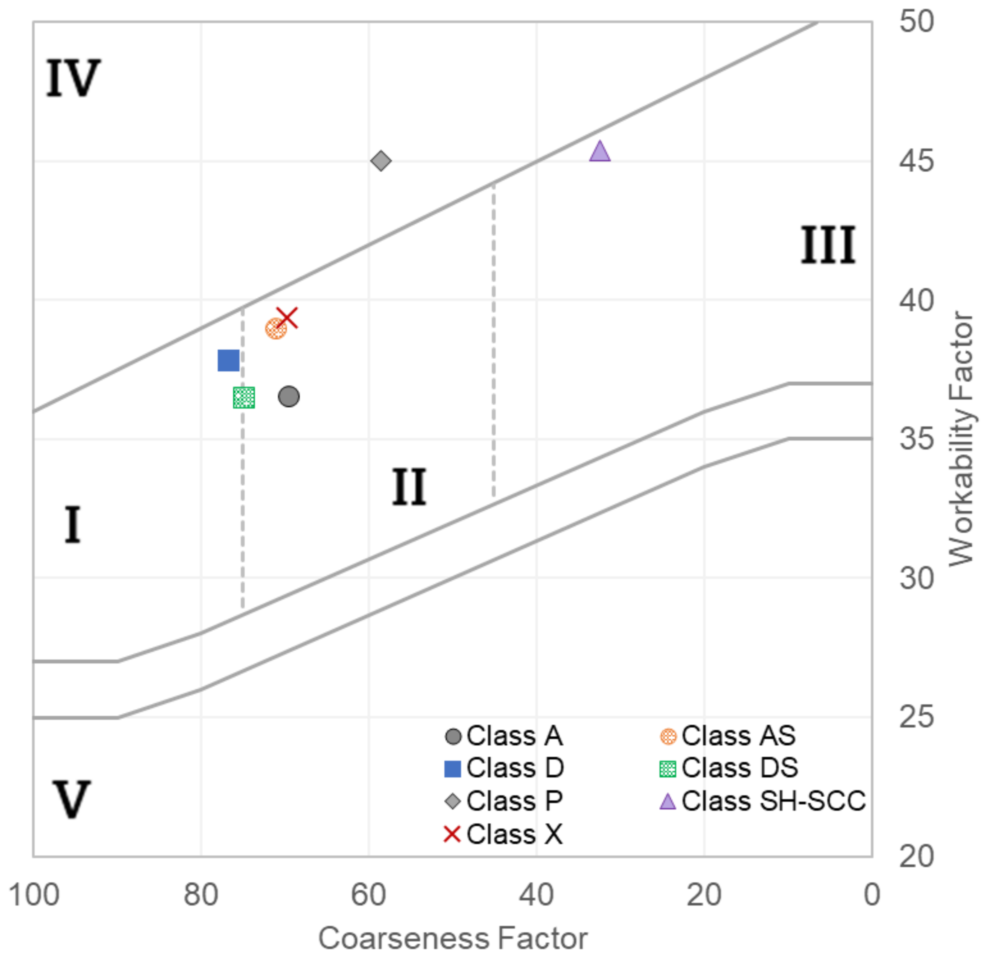

Figure 4-4 revised Shilstone Coarseness Chart for all TDOT Concrete Classifications

It is apparent that multiple concrete mixture classifications (Class A concrete, Class D concrete, and Class DS concrete) skew toward Zones I and IV. Many of these concrete designs remain in Zone II, though the dataset for each concrete class centers over there area where Zones I, II, and IV intersect. By this measure, the average Class A concrete, Class D concrete, and Class DS concrete mixtures are either gap-graded or too fine by the Shilstone chart, while also missing on the ½" (12.5 mm) sieve sizing. Both the Tarantula and Shilstone methods appear to suggest that the omission of an intermediate aggregate skewed the results from consistently achieving the optimal aggregate blend.

The only concrete mixture outside of the optimal zone for every recorded occurrence was Class P concrete, which is seemingly appropriate given the common practices of the prestressed industry. Higher cementitious contents are generally submitted for the purpose of consistently achieving high strength concrete at an early age. Class P concrete is another mixture classification that heavily utilizes manufactured sand sources, thus resulting in a blend skewed to Zone IV. Given the highly controlled environment of prestressed yards, it is plausible that aggregate optimization and cement reduction is achievable. However, given the focus and scope of this research project, there is insufficient data to suggest a specification change for Class P concrete is appropriate or necessary at this time.

Another variable in this research was the type of aggregate selected for achieving the gradation blend. Regarding the coarse aggregate stockpiles utilized, there was little to no measurable difference in the grading. However, the fine aggregate selection did alter the concrete mixture considerably. This manifested in this research through the Class A concrete designs collected. In Figure 4-5, the average Class A concrete utilizing manufactured sand as the fine aggregate was in Zone IV – i.e., too fine. The average Class A concrete utilizing natural sand, however, was in Zone II – i.e., optimal. Notably, natural sand was present more frequently in the Class A concrete designs collected during this research. The average shown in Figure 4-5 illustrates that the data is skewed toward agreeance with the natural sand designs.

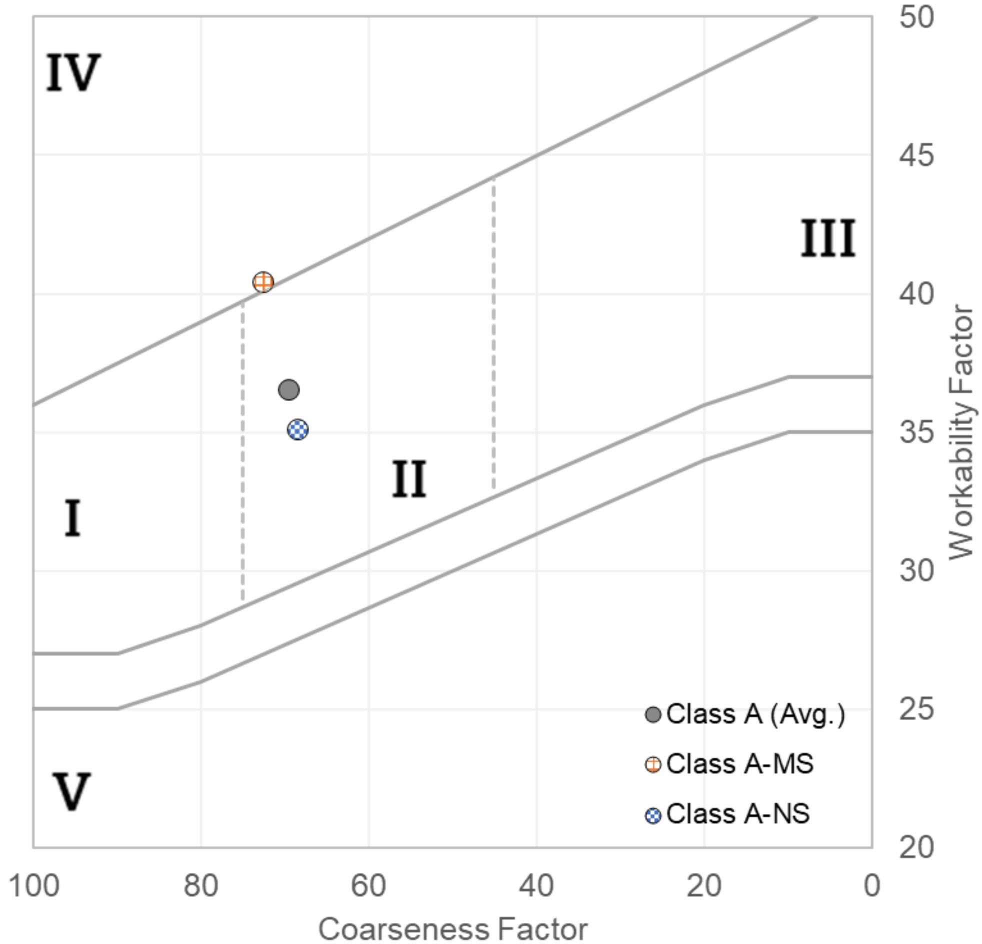

Figure 4-5 details the Shilstone chart differences between Class A concrete utilizing natural sand (A-NS) versus manufactured sand sources (A-MS)

4.2 Sequential Pressure Method/Super Air Meter

The first step of the SAM number data analysis was to set criteria for what was deemed the target performance. The metrics were determined as follows:

First, to establish the design criteria designating the target air voids for each concrete mixture. Per TDOT Standard Specifications [8] [9] which set the targets and production limitations for most concrete classes defined in Table 604.03-1 and Table 604.03-2. Design criteria for Class A, S, SCC, and SH-SCC concrete is 6% air voids with 4% to 8% acceptable during construction. Class D, DS, and L concrete are all designed at 7% air voids, with a note that due to pumping and other placement factors a range of 4.5% to 7.5% is acceptable during production. It is notable that Table 615.09-1 denotes the design criteria for prestressed and precast concrete mixtures ranging from 0% to 8%, noting that the air entraining is optional per Contractor discretion unless otherwise noted in the Plans or shop drawings. Common practice for TDOT producers is to include as little air content as possible. The Class P concrete mixtures captured in this study confirmed that industry practice, with air content ranging from 1.1% to 1.9% in this dataset. For our analysis purposes, the boundary in Figure 4-6 is set at a minimum of 4% for all concrete mixture classifications where air voids are specified.

Second, there must be a designated SAM number limit as well. This can be set either by applying a target spacing factor for concrete mixture design purposes or by setting a maximum acceptable value for field testing purposes. Both value selections have data suggesting their usefulness. Examining the spacing factor, 0.20 mm (0.008 inch) spacing factor is referenced in design guidelines to ensure a concrete mixture that can best perform against freeze-thaw conditions [21]. AASHTO T 395, Appendix A3.1 suggests that a target SAM number of 0.32 is accurately able to determine a durability factor above or below 70% around 90% of the time. RES2020-09 concluded that TDOT should adopt an acceptance limitation of 0.30. 50.0% of the test concrete mixtures achieved the criteria of 0.20, 73.5% achieved 0.32, and 78.6% achieved 0.35. For this research, Figure 4-6 was established with a SAM number of 0.35 with a dashed line indicating 0.20 for design purposes.

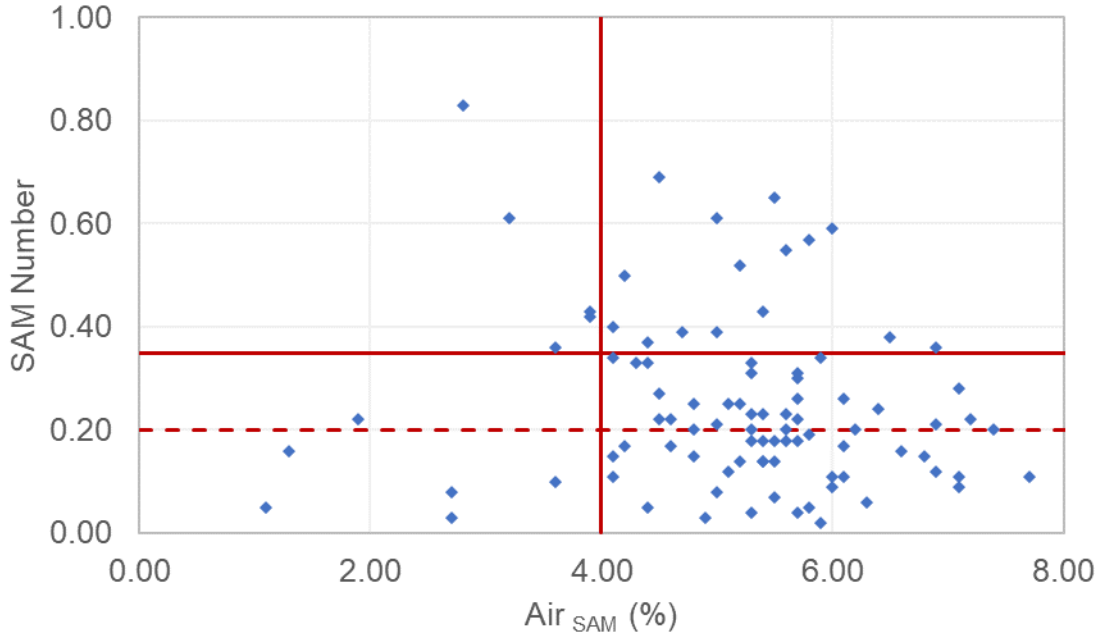

Figure 4-6 illustrates the SAM number data collected over the course of the research project

4.2.1 SAM Efficiency Chart

The data showcased in Figure 4-7 shows the entire data set from the research project. Values plotting near the lower solid line are considered highly efficient concrete mixtures as tested – i.e., a lower SAM number was achievable with lower overall air content in the concrete mixture. While any value plotting near the upper solid line should be considered a low efficiency concrete mixture. Both lines contain values that are considered appropriate to effectively design for freeze thaw durability. However, concrete mixtures near the low efficiency line do so with higher air contents, indicating the presence of larger air bubbles.

The dashed lines in Figure 4-7 denote an approximate mathematical limitation where the values surpassing the threshold are considered improbable or even impossible due to bubble sizing and spacing necessary for the points to be true. These thresholds were set by determining the difference between the solid lines at any given point and adding it to the low efficiency line and subtracting it from the high efficiency line. The resulting outcome is a set of thresholds running parallel to each efficiency line.

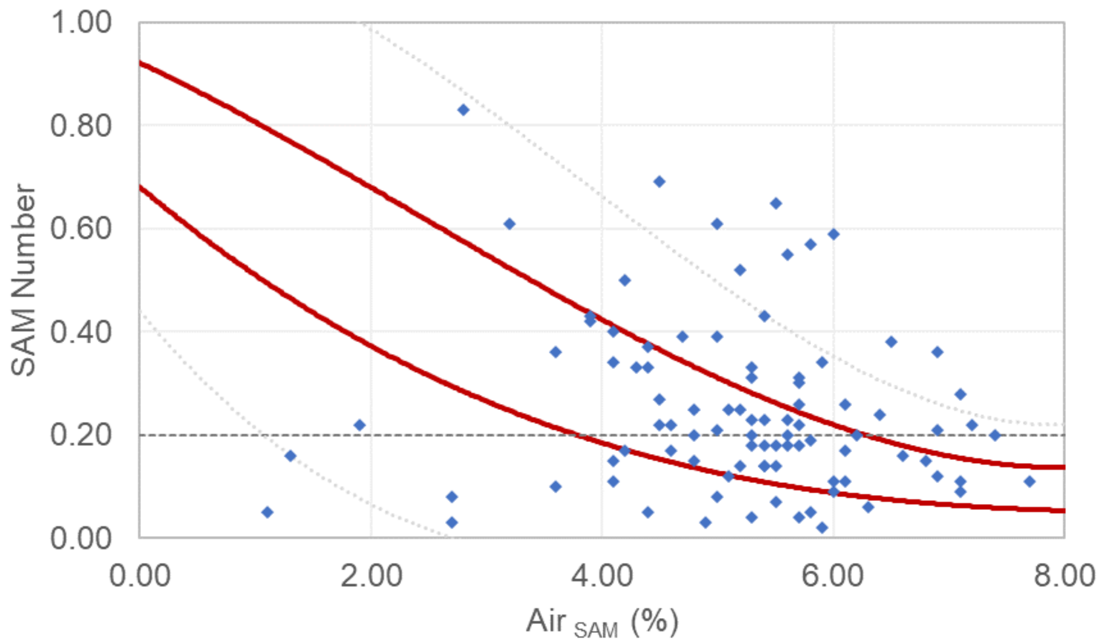

Figure 4-7 illustrates the SAM efficiency chart [22] with TDOT data overlaid

The dataset indicates that several data points were collected from a test that was potentially completed incorrectly. Further analysis of the data suggests that a check can be applied using the air void data and the SAM number to determine a range of acceptable values.

Equation 3 $\boldsymbol{Validation\ Check = A \times S}$

where A = Air content expressed as a percent (%) from the SAM

S = SAM number

When multiplied, resulting values between 0.10 and 2.30 generally indicate a test result that is likely valid. Approximately 11.5% of the recorded results were flagged as unacceptable using this criteria. While this method is rudimentary, it is the opinion of the research team that this will serve as a validation tool. Therefore, any values touching or surpassing the approximated threshold criteria must be retested to validate the recorded test result. The issues were not widespread in the dataset – i.e., single operator error was identified as the cause of the issues.

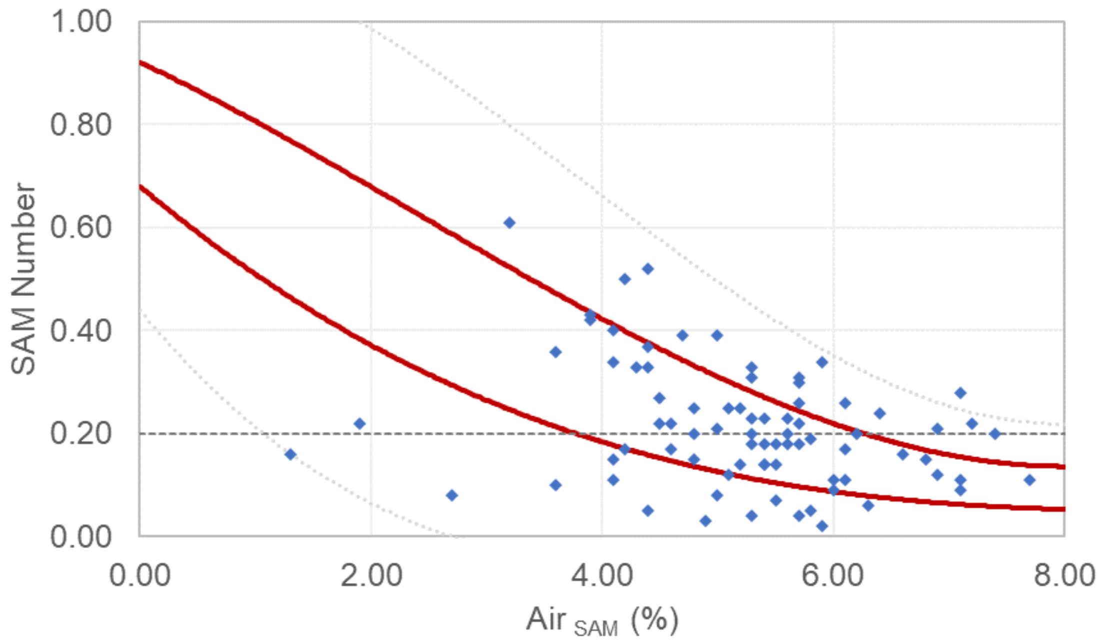

Figure 4-8 illustrates the filtered SAM efficiency chart with the Equation 3 conditional check applied

There is a practical use for Equation 3 as it can be imbedded in the TDOT Concrete Design Spreadsheet and monitored through conditional formatting to warn the designer when a test result is invalid. Figure 4-8 shows the dataset from Figure 4-7 filtered with Equation 3. Data points that fell off from Figure 4-8 were invalidated and, for a trial batch procedure, would need to be retested to achieve results conformant with Equation 3.

4.2.2 Trial Batching and Verification

Given the data, the SAM method would be best utilized during concrete mixture design trial batching procedures and as verification tools on future bridge deck projects. The concrete designs most appropriate for testing include Class D, Class DS, and Class PEM concrete mixtures. In the case of Class D concrete and Class DS concrete the primary reason is due to exposure to brine and salt during winter operations. For Class PEM concrete, the SAM method should be used to validate the viability of the air system in an alternative concrete mixture design.

4.2.3 Best Practices

A few minor issues were encountered over the course of the research project, primarily resulting in an error message. Following internal case-by-case investigations and a discussion with the SAM designer, best practices were determined to prevent and/or address future issues. Those best practices include storing the gauge with the case open in a dry environment to avoid trapping moisture in the gauge, always ensuring that new batteries were stored in the case to prevent low power related errors and troubleshooting issues with multiple people to rule out operator error.

Regarding the sampling and testing, it was also determined that that the petcock funnel was helpful to avoid unrealistic test results, such as the SAM numbers identified with Equation 3 and/or plotted on the efficiency chart outside of the dashed bounds illustrated in both Figure 4-7 and Figure 4-8. This petcock funnel efficiently allows for the air to be purged between the first and second pressure cycles.

4.3 Surface Resistivity

The first data analysis check was a system wide look at what was collected over the course of the research. Table 4-1, referencing AASHTO T 358, Appendix X1, Table X1.1 [(5)], lists target criteria for 4" by 8" (100 mm by 200 mm) concrete cylinders. For the research cylinders, the splits between high/moderate permeability, moderate/low permeability, and low/very low permeability are denoted as 12 kΩ-cm, 21 kΩ-cm, and 37 kΩ-cm respectively. These values from Table 4-1 are plotted horizontally in Figure 4-9 along with all the collected resistivity data.

Table 4-1 (AASHTO T 358, X1.1) – Chloride Ion Penetration

	Apparent Surface Resistivity[a]	
Chloride Ion Penetration	100 by 200 mm (4 by 8 in.) Cylindrical Specimens (kΩ·cm) a = 3.8 cm	150 by 300 mm (6 by 12 in.) Cylindrical Specimens (kΩ·cm) a = 3.8 cm
High	<12	<9.5
Moderate	12–21	9.5–16.5
Low	21–37	16.5–29
Very low	37–254	29–199
Negligible	>254	>199

[a] a = Wenner probe tip spacing

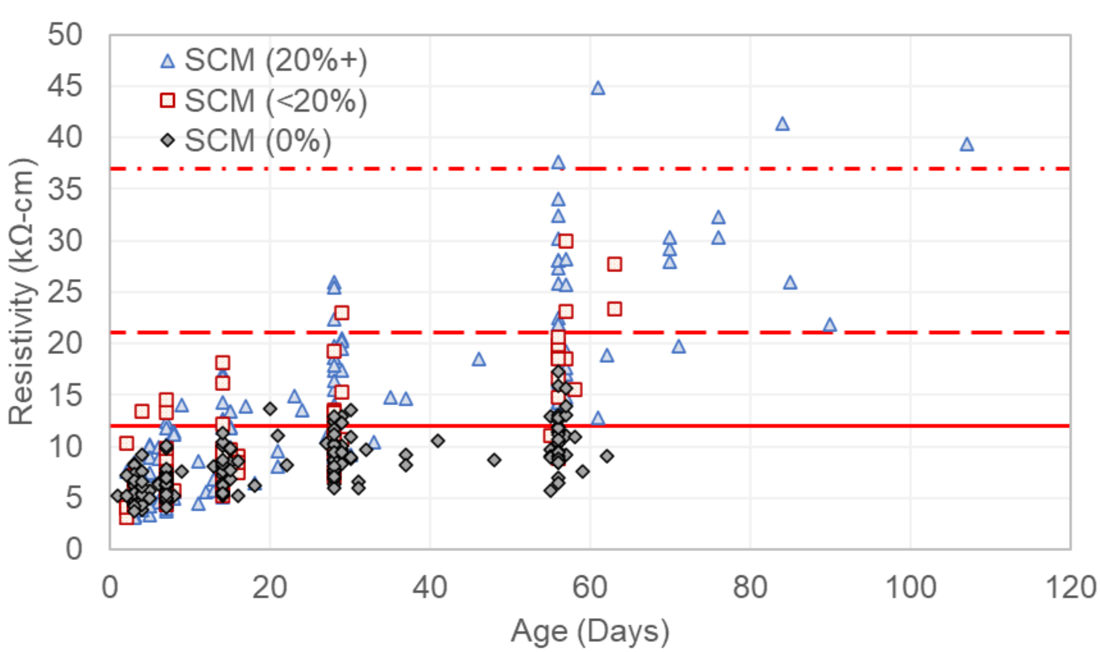

Figure 4-9 illustrates entire resistivity dataset at the age each set was tested

4.3.1 Interpreting Tennessee's Results

At the 56-day mark denoted in FHWA guidance [23] as the preferred target for acceptance, approximately 70.0% of the concrete mixture designs captured would be considered moderately permeable or better. However, further assessment of the individual variables indicates that this metric requires a frame of reference. It became evident early in data analysis that concrete mixture performance was heavily influenced by the presence of SCMs or lack thereof.

To better understand the dataset in Figure 4-9, it was organized into two categories: Figure 4-10 illustrating concrete mixtures containing SCMs and Figure 4-11 illustrating concrete mixtures with cement only. While designs with moderate permeability are still prevalent, concrete mixtures utilizing SCMs were able to achieve a lower permeability on a consistent basis. That is to say, the inclusion of SCMs more than 20% resulted in fewer cylinder sets falling into the highly permeable threshold versus those at less than 20% inclusion and those with no SCMs utilized. Conversely, none of the cement only concrete mixtures captured in this dataset were not able to achieve a low permeability designation at the 56-day mark.

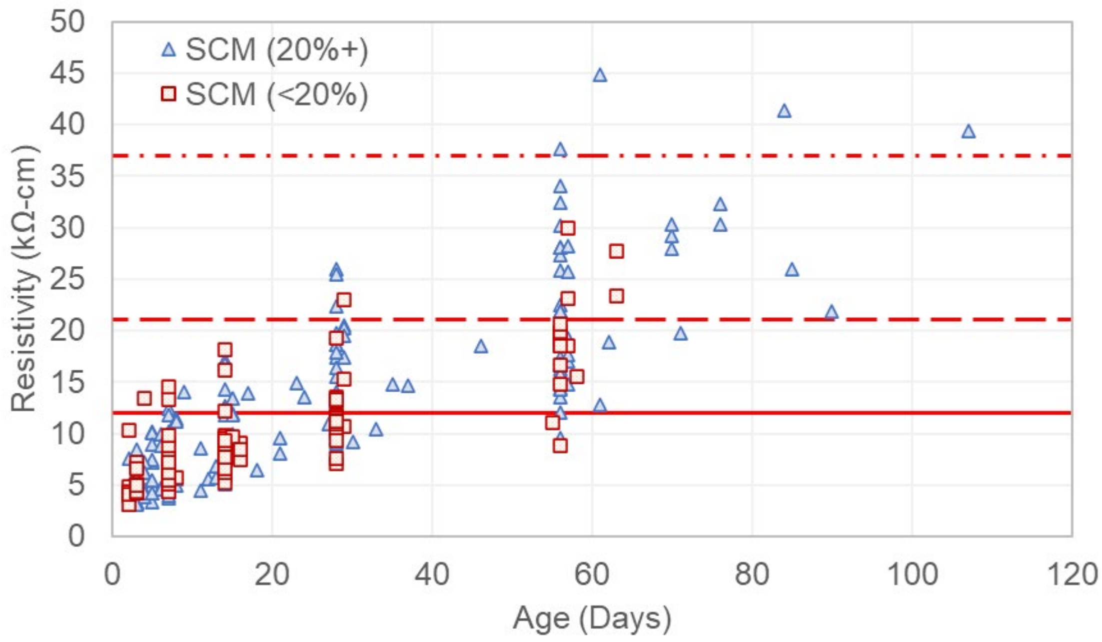

Figure 4-10 illustrates resistivity dataset for all concrete mixtures containing SCMs

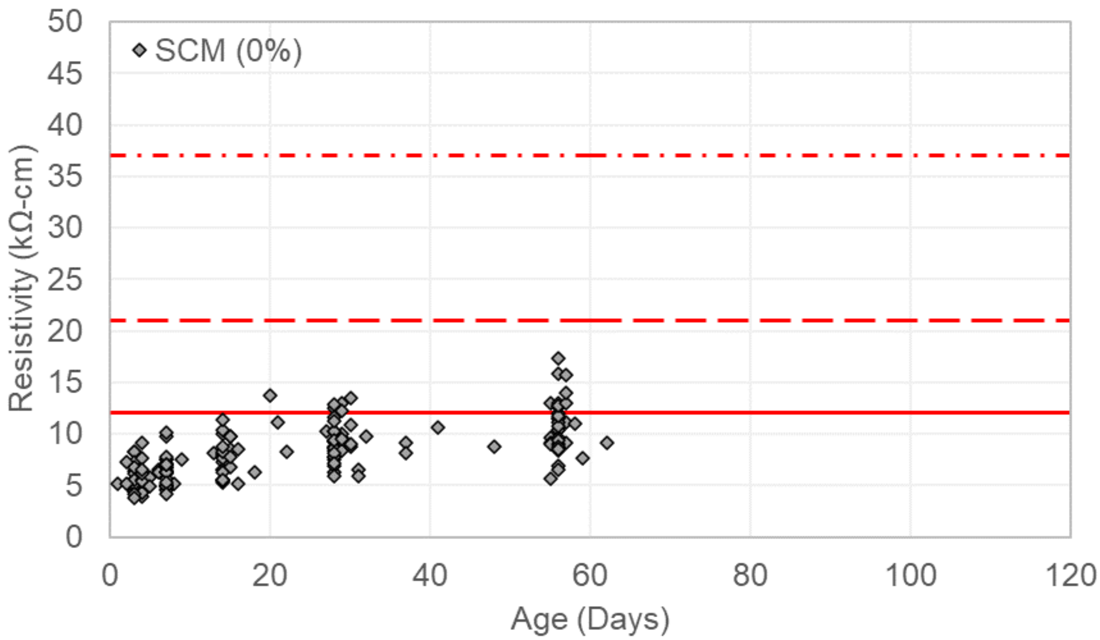

Figure 4-11 illustrates resistivity dataset for cement only concrete mixtures

SCMs were the single biggest contributor to concrete mixtures that performed well in resistivity testing – i.e., concrete mixtures with SCMs were consistently able to achieve low permeability. There is an obvious benefit with SCMs physically given the much smaller particle sizing, which lends itself to particle packing in the concrete mixture. The second benefit seems to come over time as the chemical reaction consumes the calcium hydroxide ($Ca(OH)_2$) [24], primarily showcased in the second month of this dataset. On average Class A concrete and Class AS concrete mixtures utilizing cement only designs recorded resistivity values that increased approximately 17% at the 56-day mark versus the recorded value at the 28-day mark. On average the Class A concrete and Class AS concrete mixtures utilizing SCMs experienced a 45% gain in resistivity values in month two (2), accounting for a 28% differential between the resistivity values. The Class D concrete and Class DS concrete mixtures were also compared and showcased similar results, including a 13% gain on cement only designs, a 51% gain on SCM designs, and an overall resistivity gain differential of approximately 39%.

Other constituent materials were examined to determine if the resistivity measurement could be skewed by the inclusion of certain materials. Many variables appear to contribute to the result, but a few prevailing trends emerged. First, aggregate type made an impact on the results. Granite utilized as a coarse aggregate was generally showcasing lower resistivity values versus the limestone and gravel designs. Notably, no granite design utilized a 25% SCM replacement. Investigation into minerology was outside of the scope of this research project but would be the next step in this investigation should this trend continue at 25% SCM inclusion. Second, the aggregate grading trends suggest that concrete mixtures more closely aligned with the Tarantula curve may have a marginally better chance of achieving a higher resistivity value. However, this data also coincided with SCM utilization indicating it may be a correlation instead of the cause. While either of these trends may be present, neither of these two observations were entirely confirmed within the scope of this research. Further investigation would be necessary to properly confirm and quantify either item.

4.3.2 Equivalency Approximation

One goal for the resistivity data analysis was to determine if it was possible to use a 28-day resistivity value to forecast the 56-day resistivity value. Figure 4-12 isolates the Class A concrete and Class AS concrete resistivity data and Figure 4-13 isolates same information for Class D concrete and Class DS concrete. Both figures show the 28-day and 56-day data for cement only concrete mixtures and those with the inclusion of SCMs.

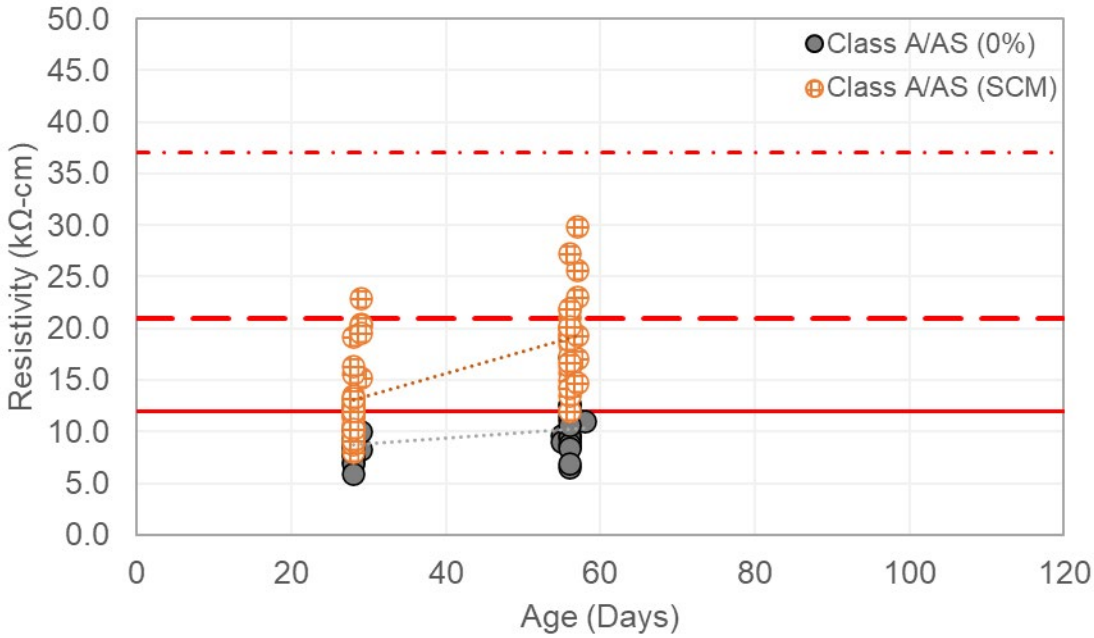

Figure 4-12 illustrates the 28-day and 56-day resistivity results Class A concrete and Class AS concrete

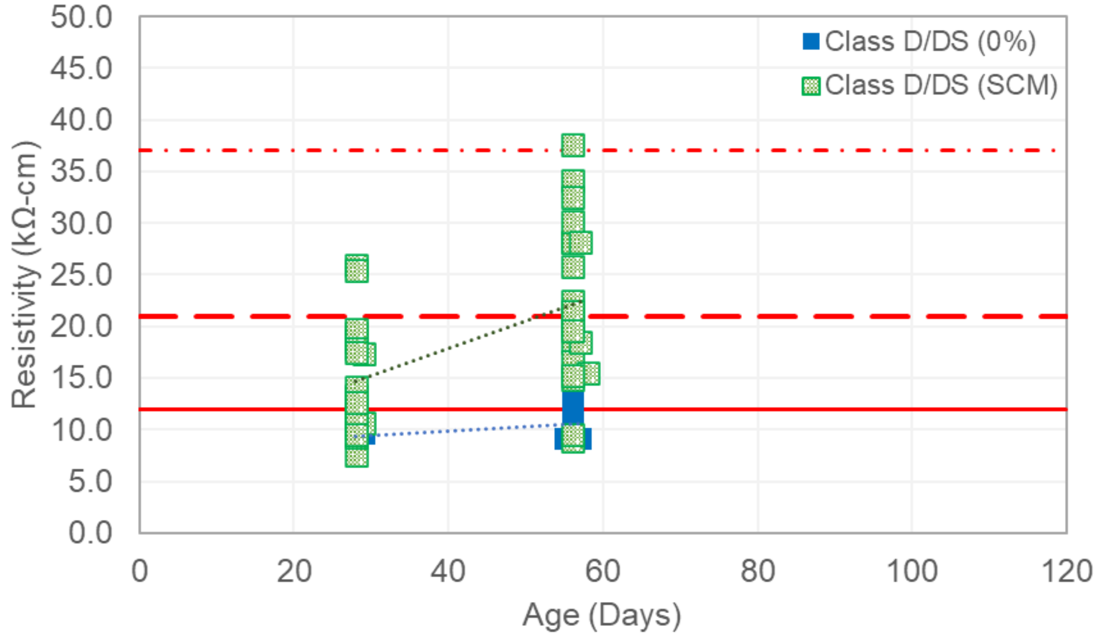

Figure 4-13 illustrates the 28-day and 56-day resistivity results Class D concrete and Class DS concrete

One possibility for these figures is embedding the functionality into the Concrete Mixture Design Template to help forecast the 56-day resistivity values for potential design submissions. This can only serve as an estimate and will result in a number that would need validated prior to use. The forecast could, however, be used to determine the viability of mixtures prior to the 28-day mark during the design phase. This can be achieved given the use of the trendline equation derived from the dataset for each scenario.

4.4 Data Validation

The batch tickets collected were used to determine if the concrete mixtures were being blended as designed. The batch tickets detailed the target per the concrete mixture design proportion and load size listed in cubic yards and the measured dispersion of each constituent material. TDOT Standard Specification, Section 604.11, in Table 604.11-1 denotes the acceptable tolerances for both cement and aggregate utilized within all concrete mixture classifications. Section 604.11 also specifies tolerances for water that shall be maintained within 1% error and admixtures that specify ±3% of the manufacturer's recommendations.

4.4.1 Aggregate Blend Validation

Class D concrete and Class DS concrete mixtures containing SCMs were selected to contribute to the validation data set for the aggregate blend. Using the provided batch tickets, tolerances were tracked for all constituent materials including coarse and fine aggregates. Table 604.11-1 details the concrete batching tolerances allowable for cementitious and aggregate materials, specifying -1% to +4% and +/-1.5% respectively. Referring to the equations used to determine the coarseness factor and workability factor for the revised Shilstone chart, the following data was plotted in Figure 4-14.

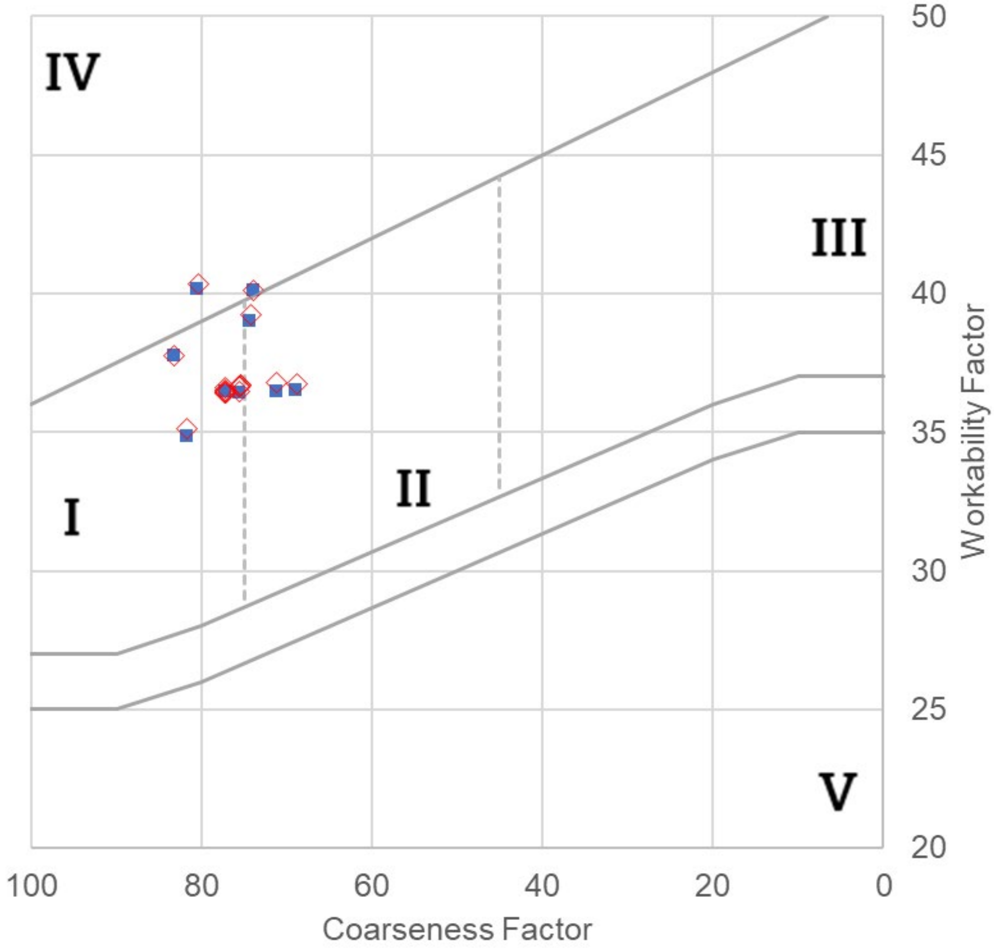

Figure 4-14 regarding the batch ticket tolerances effects on the Class D/DS concrete mixtures

The coarseness factor values for the Class D concrete and Class DS concrete affirmed that negligible differences were encountered during this research project. Workability factor values were also unchanged statistically speaking though a few were noticeably shifted to a marginally higher workability factor value. These occurrences are likely due to the skewed net positive tolerance for the inclusion of cementitious material, which would lend itself to increased workability of the mixture.

4.4.2 Admixture Validation

While admixtures were also examined, there was no conclusive evidence that admixture combinations greatly affected performance variables. Notably, every concrete mixture design that listed an admixture for air entrainment used the listing per review of the batch tickets to ensure the proper air contents were achieved for the respective concrete mixture classifications.

There were occurrences of mismatched constituent lists, although these were limited. These occurrences were exclusively the result of an alternative product from the same manufacturer listed on the concrete mixture design. A few of these occurrences were attributed to the dualpurpose admixture listings, marketed as both “mid-range water reducer (MRWR)” and “high-range water reducer (HRWR).” For example, there were a couple occurrences were a “MRWR” was listed on the concrete mixture design submittal but listed on the batch ticket as “HRWR.” While these items were flagged in the dataset, those data points are treated as errata.

Another notable item is that several batch tickets did not list the specific product name, instead nomenclature such as “HRWR” or “AEA” was used. It is not currently specified in TDOT Standard Specifications and/or procedures that it is necessary to specify the product name on the batch tickets, although it is encouraged for clarity.

Chapter 5 Conclusion

5.1 Concluding Remarks

The goal of this research was to further advance PEM practices on Tennessee concrete mixtures to ensure that durability was a part of the procedural process. To satisfy the objectives stated in the original proposal, a dataset capable of representing the entire State of Tennessee was collected. The dataset is comprised of one-hundred ten (110) fresh property datapoints and five-hundred twenty-six (526) hardened property datapoints at various ages. The data collection efforts resulted in eight (8) concrete design classifications, three (3) coarse aggregate varieties, two (2) fine aggregate varieties, three (3) cement varieties, three (3) different SCM varieties, and cement only concrete designs for analysis.

The dataset was comprised entirely of two-aggregate systems in every use case, regardless of concrete mixture classification. The evidence suggests that to consistently satisfy both the Tarantula curve and the revised Shilstone method a three-aggregate blend should be utilized. RES2023-16 suggested the use of #7 or #89 sized intermediate aggregate stockpiles to achieve this given the data collected in an industry survey.

The SAM method shall be used during the concrete mixture design trial batching phase. The use of this method during trial batching will assist designers in selection of a concrete mixture design that can withstand freeze-thaw cycles that are common in Tennessee. The data captured suggested that concrete mixtures in Tennessee are already performing relatively well when compared to the internal target SAM number of 0.35. Additional internal training would be necessary to ensure best practices are being conducted during the testing phase.

Resistivity testing shall be submitted with trial batching information for all applicable concrete mixture design submittals. Further, resistivity should be listed as both an acceptance and verification test on applicable cylinder sets submitted to the central laboratory for compression testing.

Table 5-1 shows potential performance-based criteria for the use of resistivity testing.

<table>
<tr><td colspan="2" rowspan="4"></td><td colspan="3">Compressive Strength</td></tr>
<tr><td>Pass</td><td colspan="2">Fail</td></tr>
<tr><td rowspan="2">$f'c_{req} \leq f'c_{act}$</td><td colspan="2">$f'c_{act} < f'c_{req}$
Standard Specifications 604.20 and 604.31</td></tr>
<tr><td>$0.75 \cdot f'c_{req} \leq f'c_{act} \leq f'c_{req}$</td><td>$f'c_{act} \leq 0.75 \cdot f'c_{req}$</td></tr>
<tr><td rowspan="2">Surface Resistivity</td><td>Pass
≥ 12 kΩ·cm</td><td>PASS</td><td>Structural Review;
Assess Penalty
on Strength</td><td rowspan="2">Structural Review:
May remain in place*
OR
Must be removed
and replaced*</td></tr>
<tr><td>Fail
< 12 kΩ·cm</td><td>Apply
Penetrating Sealer*</td><td>Structural Review;
Assess Penalty
on Strength; Apply
Penetrating Sealer*</td></tr>
</table>

** at no cost to the Department*

Additionally, the resistivity results were consistently better performing for concrete mixtures utilizing SCM materials at more than 20% inclusion. Due to exposure to de-icing operations, Class D concrete and Class DS concrete mixtures shall contain 25% fly ash at a 1:1 replacement rate.

To facilitate changes, the Concrete Mixture Design Template must be updated to allow for designers to have a visual tool for tracking performance results. These visuals should include the Tarantula curve, the revised Shilstone chart, the SAM efficiency chart, and the resistivity plot with permeability targets. The custom records of the Concrete Mixture Design Template must be updated to capture the data necessary to query for future questions regarding performance data.

5.2 Future Considerations

An alkali loading study is a logical next step since the concrete industry is exploring alternative pozzolanic materials and/or alternative blended cements. Efforts need to be made it determine how these alternative materials effect the current understanding of SCMs and resistivity. Efforts will need to answer whether these alternatives are viable replacements, or if one or more variables create additional complexity during the design process. Ideally, this study should also capture Slag 100 material since it is already in Tennessee's market and being utilized.

Aggregate minerology will need to be investigated further to determine whether certain aggregates are interfering with the resistivity equipment, primarily its ability to measure resistivity accurately and consistently. This research will need to identify whether the lower resistivity values correlate with actual chloride permeability values akin to RES2013-41.

Research will need to be conducted to determine the effects of blending efficiency, primarily focusing on the use of alternative aggregate gradations and at various admixture dosages. This research will need to set achievable criteria and/or procedures to follow during the design process to accurately achieve. Special attention will need to be given to monitoring the resistivity results in the future as optimized gradings allow for reduced cementitious content in concrete mixtures.

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Appendices

APPENDIX A regarding the SAM and SR Training Presentation Handout

TN TDOT Department of Transportation

WELCOME!

Super Air Meter and Surface Resistivity

Expectations

- Visit project selected by each region
    - Priority projects are IA and PEM Projects
    - Other projects if time and budget allows
- Project Site Requirements
    - Slump, mix temperature, pressure air content
    - Ten (10) total concrete cylinders (5 sets)
    - Collect inspector slump, temperature, air values
    - Note inspector cylinder numbers
    - Retrieve Batch Ticket

TN TDOT Department of Transportation

Project Site Requirements

- Slump
- Temperature (both Ambient & Concrete)
- Air (both Type B & SAM)
- Cylinders
  - Labeled Properly
- "HOBO" (or equivalent) measuring device
  - Hourly data for the duration of initial curing time
- Copy of Batch Ticket (photo is acceptable)

TN TDOT Department of Transportation

Laboratory Requirements

- Laboratory Requirements
  - Dedicated Lab Storage Space
    - Region Labs – up to a estimated 20 SF
    - Nashville Lab – up to a estimated 40 SF
  - Measure SR/Break sets at region on 3, 7, and 14 days
  - Measure SR/Break sets in Nashville on 28 and 56 days

TN TDOT Department of Transportation

Cylinder Labeling

- Mark the side of the cylinder mold with the following:
  - Cylinder # - "SR"
  - Date Made
  - Contract #
  - Age to be tested
- Do not mark on removable caps

23IA-SR

7 April 23

CNT123

3 Day

TN TDOT Department of Transportation

Cleaning Procedures

- There is a substantial amount of cleanup required
  - Rinse out the equipment so that the residue from the tested concrete will not bond to the equipment
  - Clean all instruments used during the measurement procedure
  - Clean all the concrete off the testing surface and surrounding area
  - Dispose of all the concrete in the proper designated location
  - Dry all equipment prior to storage in the cases

TN TDOT Department of Transportation

TDOT Standard Method of Test for

Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method

References

Standard Specifications

AASHTO T 395-22

TN TDOT Department of Transportation

Super Air Meter (SAM)

- Spacing factor of air voids to estimate freeze thaw resistance
- Typical air content in line with traditional air meter on dense aggregates

TN TDOT Department of Transportation

Equipment

- Super Air Meter
- Tamping Rod
- **Strike-off Plate**
- Syringe
- Scoop
- Mallet
- Funnel
- Standardization Vessel

TN TDOT Department of Transportation

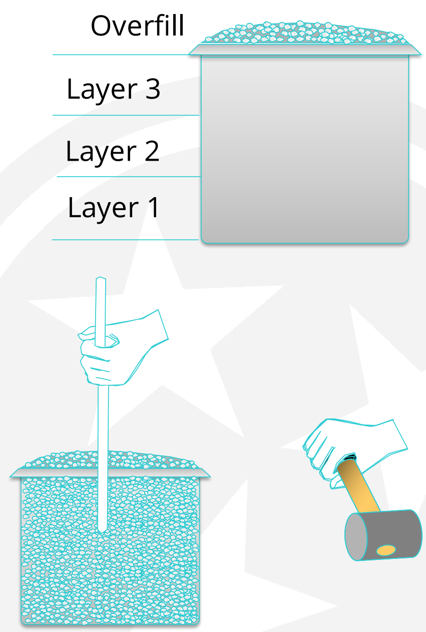
Test Procedure

- Obtain a sample of freshly-mixed concrete
  - Gather approximately 2-¼ c.f.

TN TDOT Department of Transportation

Procedure

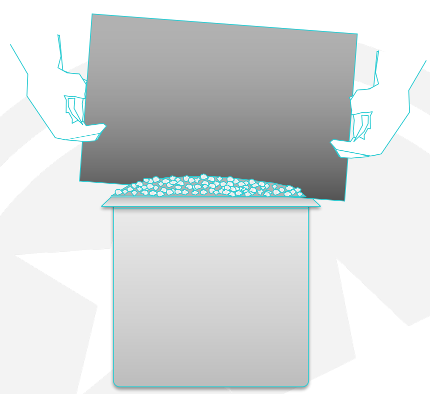
- Process is same as unit weight
- Place on flat surface
- Three equal layers
  - Rod 25 times
  - Tap 10 – 15 times
- Overfill the last layer



TN TDOT Department of Transportation

Procedure

- Strike off the concrete using a **strike-off plate**
- Place the plate to cover ⅔ of the surface and use a sawing motion to finish the covered area
- Place the plate on the same ⅔ of the surface and use a sawing motion to advance the plate until it completely slides off the measure
- Incline the plate and perform final strokes for a smooth surface



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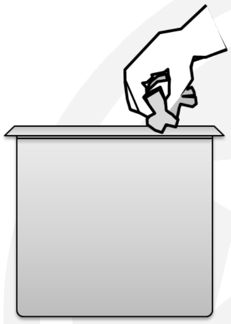
Procedure

- Carefully clean the top edge of the flange and the gasket to allow a tight seal



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Procedure

- Turn on the gauge by pressing the Enter button

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Procedure

- Tighten down the clamps opposite of each other as you would a Type B meter
  - 6 clamps vs. 4 clamps

Procedure

- Fill the petcocks with water and ensure no air bubbles are present
  - Tilt and tap meter if needed
- Close when all air bubbles are gone

Procedure: Step 1

- Press Enter to begin the SAM test
- Begin by applying 14.5 PSI
  - Apply within 0.05 PSI of exact value. Meter will indicate if you are too high or low
  - Use the air valve to bleed any excess air out if needed

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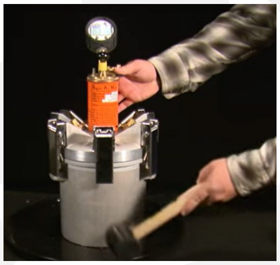
Procedure: Step 2

- Once 14.5 PSI is reached, hold the lever and hit the side of the air pot with the mallet
- After striking, continue to hold the lever down and press the enter button
  - You will be asked to hold for 10 seconds
  - Use the air valve to bleed any excess air out if needed



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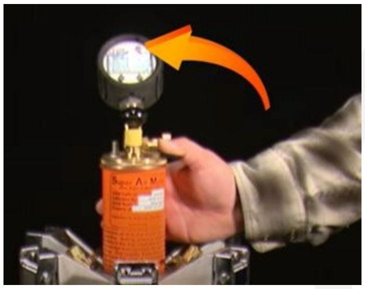
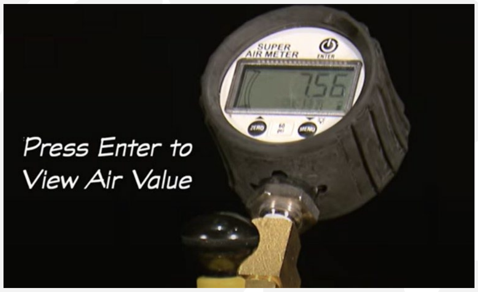
Procedure: Step 3

- Press the Enter button to display the air value of the concrete
  - This is NOT the SAM number
  - Document the air value





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Procedure: Step 4

- Next, the meter will instruct you to apply to the 30 PSI mark
  - Same process as Step 1
  - Apply with 0.05 of exact value

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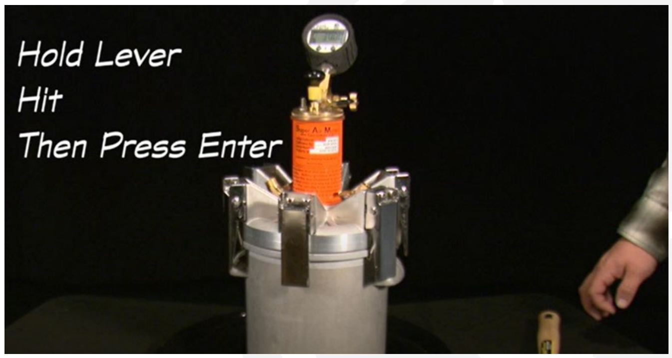
Procedure: Step 5

- Once 30 PSI is achieved, hold the lever and hit the side of the air pot with the mallet
- Press Enter and continue to hold lever down for 10 seconds



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Procedure: Step 6

- Next, the meter will instruct you to apply to the 45 PSI mark

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Procedure: Step 7

- Once 45 PSI is achieved, hold the lever and hit the side of the air pot with the mallet
- Press Enter and hold lever down for 10 seconds

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Procedure: Step 8

- Purge all air out of the meter via the air valve and petcocks until meter reads 0.0 PSI
  - DO NOT OPEN CLAMPS
- ***First cycle is complete***

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Procedure: Step 9

- Refill the petcocks with water
- Expel any air bubbles
  - Tilt and tap meter if needed
- Close petcocks when all air is expelled and begin the test again

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Repeat the Test

- Repeat Steps 1-7
  - Apply 14.5 PSI -> Hold lever, hit pot, press Enter while holding lever and wait 10 seconds
  - Apply 30.0 PSI -> Hold lever, hit pot, press Enter while holding lever and wait 10 seconds
  - Apply 45.0 PSI -> Hold lever, hit pot, press Enter while holding lever and wait 10 seconds

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Data Summary

- Once the second cycle is complete, document your SAM number and Air Value
- 12 minutes are allotted to complete the test once the lid is set
  - Exceeding 12 minutes invalidates the test

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Let's Practice!

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TDOT Standard Method of Test for

Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration

References

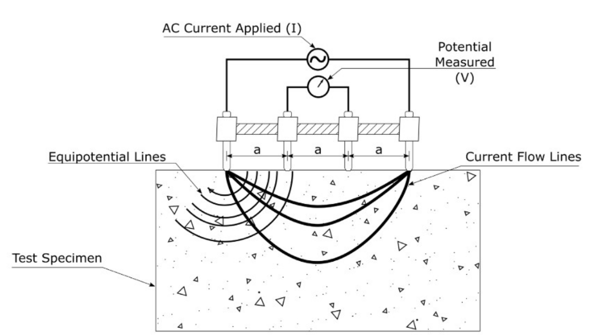
Standard Specifications

AASHTO T 358-22

TN TDOT Department of Transportation

Surface Resistivity (SR)

- Electrical resistivity of concrete samples provides indication of resistance to chloride ion penetration
- Can be useful in life cycle estimation



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Equipment

- Surface Resistivity Meter
  - Determine what value is being reported by device prior to recording and interpreting results
- Specimen holder
  - Non-electrically conducive
  - Prevents rotation
- Non-contact infrared thermometer

Interferences

- Mixes including calcium nitrite indicate lower resistivity values
- Lime-water curing reduces resistivity by 10% compared to moist room curing
- Test not valid for samples containing reinforcing
- Water saturation and temperature of cylinders

Test Samples

- Two (2) cylinders per SR measurement
- After stripping make four (4) circumferential marks on the top of the finished circular face
  - Assign one mark as 0-degrees
  - Going counterclockwise, assign the next mark as 90-degrees, and so on
  - Extend marks onto longitudinal sides of each sample

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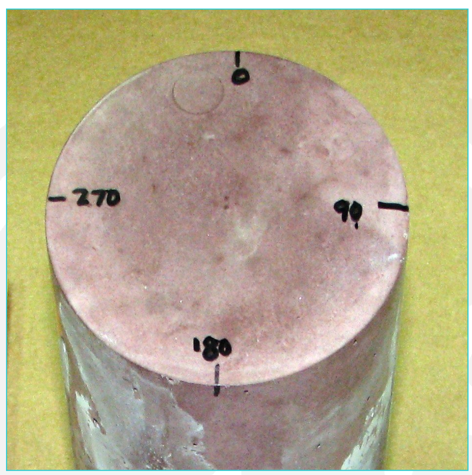
Circumferential Marks



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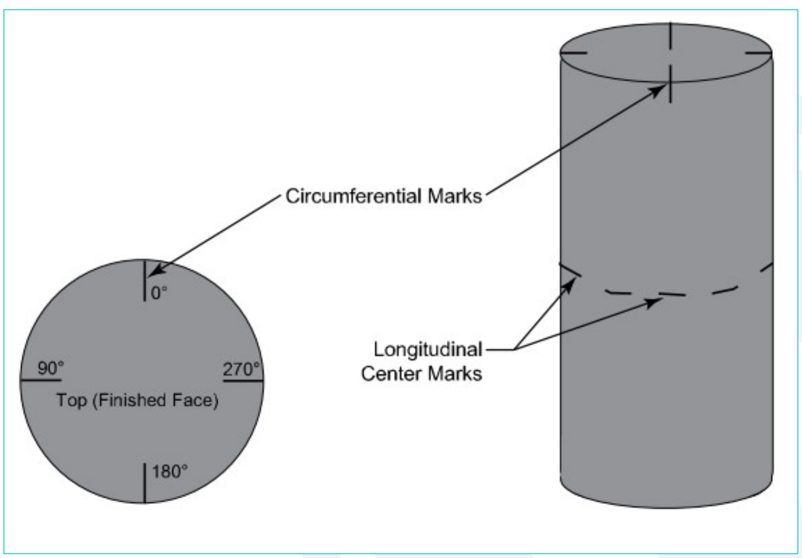
Longitudinal Center Marks

- On the longitudinal sides, mark the center of the sample to use as a visual reference during testing

Sample Marking



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Curing and Conditioning

- Moist-cure in moist rooms or in lime-saturated water tanks until age of testing
- Must remain in 100% relative humidity condition from the moment of mold removal to the moment of test

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Cylinder Testing

- Cylinders must be tested within 5 minutes of being removed from the moist curing environment
  - If not achieved, replace in the conditioning environment and retest after a period of at least 30 minutes
- Concrete specimen temperature shall be measured and recorded before testing begins

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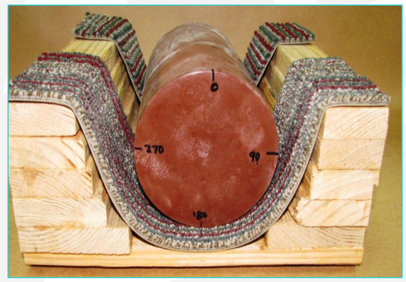
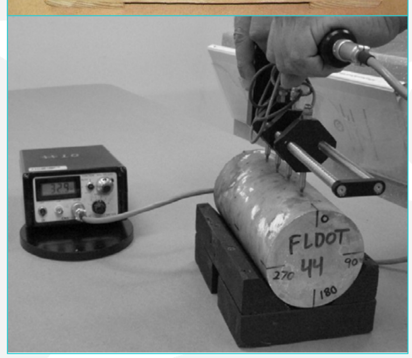
Procedure

- During the test, ambient air temperature shall be maintained at 20 to 25°C (68 to 77°F)
- Remove first sample from curing environment and place on holder with 0-degree mark on top
- Clean excess moisture with sponge or towel



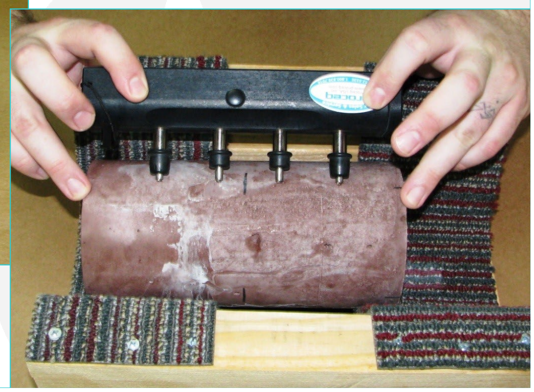
Procedure

- Place the probe on the longitudinal side of the sample
  - Align probe pins with circumferential marks
  - Longitudinal center mark must be equidistant between two probe pins
  - Avoid placing probe tips on holes or surface imperfections
- Record the measurement after the reading stabilizes



Procedure

- Rotate the cylinder and repeat test at the 90-degree,180-degree, and 270-degree marks



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Procedure

- Repeat testing at all four (4) circumferential marks to generate a second data set

Table 1—Sample Table for Recording the Surface Resistivity Readings

Sample	Surface Resistivity (SR) Readings, kΩ-cm								
	0°	90°	180°	270°	0°	90°	180°	270°	Average
A									
B									
C									
								Set average	
								Curing condition correction (· 1.1 lime tank or 1.0 for moist room)	
								Penetrability based on test	

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Data Summary

- Eight (8) SR readings per cylinder

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Data Collection

- SAM QR Code
- SR QR Code

INACTIVATED SAM QR

INACTIVATED SR QR

- Editorial note: QR codes inactivated at the end of the project data collection phase.

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APPENDIX B regarding the SAM and SR Research Procedures

Tennessee Department of Transportation
Division of Materials and Tests

Procedures for RES2023-27: Super Air Meter (SAM) and Surface Resistivity (SR) Research
(Internal Project Number: 99SPR2-F7-060)

Purpose — This document details the procedure and requirements for the implementation of the Super Air Meter (SAM) and Surface Resistivity (SR) equipment and associated test methods within the Department's Quality Assurance (QA) program.

Background — The data provided by SAM and SR testing is integral to the improvement of concrete durability as a part of the Department's Performance Engineered Mixture (PEM) initiatives. The SAM number has been shown to be an indicator of the freeze-thaw durability. The SR value correlates well with the permeability of concrete, an indicator of how susceptible a structure is to degrading elements such as road salt. This project will expand the Department's experience and institutional knowledge. The goal is to provide data on local materials to support the development and implementation of a measurable specification for acceptance.

1. Project Selection

1.1. In accordance with SOP 1-2, all projects where the estimated concrete usage requires the presence of IA inspectors to be on site.

1.2. Tests may be performed by either IA inspectors, Central Office personnel, or their designated representative(s). This testing shall be performed in addition to any standard IA task(s) and will not preclude the procedures found in SOP 1-2.

2. Field Testing

2.1. Perform the SAM test per AASHTO T 395 each time an item is identified for testing. Record the Air Content (nearest 0.1%) and the SAM Number (nearest 0.01).

2.2. Cast 4”x8” specimens for SR per AASHTO R 100 from the same concrete which was SAM tested. Five (5) sets shall be made for testing at 3, 7, 14, 28, and 56 days. Label all specimens for SR testing per Appendix C.

2.3. Report the data using the SAM Form linked in Section 4. Attach the batch ticket representing the tested concrete.

2.4. The person who makes the specimens is responsible for ensuring the specimens are handled appropriately up-to placement in the initial curing conditions. Regional M&T staff shall be responsible for transport of the specimens from initial curing to final storage at the Regional or Central M&T laboratory.

3. Laboratory Testing

3.1. Perform SR testing per AASHTO T 358 on each set of specimens at their required age in either the Regional or Central M&T laboratory.

3.2. After performing SR, break the set of specimens.

3.3. Record SR (nearest 0.1 kΩ-cm) and strength (nearest 10 psi). Report this task using the SR Form linked in Section 4.

3.4. SR testing shall be distributed as follows:

3.4.1. Specimens for 3, 7, and 14 days shall be stored and tested at the Regional Laboratory.

3.4.2. Specimens for 28 and 56 days shall be stored and tested at the Central Laboratory.

4. Data Reporting Once data collection is completed, enter the data via the appropriate Microsoft Forms document.

SAM Form: SR Form:

Inactivated QR codes

5. Schedule and Time Reporting

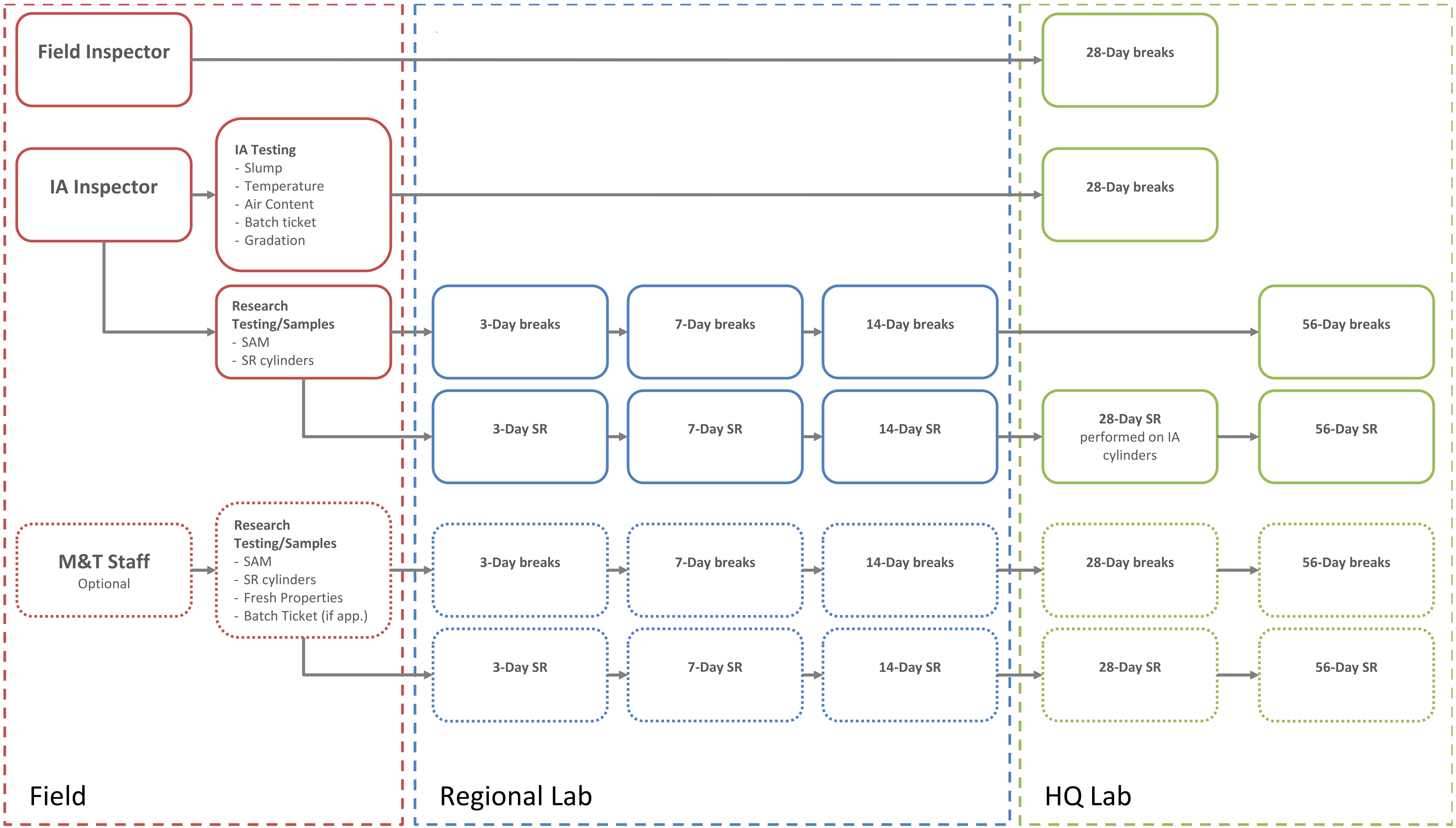
5.1 All work must be documented on the master calendar for this research project. When performing work as a part of this project, create an appointment in Outlook and add HQ.MaterialsandTests@tn.gov as a required attendee. Please include the following information:

- Title: Begin with “RES2023-27:” then “Contract Number”
- Date: Set the appointment for the day the task took place
- Time Reporting:
    - Report to the nearest half-hour
    - Travel time to/from project for fresh property testing shall be recorded
    - Time spent transporting specimens shall *not* be reported
- Body: Include a brief description of the task performed during this specific time

5.2 Please use the corresponding TX Number for all project and laboratory work completed as a part of this project:

- HQ: TX00307632
- R1: TX00308496
- R2: TX00308497
- R3: TX00308498
- R4: TX00308499

Appendix A': Flowchart Detailing Materials and Tests RES2023-27 Commitments



Appendix B': Fresh and Hardened Properties Checklists

Fresh Properties Checklist: *Completed at the job site during normal IA activities*

Information	Entry
Date of Pour	
Mixture ID	
28-Day Strength	
Contract Number	
Operator Name	
Initial Curing Description	
Specimen Numbers (M&T Personnel)	
Specimen Numbers (Field Inspector)	
Slump	
Temperature (˚ F)	
Unit Weight	
Air by traditional pressure meter	
Air by Pressure Method	
SAM number	
Copy of the Batch Ticket	

Hardened Properties Checklist: *Completed at 3, 7, 14, 28, and 56 days*

Information	Entry
Date of Pour	
Date of SR Testing	
Mixture ID	
28-Day Strength	
Contract Number	
Operator Name	
Laboratory Curing Description	
Specimen Numbers (pair)	
SR Specimen 1 (0˚)*	
SR Specimen 1 (90˚)*	
SR Specimen 1 (180˚)*	
SR Specimen 1 (270˚)*	
SR Specimen 2 (0˚)*	
SR Specimen 2 (90˚)*	
SR Specimen 2 (180˚)*	
SR Specimen 2 (270˚)*	
Cylinder 1 Break (Nearest 1 psi)	
Cylinder 2 Break (Nearest 1 psi)	

* *Measure/Record two (2) SR values per location on the specimen*

Appendix C': Specimen Labeling

1A IA SR	- Cylinder Number + “SR”
1/1/2023	- Date Made
CNZ 123	- Contract Number
3 DAY	- Age to be Tested

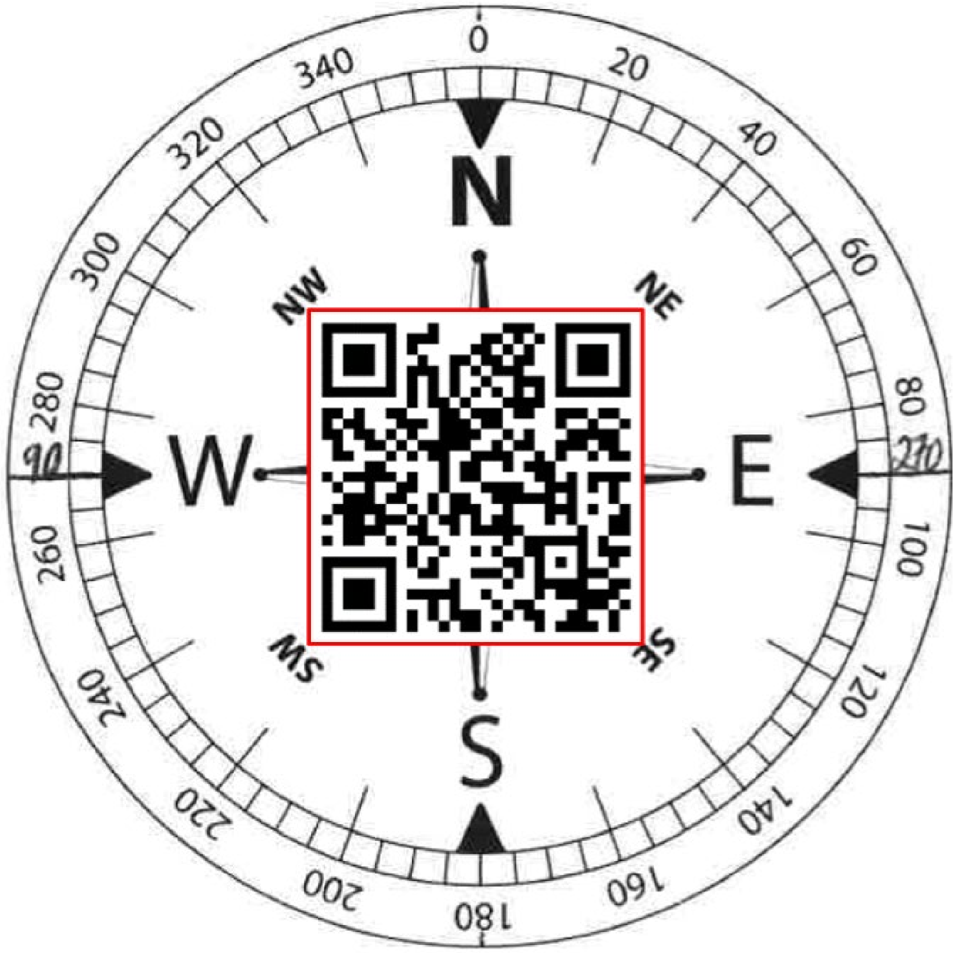


Figure 0-1 depicts a compass printed for SR scribing purposes with the QR code inlayed for reporting