Evaluation of Current WI Mixes Using Performance Engineered Mixture Testing Protocols - Interim Report

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16. Abstract
This study investigated performance related tests with respect to current WisDOT concrete mixtures. Performance tests included the super air meter, hardened air voids, surface and bulk resistivity, formation factor, porosity, optimized gradations, vibrating Kelly ball, box test, coefficient of thermal expansion, and compressive and flexural tests. Several project locations were selected that represented various regions and aggregate sources throughout the state of Wisconsin. Results suggest the valuable of performance tests, which include compressive and flexural strength, super air meter, surface resistivity, coefficient of thermal expansion, and using the optimized gradation curve (Tarantula Curve).

17. Key Words
Performance, Engineered, Mixtures, Portland, Cement, Concrete, Air, Voids, Super, Air Meter, Vibration, Kelly, Ball, Box, Porosity, Resistivity, Bulk, Surface, Formation, Factor, Thermal, Expansion, Compression, Flexural

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1.0 Introduction

Construction specifications as provided by a state highway agency (SHA) typically describe the characteristics of the materials to be used and/or a process for performing work on a project. While specifications cover many aspects of construction, the ideal specification should provide a link between measurable aspects of concrete and anticipated performance of the concrete in a given environment. Most concrete specifications have historically been prescriptive, in other words, more of a means and methods for the construction of concrete pavement. One of the main concerns with this approach is that most of the risk/liability for the performance of the structure is on the SHA and limits the incentive for contractors to innovate their product. A potential alternative that is being evaluated are performance-related specifications (PRS) [1]. A PRS gives the expected performance of a concrete mixture and then relies on the contractor/producer to provide this material while permitting for less restrictions on the constituents of a mixture. The implementation of these new innovations has shown the ability to improve performance while decreasing the unit cost of the material while still meeting performance expectations.

PRS's can take many forms [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Goodspeed et al. [2] developed a PRS for high performance concrete by establishing performance grades based on eight standard tests. Ozyilidirim [3] discussed the development of quantitative relationships linking tests to performance. NRMCA developed performance-based standards that relate hardened concrete requirements to established testing criteria [1]. PRS have also been developed in the late 1990s for pavements [4, 5, 6] that link tests, performance and repair costs. While not a specification per se, The International Federation for Structural Concrete (fib) has developed a model code that outlines calculations of several durability related distresses [7], as have others [9, 10, 11]. Furthermore, the Illinois Tollway has been implementing performance-based specifications, which incorporate dowel bar alignment, thickness, strength and smoothness into a payment calculation.

In response to a directive from the Federal Highway Administration (FHWA) an expert task group was established to examine Performance-Engineered Mixtures (PEM) [6]. This effort has produced the AASHTO PP-84 guide specification that uses a series of standardized tests to evaluate the concrete mixtures. These tests can be used either to design, qualify the mixture, or accept the mixture.

Recent research has shown that blending of different aggregate sizes allows for a reduction in the paste content of a concrete mixture while still showing satisfactory constructability performance by using the Tarantula Curve. The Tarantula Curve is a tool to evaluate the performance of the mixtures. Also, several emerging test methods, Box Test, the V-Kelly, surface resistivity, and the Super Air Meter, have become more practical and useful that give important insights into the constructability and the long-term durability of the concrete. Since these tests can be completed quickly and are not overly costly, the tests have great potential.

2.0 Research Objectives

The objectives of this study are to:

1) Use performance-based testing methods on current WisDOT mixtures, and
2) Collect a comprehensive database of results on several WisDOT mix designs and assess how they compare to proposed Performance-Engineered Mixtures (PEM) specifications. This objective will be completed using the following three tasks:
    - i. Perform field-testing of fresh concrete at the plant and in front and behind the paver using PEM test methods.
    - ii. Perform lab testing on hardened concrete specimens using PEM test methods.
    - iii. Evaluate how current Wisconsin mixture designs fit into proposed PEM specifications.

Based on the WisDOT request for proposal the research is focused on gaining new information on three primary properties:

Strength Properties

- i. Flexural vs. Compressive Strength.

Durability Properties

- i. Surface Resistivity,
- ii. Bulk Resistivity,
- iii. Porosity,
- iv. Formation Factor,
- v. Coefficient of Thermal Expansion,
- vi. Super Air Meter, and
- vii. Hardened Air Voids

Workability Properties

- i. Vibrating Kelly Ball
- ii. Box Test

3.0 Test Methods and Project Selection

In order to produce more complete and representative concrete performance datasets from Wisconsin, Behnke Materials Engineering (BME) worked with the Project Oversight Committee (POC) and the Wisconsin Concrete Pavement Association (WCPA) in order to select project locations in different regions throughout the state. This widespread assortment of projects allows for the analysis of concrete products consisting of different aggregate types such as igneous and glacial gravels, limestones, and dolomites. Project locations with basic aggregate source information is presented in the following section, followed by testing procedures, and sample preparation.

3.1 Project and Testing Breakdown

3.1.1 Project Selection Information

The eight total project site visits were conducted throughout the 2017 and 2018 construction seasons. An effort was made to select projects in all WisDOT regions to incorporate the variety of different materials (i.e.: aggregate, cementitious products) and methods (i.e.: contractors) used throughout the state. Final project selection was approved by the Project Oversight Committee (POC) prior to the field visit. Table 1 shows the outline of the projects visited for this research effort and Figure 1 shows a map of where these projects are located.

Table 1: Project and Aggregate Source Information

					Aggregate Information			
Project ID	**Roadway**	**Location**	**Region**	**Year Visited**	**Coarse Agg. Source**	**Specific Gravity***	**Absorption %***	**Classification**
1517-07-83	Summit Avenue to Northview Road	Appleton	NE	2017	Ben Carrie	2.768	0.846	Limestone
2025-13-71	USH 10 to STH 441	Capitol Drive	SE	2017	Genessee	2.708	1.346	Gravel
1401-02-71	USH 2 / Belknap Street	City of Columbus	SE	2017	Michels Columbus	2.584	2.440	Dolomite
8680-00-71	James Street Industrial Drive to River Road STH 16	City of Superior	NW	2017	Robertson	2.753	1.035	Quartzite
2788-00-72	Five Fields Road to Wethersfield Road	West Waukesha Bypass	SE	2017	Lafarge Colgate	2.736	0.827	Gravel
1003-10-84	IH 39 - Illinois State Line - Madison, STH 11 to CTH O	I-39 Rock County	SW	2018	Townline	2.646	1.575	Gravel
1007-11-71	IH 39 - Illinois State Line - Madison, E Church Road to Church St. NB	I-39 Dane County	SW	2018	Prairie Ave Concrete	2.672	1.399	Gravel
1022-08-72	IH 94, 250th Street to Wilson Creek	I-94 Menomonie	NW	2018	Hughes	2.594	2.585	Dolomite

*Specific Gravity and Absorption data acquired from WisDOT Approved Aggregate Source List.

Figure 1: Project Location Map

3.1.2 Test Sessions

The concrete was sampled at the plant, before the paver, and after the paver. This will be known as Plant, Before-Paver, and After Paver. This was done four times for each project except for Columbus, and are referred to as "sessions" herein. These sampling sessions were performed over two days in both the morning and afternoon (numbered chronologically – sessions 1 through 4), to determine the variability of the material on the project. This approach would capture any changes of properties as plant and field conditions vary throughout the day.

3.2 Sample Preparation

3.2.1 Sampling

An objective of this research was to better understand how the concrete mixtures changed from production at the plant, to placement before the paver, and then after the paver consolidated the concrete. Plant sampling was conducted by either a partially filled loader bucket or if a mixer truck was used (which was for all projects except Superior), a small portion of material was discharged prior to the truck leaving the plant. Before-paver samples were taken on-grade after the material had been discharged but prior to the material entering the paver. After-paver samples were taken immediately after the paver past over the material but before the finishing crew. The before and after-paver samples were taken at the same location for each session so the material sampled would be the same, however, the after-paver sample had been run through the paver. Due to workflow, the plant samples were not taken from the same truck as the field samples; however, the research team feels that this concrete is representative of the concrete that was being produced at the project. Appendix A lists all the sampling sessions with corresponding testing.

3.2.2 Consolidation

Various consolidation methods were used throughout the project including rodding, a battery-powered vibrator, and a 120V AC powered vibrator. At the beginning of the project consolidation was not considered as a primary testing variable, however, high variability of test results was observed which drove the research team to evaluate consolidation procedures as a method to reduce variability. The initial testing plan for the strength specimens (compressive strength and beam modulus of rupture) called for consolidation using a battery-powered vibrator because that is the standard practice of WisDOT. For the hardened specimens, AASHTO T 23 was followed for casting and curing while consolidation was accomplished using either rodding or a battery-powered vibrator. For the plastic testing, both the vibrating Kelly ball (V-Kelly) and the box test required the use of the 120V AC powered vibrator, however, these two tests require different vibration speeds and vibration heads. The V-Kelly requires a 13/16” square head vibrating at 8,000 vibrations per minute (VPM) while the Box test requires a 1” square head at 12,500 VPM. The variable speed *Wyco Sure Speed – WVG1* was used for all testing.

3.2.3 Casting and Curing

Specimen preparation was based primarily on AASHTO T 23 with a few exceptions that will be discussed in latter sections. Due to the maximum aggregate size of all evaluated mixtures being 1.5”, all concrete cylinders were required to be the 6” x 12” size. Disposable plastic molds were used for all cylinders with a tightly fitting cap. Reusable steel molds were used for casting beams with moist burlap set on the surface with a tarp over the top to reduce moisture loss. Per AASHTO T 23 all hardened specimens were cured onsite for 24-48 hours. The samples were then transported back to the testing facility. AASHTO T 23 allows a maximum transportation time of 4 hours; however, the Superior project was outside of the 4-hour range so extra care was taken to keep these samples at a uniform temperature and to minimize moisture loss and ensure that no damage incurred.

All specimens except for the surface resistivity samples were cured in a lime solution at the Behnke Materials Engineering (BME) facility. The surface resistivity samples were cured in a cure room at the S.T.A.T.E. Testing facility as lime-water solution is known to lower the resistivity readings on average by 10% per the testing standard. All strength and resistivity samples remained in the curing condition until testing was complete. The remaining specimens were cured for 7 days and then removed from curing environment and stored in the dry condition.

3.3 Strength Properties

3.3.1 Compressive Strength

Compressive strength of the concrete was measured via AASHTO T 22 method using 6” x 12” cylindrical specimens. Eleven specimens per project were cast for each project for strength testing and all eleven specimens were cast in testing session 2. Two specimens were tested at 3, 7, 14, 28, and 90 days after casting.

3.3.2 Modulus of Rupture

The modulus of rupture (MOR) for the concrete beams were measured according to AASHTO T 97 which uses three-point bending. One beam was tested at 7, 14, and 90 days after casting while three beams were broken at 28 days after casting. All samples were cast from material that was sampled in testing session 1 for each project and from material that was sampled from the before-paver location.

3.4 Durability Properties

Durability is the ability for a material to last for extended periods of time without significant deterioration to its physical structure or properties. Materials that are durable are desirable for many reasons such as cost savings, conserving resources, reducing waste and the environmental impacts of repair or replacement. These properties are particularly important to concrete products that are exposed to the environment because concrete will be subjected to weathering, chemical attack, and abrasion; all of which will deteriorate the concrete’s engineering properties over time. The following test methods are designed to assess the durability of concrete products.

3.4.1 Surface Resistivity

Each mixture’s surface resistivity was measured according to AASHTO T 358 using 6” x 12” cylindrical specimens. Nine cylinders were cast for each project location, where three samples were produced during each testing session for the first three sessions. Cylinders were stored in a temperature-controlled (21 - 25°C) cure room at 100% humidity when not being actively tested. A cure room was chosen in lieu of limewater since limewater is known to reduce resistivity on average by 10%. All cylinders were tested at intervals of 7, 14, 28, 56, and 90 days after casting. Samples were removed from the cure room for testing and ambient temperature was not recorded during testing although the samples were tested in a temperature-controlled laboratory environment. Samples were returned to the cure room immediately after testing. The samples were reused, so all nine cylinders from each project location were tested at each of the required curing intervals.

Table 2 shows the AASHTO defined levels of chloride ion penetration for a given surface resistivity measurement. Resistivity is inversely related to chloride ion penetration, meaning the higher the resistivity the lower the chloride ion penetration, which is a desirable property. The typical trend is for the surface resistivity to increase as the concrete has longer times to cure. This means that potential for chloride ion penetration decreases with curing time. Figure *2* shows the device used to measure surface resistivity.

Table 2: Chloride ion penetration levels as specified by AASHTO T 358 Table 1.

Chloride Ion Penetration	
Level	**Surface Resistivity Reading (kΩ-cm)**
High	< 9.5
Moderate	9.5-16.5
Low	16.5-29
Very Low	29-199
Negligible	> 199

Figure 2: Surface Resistivity Apparatus.

3.4.2 Porosity, Bulk Resistivity, and Formation Factor

Concrete samples from Rock County, Dane County, and Menomonie projects were examined for porosity and bulk electrical resistivity measurements.

3.4.2.1 Porosity

Porosity measurement was conducted on the cylindrical specimens with a diameter of 152 ± 2 mm (6 ± 0.08 in.) and a thickness of 51 ± 1 mm (2 ± 0.04 in.). The volume of permeable pores was determined according to ASTM C642-13 with the exception that the concrete specimens were saturated by vacuum, instead of being placed into boiling water. Vacuum saturation has been shown to be a comparable method of sample conditioning which enables the saturation of all air voids in the specimen. After the specimens were oven dried at 105 ± 2 °C (221 ± 3.6 °F), the mass was measured and then they were placed into the vacuum chamber with a vacuum level of 933 ±

266 Pa (7 ± 2 Torr) for 3 hours. Saturated limewater was drawn into the vacuum chamber and specimens were maintained in vacuum for another hour. The specimens were kept submerged for another 48 hours after the vacuum session. The mass of the saturated surface-dry (SSD) samples and their apparent mass under water were measured to calculate the porosity. Eight cylinders of each mixture were tested for porosity.

3.4.2.2 Bulk Electrical Resistivity

The electrical resistivity was measured on the concrete specimens with a diameter of 152 ± 2 mm (6 ± 0.08 in.) and a thickness of 51 ± 1 mm (2 ± 0.04 in.). Specimens were conditioned using Option A (immersion in a calcium hydroxide saturated simulated pore solution) of AASHTO TP 119-17. The calcium hydroxide simulated pore solution consists of 7.60 g/L NaOH (0.19M), 10.64 g/L KOH (0.19M), and 2.0 g/L $Ca(OH)_2$. Eight cylinders of each mixture were tested for electrical resistivity. Specimens were immersed in a 5-gal bucket with enough calcium hydroxide saturated simulated solution to cover the specimens by 38 mm. The resistance of the specimens was measured using a resistivity meter with a frequency of 1 kHz at 23 ± 2 °C (73.4 ± 3.6 °F). The electrical resistivity was calculated according to AASHTO TP 119-17. Figure 3 shows the device used to measure bulk resistivity though this can also be done using any surface meter [12].

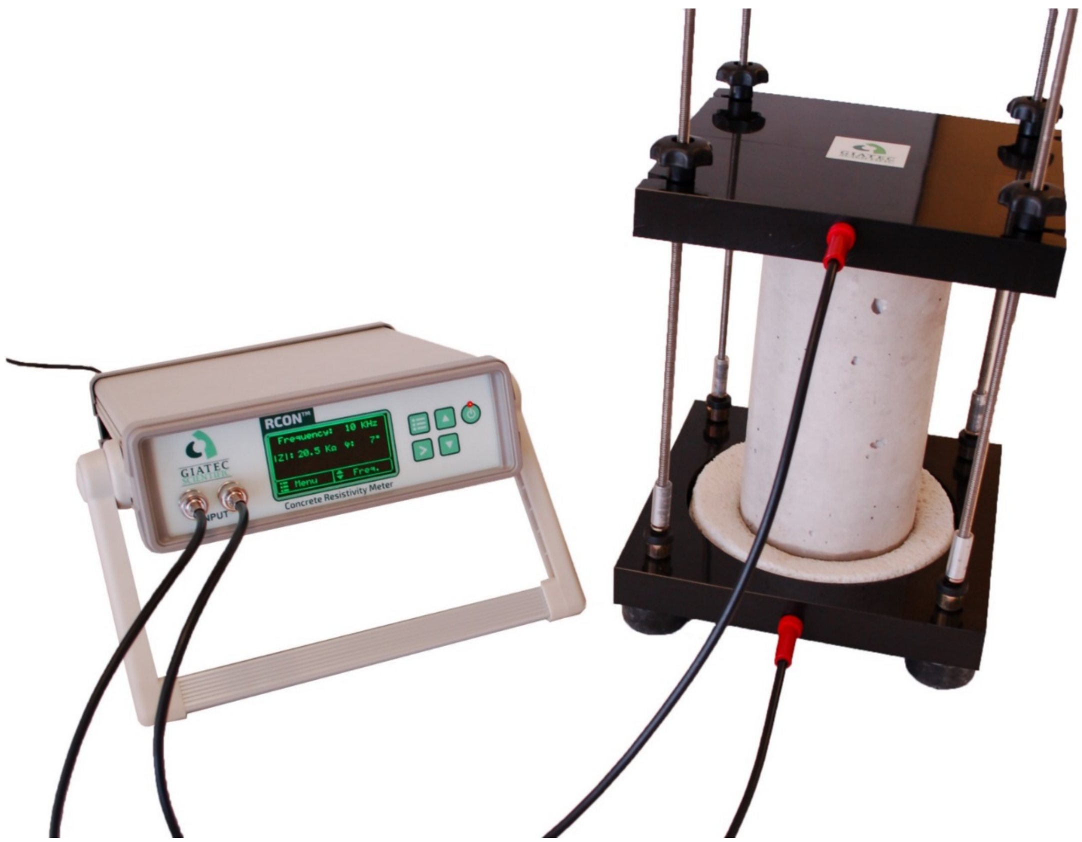


Figure 3: Bulk Resistivity Apparatus.

3.4.2.3 Formation Factor

The intent of the formation factor is to describe the pore network and its connectivity. Ideally less pore connectivity leads to higher durability as less material is able to penetrate the concrete and cause corrosion. The formation factor (*F*) is calculated as the ratio of the electrical resistivity (obtained through Bulk Resistivity) of the saturated concrete (ρ_C) with simulated pore solution to that of the simulated pore solution:

$$F = \frac{\rho_C}{\rho_{ps}} \tag{1}$$

where ρ_{ps} is the electrical resistivity of the simulated pore solution (0.128 Ω·m). Given this relationship, high Formation Factor values are desired to increase the predicted durability.

3.4.3 Coefficient of Thermal Expansion

The coefficient of thermal expansion/contraction describes how much concrete will expand or contract under changing thermal conditions. This is particularly important in paving applications. Because concrete is usually sawcut to prevent shrinkage cracking during curing, this creates individual slabs. These slabs will warp (convex or concave) depending on the thermal gradient throughout the depth of the concrete slab. In cases where the concrete is highly susceptible to thermal expansion or contraction, premature damage to the concrete slabs can occur. It also can become a road hazard to the motoring public in the most severe cases. This is particularly important in paving applications where the concrete is subject to severe thermal cycling. It is generally assumed that higher coefficients of thermal expansion are not desired because this will cause the least volumetric stability under changing thermal conditions. Both the cement paste and coarse aggregates play a significant role in the thermal expansion and contraction properties of the mixture. Limestone aggregates typically have the lowest expansion and quartz-based aggregates typically have the highest coefficient of thermal expansion.

Concrete cylindrical sample specimens were tested to determine the coefficient of thermal expansion (CTE) according to AASHTO T 336. Specimens were conditioned for no less than 48 hours by submersion in limewater and until two successive weighings of the surface-dried sample at intervals of 24 hours show an increase in weight of less than 0.5%. Specimen lengths were measured at room temperature after removal from the conditioning tank and then placed into the measuring apparatus. CTE values are determined by taking measurements with the LVDTs at 10°C and 50°C and then 10°C again to simulate heating and cooling segments, where a segment is the measured length change for a given heating (10°C to 50°C) or cooling change (50°C to 10°C). A cycle is two consecutive segments. The following equation is used to calculate the CTE:

$$CTE = \frac{CTE_1 + CTE_2}{2}, \left[reported\ units = \frac{\mu\varepsilon}{°C}\right] \tag{2}$$

where

$$CTE_n = \frac{\left(\frac{\Delta L_a}{L_0}\right)}{\Delta T} \tag{3}$$

$$\Delta L_a = \Delta L_m + \Delta L_f \tag{4}$$

$$\Delta L_f = C_f \times L_0 \times \Delta T \tag{5}$$

$\Delta L_a =$ actual length change of specimen during temperature change, mm

$L_0 =$ measured length of specimen at room temperature, mm

$\Delta T =$ measured temperature change, °C (increase = positive, decrease = negative)

$\Delta L_m =$ measured length change of specimen during temperature change, mm (increase = positive, decrease = negative)

$\Delta L_f =$ length change of the measuring apparatus during temperature change, mm

$C_f =$ correction factor accounting for the change in length of the measurement apparatus with temperature, $\frac{\frac{mm^{-6}}{mm}}{°C}$

3.4.4 Air Void System

It is very common in the production of concrete to include chemical admixtures called air entrainers. Air entrainers are essentially surfactants that are typically added to the mix water, and less often as a dry powder to the dry cement. Air entrainment's purpose is to encourage the formation of small spherical air bubbles during mixing of fresh concrete that will be evenly distributed throughout the hardened cement paste. It can also help improve the workability during the mixing and forming stages. Ultimately, the purpose of these air voids is to decrease the susceptibility of the concrete to freezing water within the pores. When pore fluid freezes, it expands, and the entrained air void system provides extra space for the ice to expand into. If the pressure induced by the freezing water exceeds the tensile strength of the concrete, the cavities will dilate and rupture causing cracks, scaling, and crumbling. Ideally, the entrained air voids should be closely spaced, yet still isolated from each other and from large capillary pores. This reduces the possibility for the voids to become filled with water, rendering them ineffective. Additionally, if concrete is not properly consolidated larger "entrapped" air voids may be present which contribute to the overall air content, however, do not provide the same durability benefits that entrained air voids provide. Entrapped air should be minimized in all concrete mixtures.

3.4.4.1 Super Air Meter (SAM)

The SAM device is similar to the ASTM C231 Type B air meter with some modifications. The SAM uses six restricted clamps to account for increased pressures and a digital pressure gauge for testing. The device is shown in Figure 4.

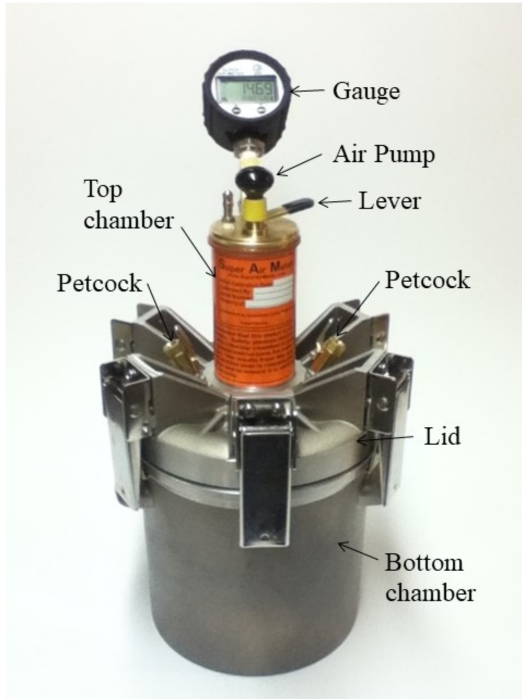


Figure 4: SAM testing device.

The first step is to fill, consolidate, and strike off the fresh concrete in the bottom chamber in accordance with ASTM C231. The top rim of the bottom chamber and the bottom ring of the lid are cleaned thoroughly to ensure a proper seal. The rim of the bottom chamber should be free of any concrete, aggregates, or paste. This cleaning is important for a proper seal between the top and bottom chamber since the pressure increments are higher for the SAM than the Type B meter.

The clamps then fasten the lid to the bottom chamber and water is added through the petcock valves to fill the void between the bottom of the lid and the top of the concrete. Once all the air bubbles are out of the bottom chamber, the petcocks are closed. Next, the top chamber is pressurized to 14.50 psi ± 0.05 psi and allowed to equalize. The bottom chamber is struck with a rubber mallet while the lever is pressed to allow the two chambers to equalize. The lever is held down for 10 seconds to reach equilibrium. The pressure value on the gauge is recorded and used to calculate the volume of the air in the concrete [13, 14, 15, 16, 17]. The top chamber is then pressurized up to 30.00 PSI ± 0.05 PSI without opening the petcocks. The lever is held down for 10 seconds to reach equilibrium while the bottom chamber is hit on all sides. The top chamber is then pressurized to 45.00 PSI ± 0.05 PSI without opening the petcocks. The lever is then held down for 10 seconds and the sides of the bottom chamber are hit with a rubber mallet. This pressure value should be recorded and will be called, Pc1. The pressure is then released from the bottom chamber by opening the petcock valves. The lid is left attached while water is added to the bottom chamber through the petcocks to fill the space between the lid and the concrete and the procedure is repeated. After completing the 45 PSI pressure step, the equalized pressure is recorded as Pc2. The test takes an experienced user between 8-10 minutes to complete. Figure 5 shows a typical data set and a video of the test is available [18].

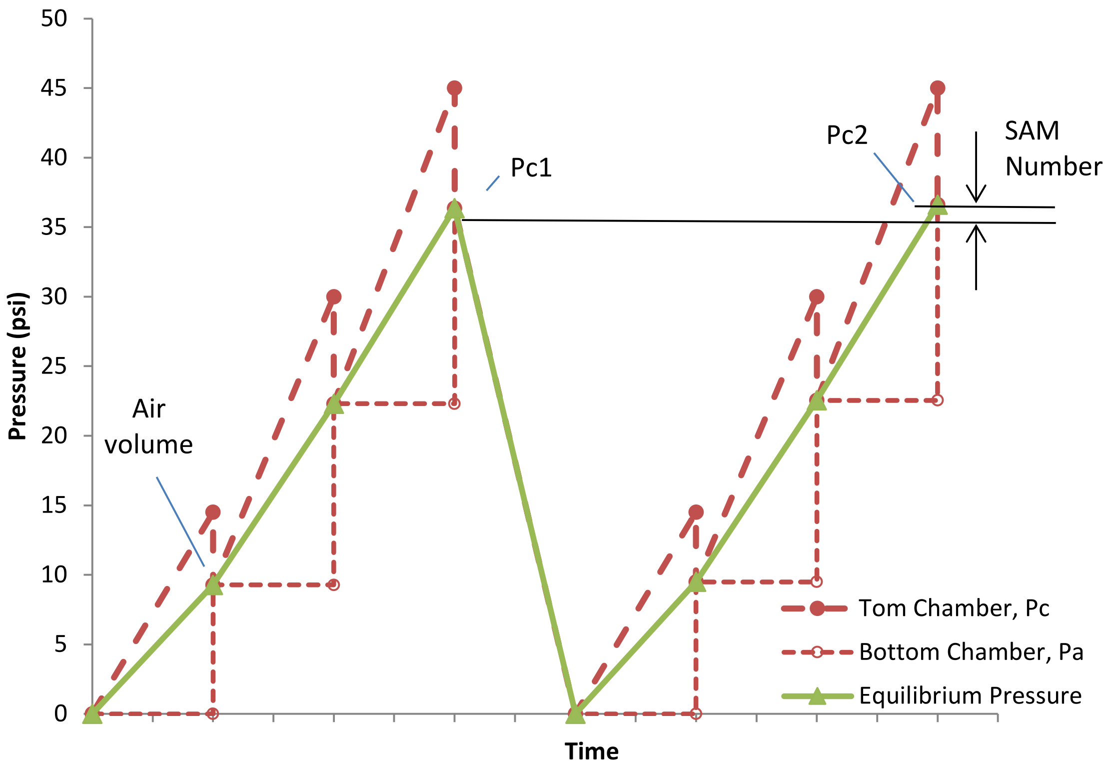


Figure 5: SAM pressure steps graphically shown for the top and bottom chambers.

The SAM Number is the term used to quantify the differences in the two pressure curves shown in Figure 5. Mathematically, this term is shown as: SAM Number = Pc2 – Pc1.

Pc1 is the first equalized pressure at 45 psi and Pc2 is the second equalized pressure at 45 PSI. The SAM Numbers ranged from 0.03 to 0.78 for the mixtures represented. The SAM Number is an empirical number that will be correlated to other parameters such as Spacing Factor. The SAM Number is used as a correlative number because it is unitless.

3.4.4.2 Hardened Air Voids

The ASTM C 457 hardened air void analysis was completed by Oklahoma State University. Concrete samples were cut into ¾" thick slabs and polished with sequentially finer grits. The surface of the sample was preserved with an acetone and lacquer mixture to strengthen the surface before it was inspected under a stereo microscope. After an acceptable surface was obtained, the sample is cleaned with acetone. The surface was then colored with a black permanent marker, the air voids were filled with less than 1 µm white barium sulfate powder, and the air voids within the aggregates were blackened under a stereo microscope. This process makes the concrete sample black and the voids in the paste white. Sample preparation details can be found in other publications [19, 20]. The samples were analyzed with ASTM C457 method C by using the Rapid Air 457 from Concrete Experts, Inc. A single threshold value of 185 was used for all samples in this research and the results do not include chords smaller than 30 µm. These requirements have shown to provide similar techniques by others and satisfactory results with the materials and instrument used [20, 21, 22].

3.5 Workability

Adequate and application-specific workability of concrete is essential to slipform paving operations. If the mixture does not respond well to vibration, then the material will not properly consolidate, and this will leave unintentional “entrapped” air voids at the surface and within the pavement. If the concrete is too workable then the material will not retain its shape after passing through the paver. The traditional method of quantifying workability is through the slump cone test under AASHTO T 119; however, this does not characterize how the material behaves under the influence of vibration. This is important to consider as slipform pavers rely on vibration for forming and consolidating the mixture which requires the workability to be in a specific range to obtain proper consolidation while allowing the material to stay formed without slumping after the paver passes. It is also important to note that not all material with the same slump perform the same under vibration which identifies a need for a new procedure to be implemented to characterize workability for slipform mixtures.

The Tarantula Curve was used to produce concrete mixtures with adequate workability as shown in Figure 6. The Tarantula Curve boundary and the coarse and fine sand limits were chosen to help designers produce concrete mixtures with good workability. Any mixture within the curve would be expected to have good workability with enough cementitious and water contents. It is important to realize that aggregate gradations will vary in practice. This means that mixtures that are designed to be close to the Tarantula Curve may violate the limits as the gradation varies. This may require a higher amount of cement paste in the mixture to obtain satisfactory performance of the mixture. One way to address this is to encourage producers to make their aggregate gradations be far enough away from the limits that they will not violate the boundary under typical variations in the gradation. One way to encourage this is to have an inner boundary, known as the warning band, that helps account for the variability in the aggregate gradation. The warning band in Figure 6 is 3% lower than the specified boundary. This is an estimate based on previous testing, but this should be investigated in greater detail.

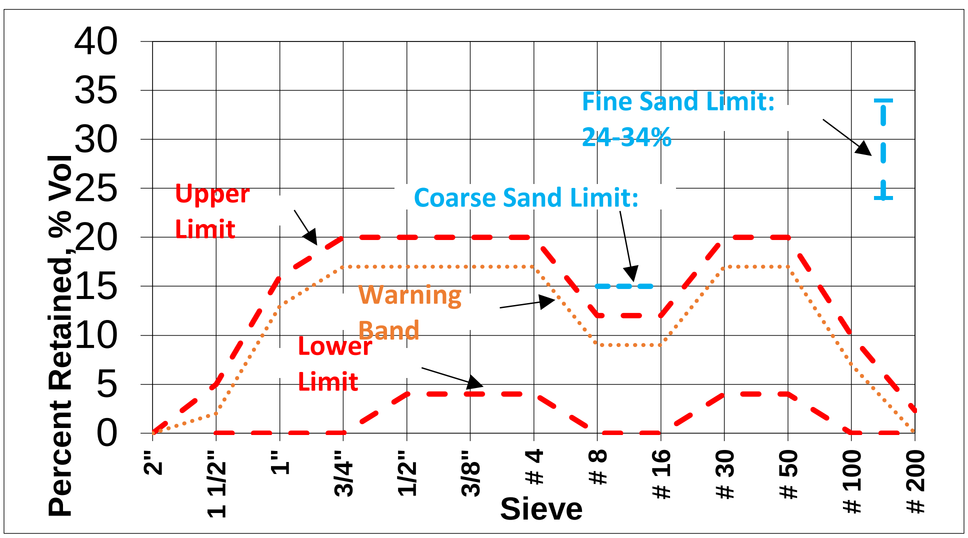


Figure 6: Tarantula Curve guidelines for workable mixtures.

Based on Oklahoma State University previous research, there is additional correlation between the proximity to the warning band and cementitious content.

3.5.1 Vibrating Kelly Ball (V-Kelly)

The V-Kelly test method is aimed at characterizing the properties of the plastic concrete under vibration. The V-Kelly test is a relatively new concept that is based on a penetration based test that was developed as an alternative to the slump cone test [23, 24, 25]. The original method involved placing a frame and weighted semispherical ball as shown in Figure 7. The penetration of the ball is monitored over time. The original test was formerly standardized in ASTM C360-92, The Standard Test Method for Ball Penetration in Freshly Mixed Hydraulic Concrete. Due to lack of adoption of the test method the test procedure was discontinued from ASTM in 1999.

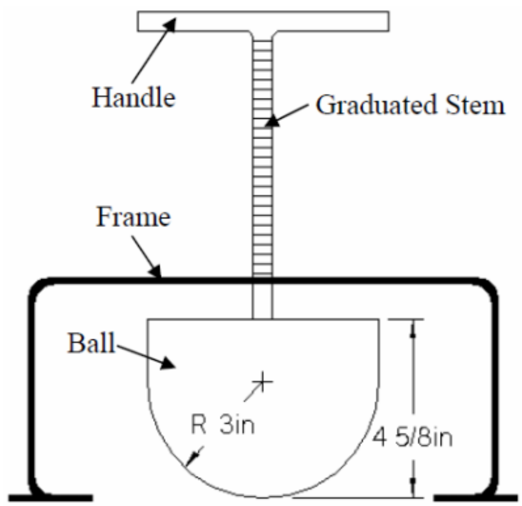


Figure 7: Schematic of the testing apparatus for ASTM C360-92. [26]

The ASTM C360 procedure was then modified by Iowa State University to add vibration to the test. The test is similar, but a vibrator is attached to the ball and the rate of penetration is measured over 30 seconds. Once the data is obtained a curve fit is used to determine the V-Kelly Index (V_{Index}) from the following relationship:

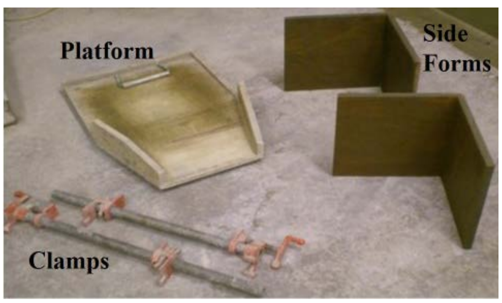
$$D_{Pene} = V_{index} \times \sqrt{t} + c$$

Where:

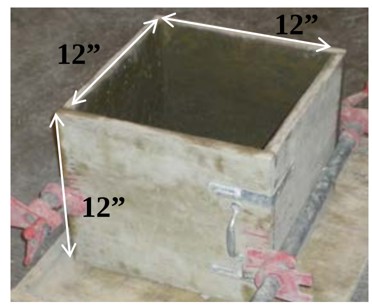
D_{Pene}:	Penetration at time *t* (in)
V_{Index}:	V-Kelly Index
t:	Time (sec)
c:	Initial Penetration (in)

3.5.2 Box Test

A mixture for a slipformed paver requires the concrete to be flowable enough for consolidation, but still hold an edge. The Box Test was developed to visually quantify the workability based on comments from the slipformed paving industry. This test has successfully been used as a tool during the trial batching process to understand the performance response to vibration and the ability of the mixture to hold an edge. The components of the Box Test are shown in Figure 8(a). The two L-shaped forms have been made to form a hollow box on top of the platform as shown in Figure 8(b). The two pipe clamps with a span of 18 inches or a ratchet strap can be used to hold the L-shaped forms together. The vibrator parameters of frequency and head size has been specifically designed to be comparable to the consolidation of a slipformed paver, and therefore it is imperative to use the proper vibrator when conducting this test. A 1-inch square head electric vibrator operating at 12,500 vibrations per minute is required to provide the consolidation to the concrete.



(a)



(b)

Figure 8: (a) components of the Box Test and (b) dimensions of the Box Test.

After the components of the Box Test have been assembled, concrete can be uniformly hand scooped into the box up to a height of 9.5 in. Then a 1 in. square head vibrator running at 12,500 vibrations per minute is inserted and allowed to vibrate downward into the concrete for three seconds. Then the vibrator continues vibration while raising the vibrator upward for three seconds and then finally removing the vibrator from the box of concrete. Immediately, the clamps are to be removed from the side wall forms and then both side wall forms are removed. This process can be described as a four-step process as shown in Figure 9.

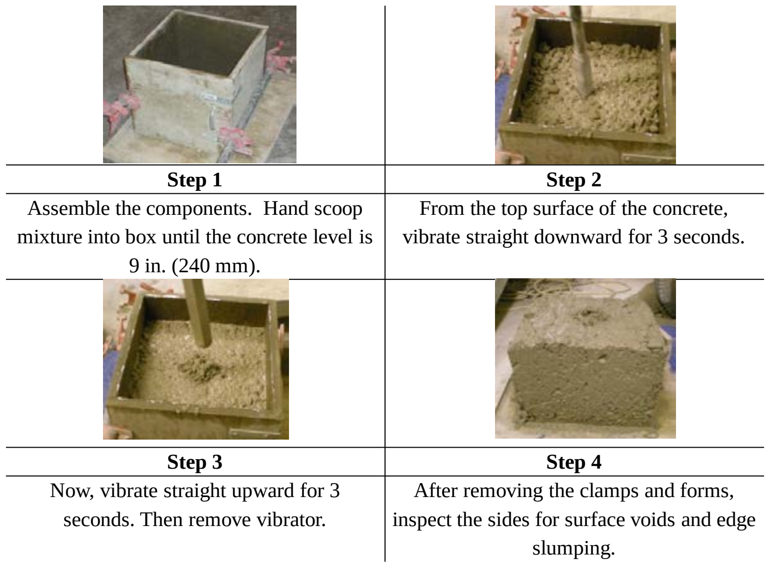


Figure 9: The four steps of the Box Test.

The response of a mixture to vibration can be assessed by the surface voids observed on the sides of the box using Figure 10. If a mixture responded well to vibration, the overall surface voids should be minimal because the vibration waves were able to transfer through the concrete and remove these voids. If, however, the sides of the concrete mixture had large amounts of surface voids, it did not respond well to vibration. The average surface voids for each of the four sides were estimated with a number ranking using Figure 10 and an overall average visual ranking was given to each test. The average of four sides with 10-30% surface voids, or a ranking of 2 for a mixture was deemed a good vibration response with an acceptable number of voids.

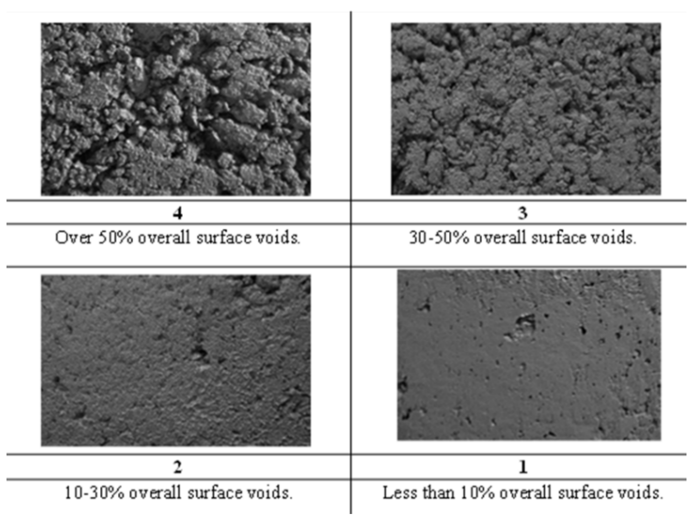


Figure 10: The Box Test Ranking Scale.

The Box Test can provide insight into possible edge slumping issues. The top and bottom edge slumping can be measured to the nearest 0.25 in. by placing a straightedge at each corner and using a tape measure to find the length of the highest extruding point. It is common for well-performing paving mixtures to have less than 0.25” of edge slumping with the Box Test.

4.0 Data Analysis

4.1 Mix Design Analysis

During the project, it was realized that although producers were using the WisDOT spreadsheet, some of the mixtures were not within the Tarantula Curve. This means that the workability of these mixtures may be impacted. This section discusses the gradation for each project and compares the performance to the Box Test.

4.1.1 Appleton

The Appleton gradation, as shown in Figure 11, was within the Tarantula Curve on all limits except for the coarse sand limit. Further, the amount on the ½" sieve is very close to the recommended limit. The coarse sand is responsible for cohesion within the mixture. In some of the Box Test results, shown in Figure 12, the corners of the box did not remain in place. This shows the lack of cohesion of the mixture. The other results of the Box Test show good performance with some surface voids but minimal edge slumping. It is recommended to increase the coarse sand content of this mixture to be within the Tarantula Curve limits.

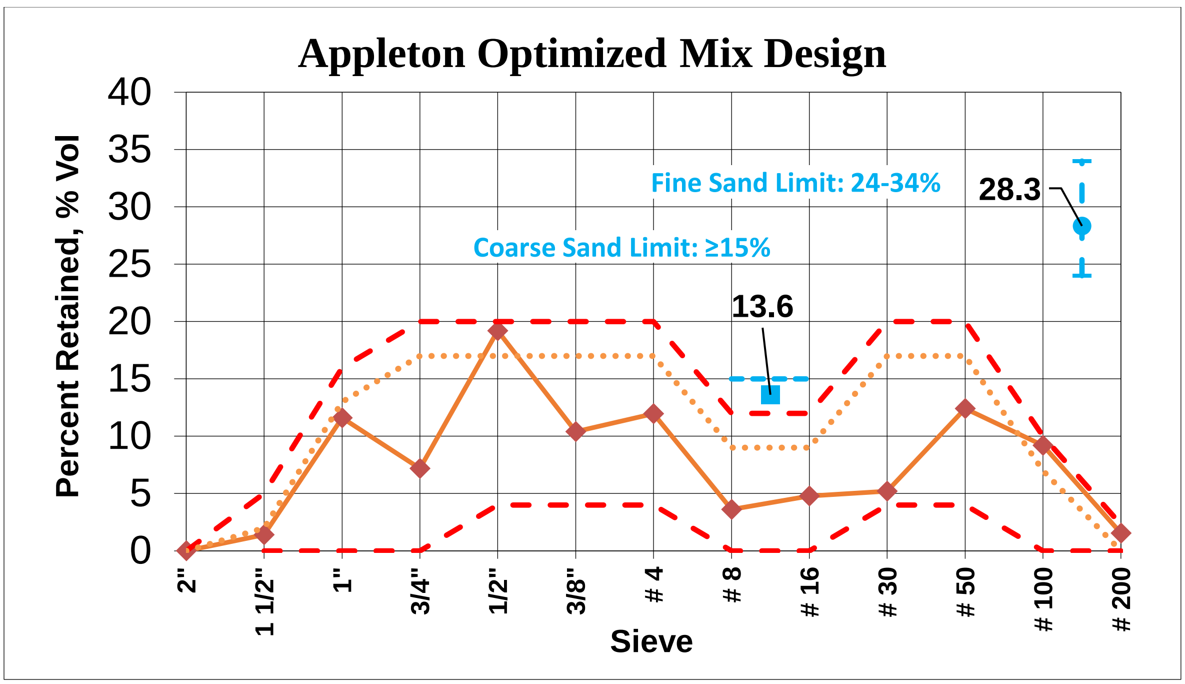


Figure 11: Appleton Tarantula Curve.

Figure 12: Appleton Box Test Photos.

4.1.2 Capitol Drive

The mixture for Capitol Drive, as shown in Figure 13, is within the Tarantula Curve but is right at the limit for the ½" sieve. The performance in the Box Test, shown in Figure 14, looks to be very good in the images. Because this mixture is within the limits of the Tarantula Curve the cementitious content is recommended to be 500 lbs. with a W/C < 0.43. This mixture used a much higher cementitious content of 565 lbs. and W/C = 0.37. This low W/C is not desirable as it will cause autogenous cracking of the concrete. This low W/C was probably necessary to make the concrete mixture hold and edge because of the higher cementitious content. It is recommended that the cementitious content be reduced for future mixtures.

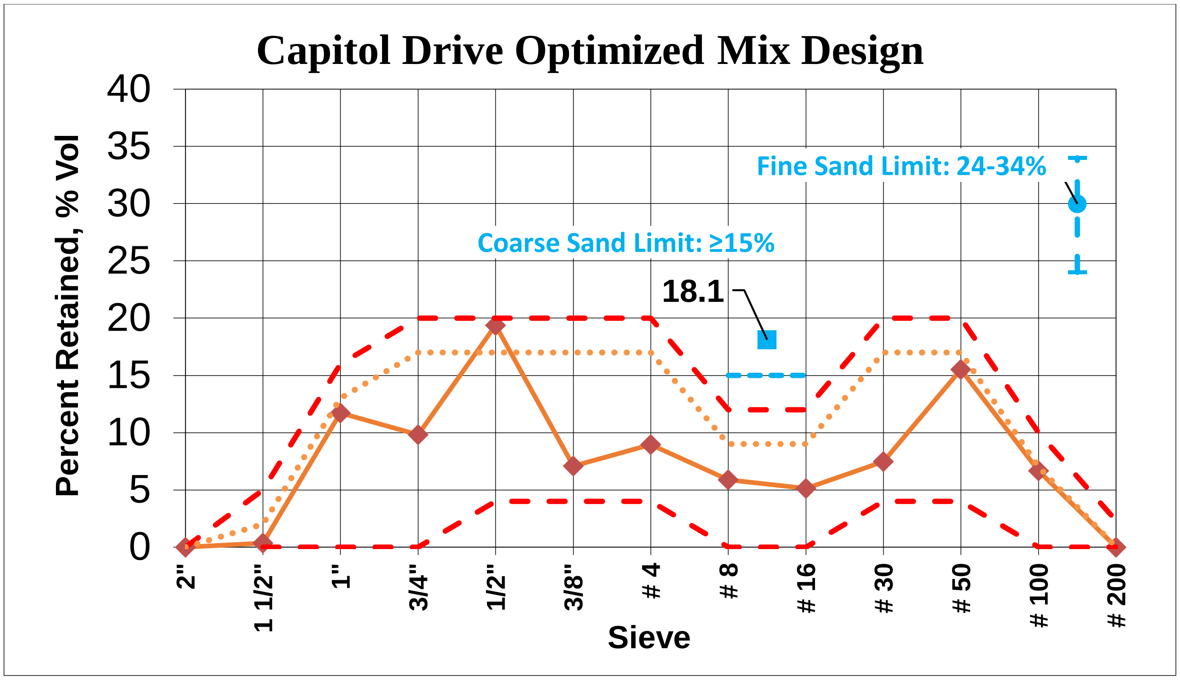


Figure 13: Capitol Drive Tarantula Curve.

Figure 14: Capitol Drive Box Test Photos.

4.1.3 Columbus

The mixture for the Columbus project, as shown in Figure 15, violated the limit for the ½" sieve and the fine sand content. Most of the images from the Box Test, shown in Figure 16, show a higher amount of surface voids than would be preferred but the results are acceptable. When these voids are within the volume of the concrete then they will be expected to lower the strength and decrease the long-term performance of the pavement. Since this mixture is outside the Tarantula Curve then a cementitious content > 550 lbs. is recommended. This matches what is provided. The cementitious content could be reduced in this mixture with slight changes to the gradation.

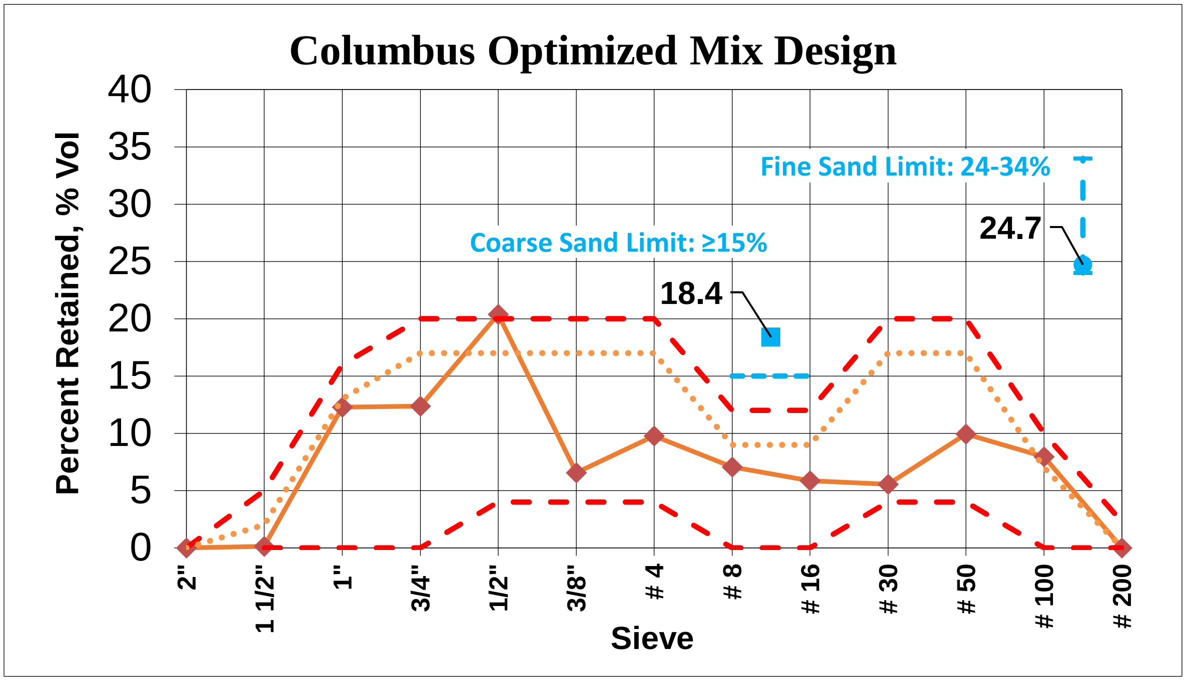


Figure 15: Columbus Tarantula Curve.

Figure 16: Columbus Box Test Photos.

4.1.4 Superior

The mixture for the Superior project, shown in Figure 17, was right at the limits for the ½" sieve and the fine sand content. If a mixture is at the limits of the Tarantula Curve that will be used for production concrete, then one would expect to produce some mixtures that do not have satisfactory performance. A design is expected to be out of the suggested limits about 50% of the time if the gradation used in the design is the average for the aggregate. Most of the Box Test results, shown in Figure 18, look good with some edge slumping on the last few images. Because the mixture is within the boundaries of the Tarantula Curve then a cementitious content of 500 lbs. with a w/cm of 0.43 may be possible.

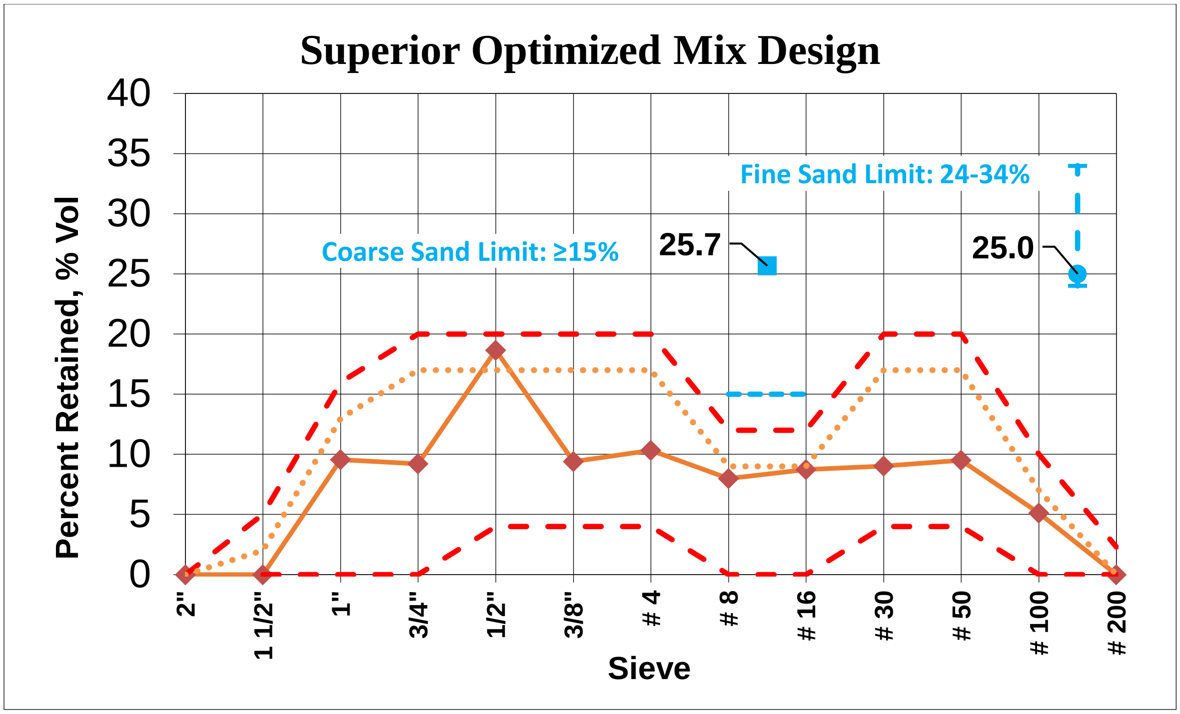


Figure 17: Superior Tarantula Curve.

Figure 18: Superior Box Test Photos.

4.1.5 West Waukesha Bypass

The mixture for the West Waukesha Bypass was out of the Tarantula Curve on the fine sand and very close to the limit in the 1" and #8 sieve, as shown in Figure 19. This would predict that the mixture would have consolidation issues. The Box Test performance, shown in Figure 20, demonstrates this. In nearly every image one can see large voids on the surface of the Box Test. This means that these large voids are within the concrete. These voids will reduce the strength of the concrete and can lead to premature cracking. It is recommended that the gradation of this mixture be adjusted to improve the performance of the mixture. The mixture used a cementitious content > 550 lbs. Based on the results the cementitious content should likely be increased if this gradation is used. While it may be possible to fix this issue with a larger amount of cement paste in the mixture, it is not desirable for the durability, sustainability, and cost of the concrete. Small changes in the aggregate gradation would be expected to have improved performance.

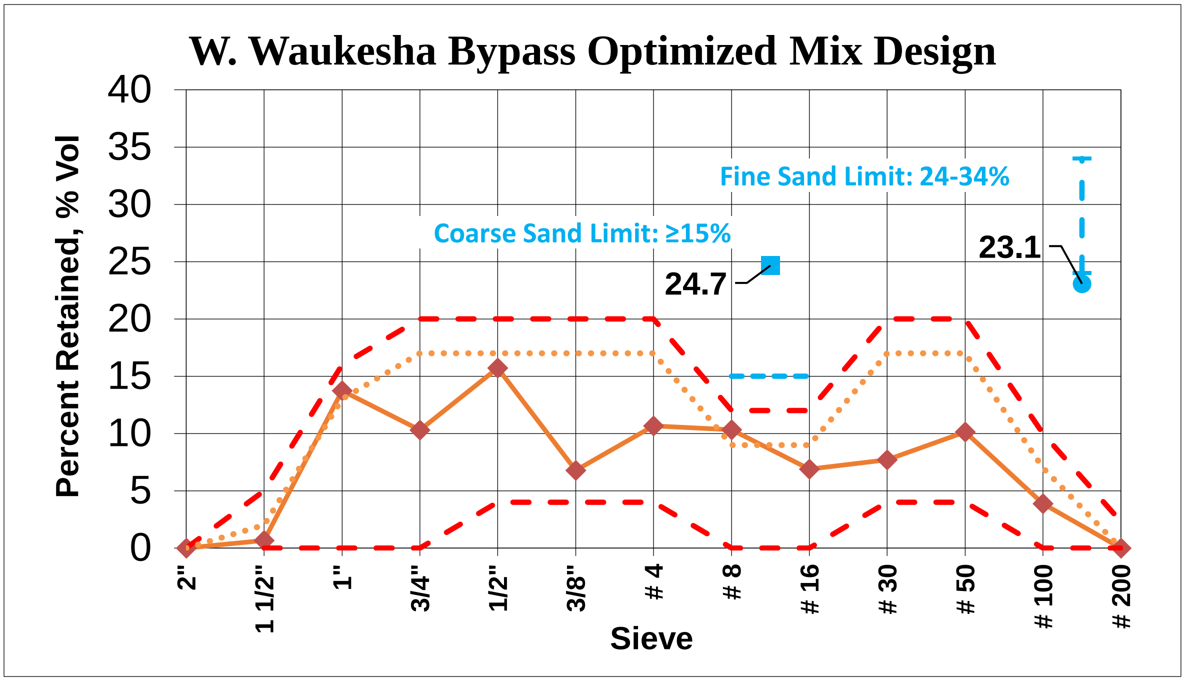


Figure 19: West Waukesha Bypass Tarantula Curve.

Figure 20: West Waukesha Bypass Box Test Photos.

4.1.6 I-39 Rock County

The mixture for I-39 in Rock County is within the Tarantula Curve limits as shown in Figure 21, and the Box Test results, shown in Figure 22, for Rock County typically showed good performance with some consolidation issues in some of the box corners. There was edge slumping issues observed in the last few photos. This means that edge slumping may be a concern in the field. This shows that there was some inconsistency in the production of the concrete. This could be caused my additional water in the mix or perhaps a change in gradation of the coarse sand for these mixtures. It is not possible to tell from the data collected. This mixture could have probably been dropped to 500 lbs. of total cementitious material in the mixture and had satisfactory performance as long as the W/C is less than 0.42.

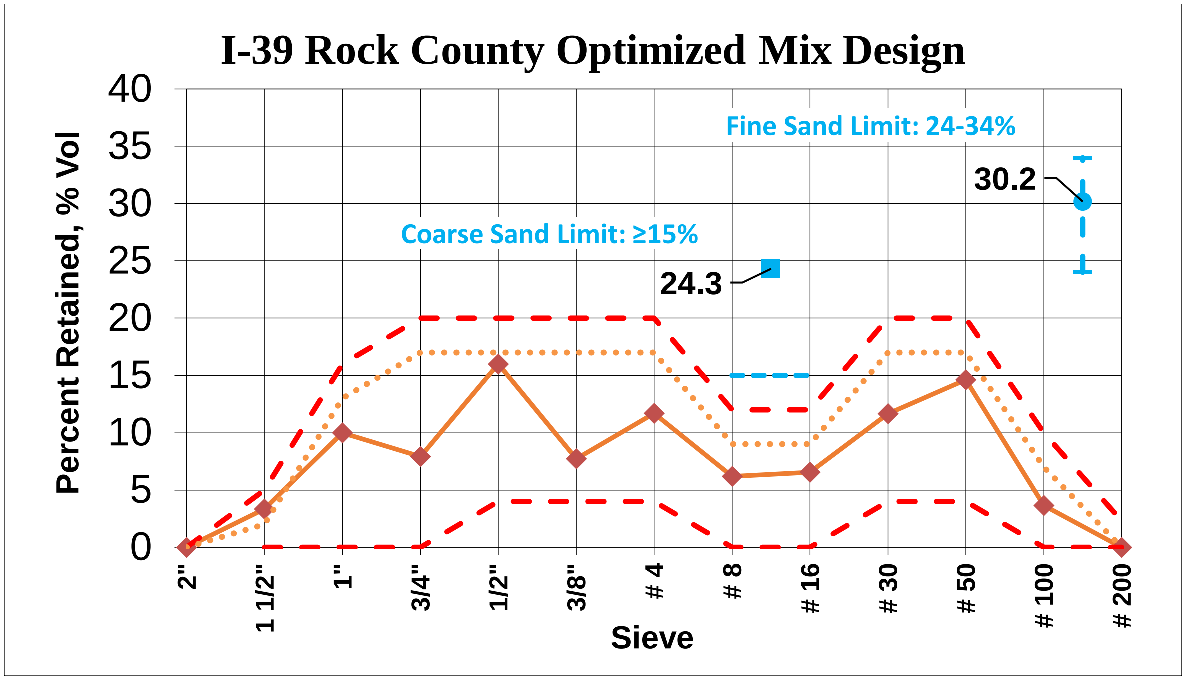


Figure 21: I-39 Rock County Tarantula Curve.

Figure 22: I-39 Rock County Box Test Photos.

4.1.7 I-39 Dane County

The Dane County mixture is outside the warning band on the 1 ½" sieve but within the Tarantula Curve limits, as shown in Figure 23, and the Box Test results, as shown in Figure 24, for the Dane County typically showed good performance. There were a few consolidation issues on some tests and there was edge slumping issues observed in the last photos. This means that edge slumping may be a concern in the field with these mixtures. This shows that there was some inconsistency in the production of the concrete. This could be caused my additional water in the mix or perhaps a change in gradation of the coarse sand for these mixtures. It is not possible to tell from the data collected. Because the mixture is outside the warning band but within the Tarantula Curve limits then this mixture could probably use 500 lbs. of total cementitious in the mixture and the w/cm increased to 0.42 and satisfactory performance would have been obtained.

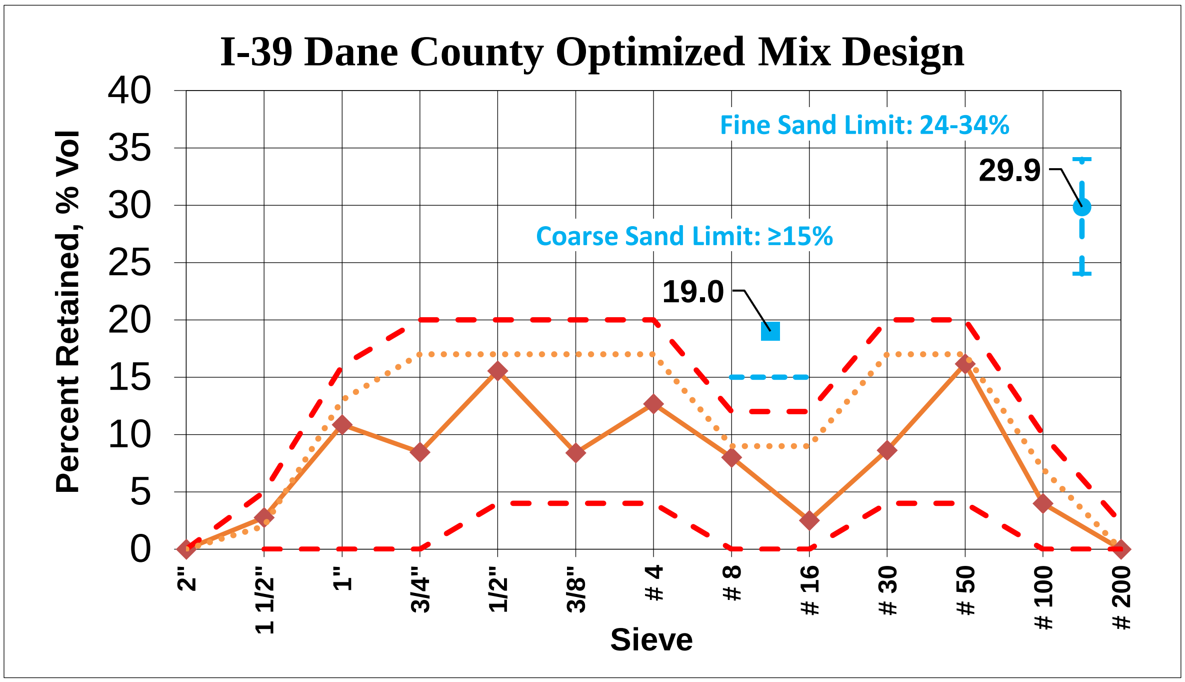


Figure 23: I-39 Dane County Tarantula Curve.

Figure 24: I-39 Dane County Box Test Photos.

4.1.8 Menomonie

Menomonie's mix design, shown in Figure 25, was within the warning band and lower limit of the Tarantula Curve and showed outstanding performance in the Box Test, as shown in Figure 26. None of the tests showed consolidation or edge slumping. This means that even as the gradations of the mixture varied the aggregates were likely within the Tarantula Curve limits. This helps ensure satisfactory performance. Because the mixture is within the warning bands it is likely that the total cementitious material could be reduced to 450 lbs. and still achieve satisfactory performance as long as the W/C was kept below 0.42.

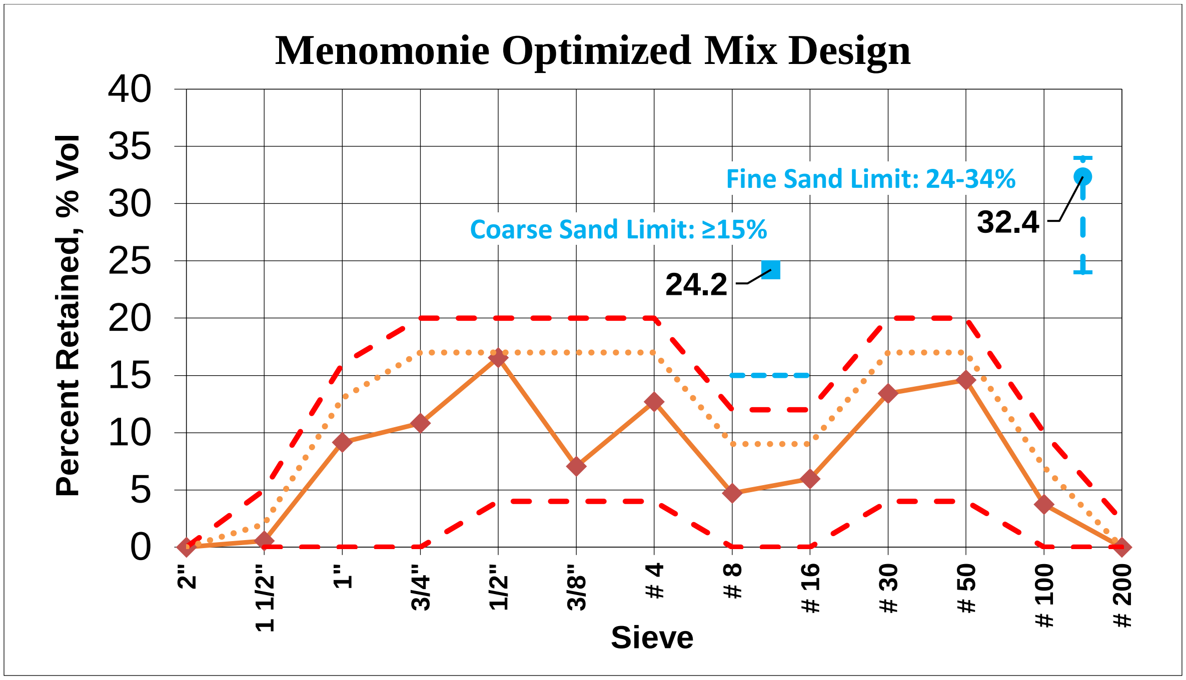


Figure 25: Menomonie Tarantula Curve.

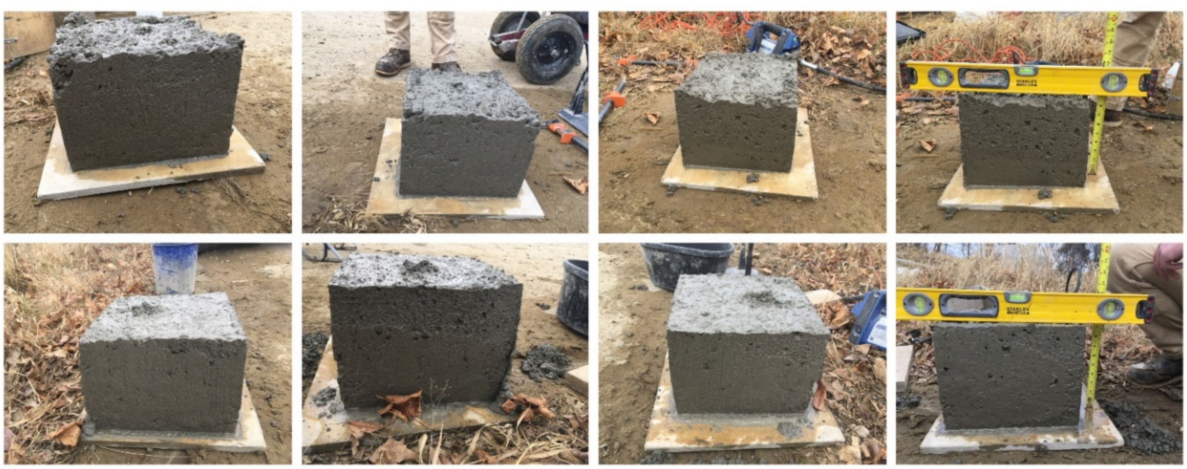


Figure 26: Menomonie Box Test Photos.

4.1.9 Mix Design Summary Table

Table 3: Mix design by location.

		Location							
		Appleton	Capitol Drive	Columbus	Superior	W. Waukesha Bypass	I-39 Rock County	I-39 Dane County	Menomonie
General Design	Coarse Sand Spec: ≥ 15%	13.6%	18.1%	18.4%	25.7%	24.7%	24.3%	19.0%	24.2%
	Fine Sand Spec: 24-34%	28.3%	30.0%	24.7%	25.0%	23.1%	30.2%	29.9%	32.4%
	Total Cementitious	455 lbs.	565 lbs.	565 lbs.	530 lbs.	565 lbs.	565 lbs.	520 lbs.	520 lbs.
	W/C	0.41	0.37	0.39	0.42	0.41	0.40	0.40	0.38
Supplementary Cementing Materials	Fly Ash	19%	30%	30%	23%	0%	30%	30%	30%
	Slag	0%	0%	0%	0%	30%	0%	0%	0%
Admixtures	Air Entrainer Name	General Resource Technology	Polychem SA - General Resource Technology	Polychem SA - General Resource Technology	Polychem SA - General Resource Technology	Air 360 - Sika	Polychem SA - General Resource Technology	MasterAir-AE 90 - BASF	N/A
	Water Reducer Name	General Resource Technology	400NC - General Resource Technology	400NC - General Resource Technology	400NC - General Resource Technology	Plastocrete 161 - Sika	400NC - General Resource Technology	MasterGlenium 7511 - BASF	N/A
Tarantula Curve	Warning Band Exceeded?	YES	YES	YES	YES	YES	YES	YES	NO
	Out of Specification?	YES	NO	YES	NO	YES	NO	NO	NO
Workability*	Box Test	1.3 (0.3)	1.8 (0.3)	1.8 (0.3)	2.1 (0.3)	1.9 (0.3)	2.1 (0.3)	2.3 (0.3)	1.3 (0.4)
	V-Kelly**	0.89 (0.10)	0.80 (0.13)	0.51 (0.15)	0.71 (0.11)	0.72 (0.12)	0.62 (0.08)	0.55 (0.21)	0.70 (0.11)

*Note: For the workability values, the value appearing in parenthesis is the standard deviation.

**Note: V-Kelly units are $\left(\frac{in}{sec}\right)^{\frac{1}{2}}$

4.2 Compressive and Flexural Strength Analysis

Figure 27 and Figure 28 show the compressive strength and flexural strength gain over the first 90 days of hydration. The strength gain for both measurements is the largest between 3 and 7 days and then substantially decreases. It is worth noting that the flexural strength of the W. Waukesha Bypass sample dropped at 90 days. This is likely due to a poorly constructed beam, and because only one beam was broken at 90 days, this is the only value that could be reported. This value is should not be viewed as a representative strength result. To better compare the results Figure 29 uses bar charts to compare both the compressive strength and flexural strength at 28 days. This figure is helpful as it shows the relative rank of compressive strength and flexural strength amongst the projects. An important observation from Figure 29 is that the mixtures with the highest compressive strengths did not always have the highest flexural strengths, which is especially apparent with the Menomonie mixture which had the highest compressive strength but the lowest flexural strength among all locations tested. This shows that the two measurements are not the same and can't be directly correlated with a simple equation or relationship. These observations are probably caused by differences in bond strength between the paste and aggregates for the different mixtures. Since concrete pavements are loaded in flexure and the bond between the aggregates and paste is important then it is logical to continue to test the flexural strength of the concrete.

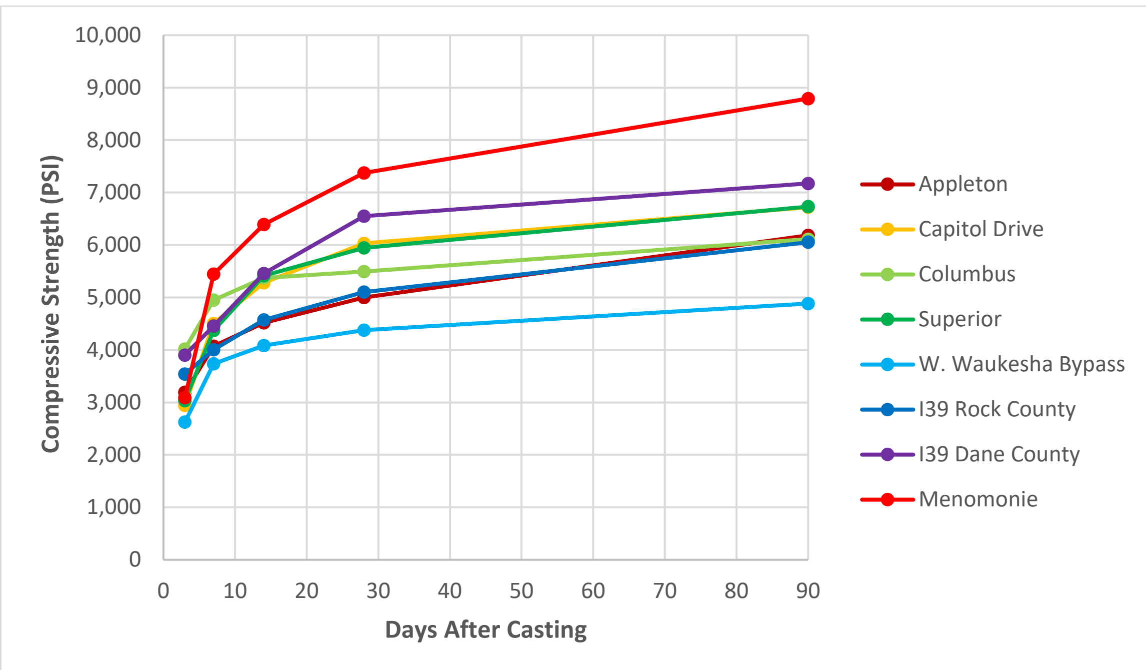


Figure 27: Compressive Strength development with curing time.

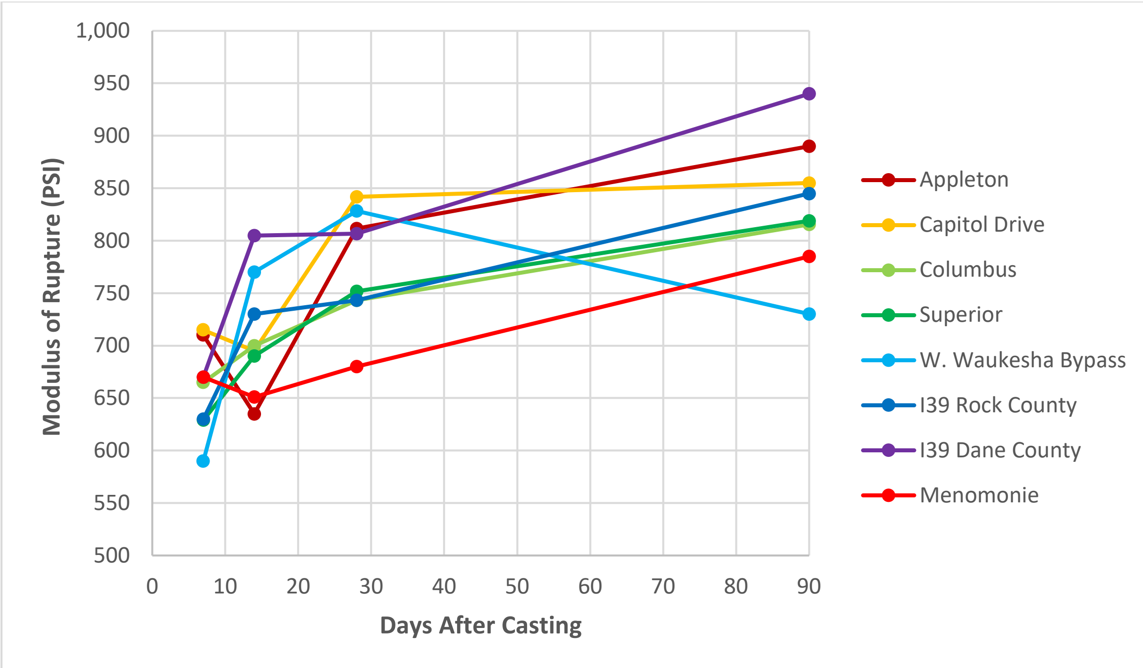


Figure 28: Modulus of Rupture strength development with curing time.

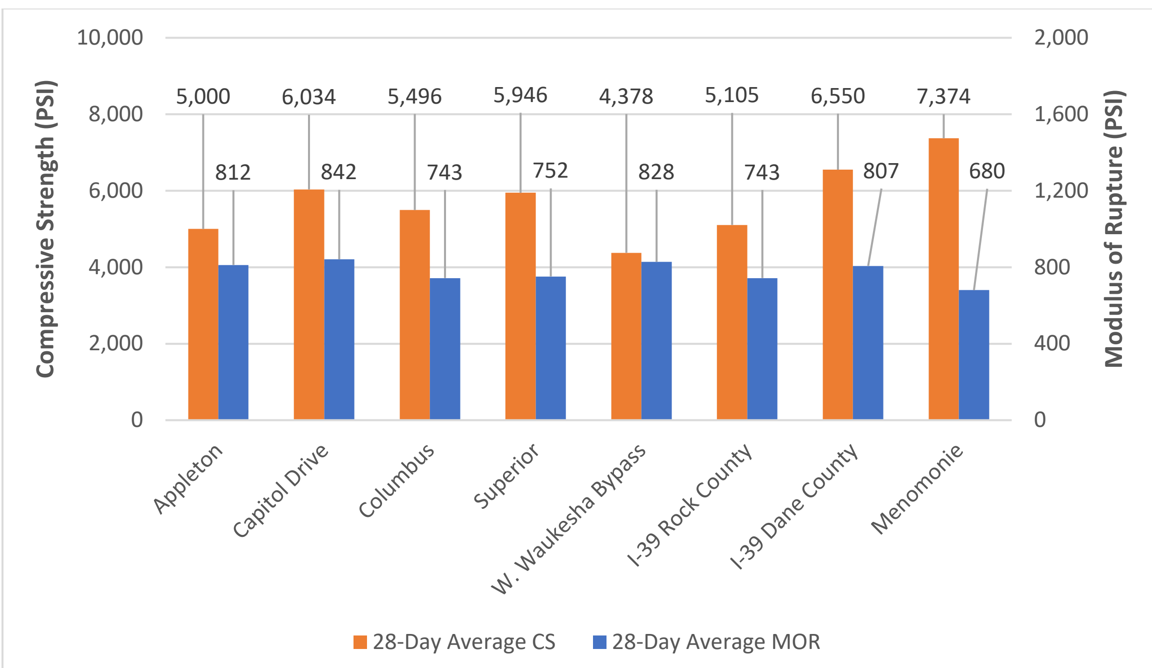


Figure 29: 28-Day compressive strength vs. 28-day modulus of rupture.

4.3 Analysis of Durability Properties

4.3.1 Air Void Analysis

Figure 30 shows the air content and Spacing Factor comparison for the samples investigated with a hardened air void analysis. A horizontal line shows a Spacing Factor of 200 μm. This is the recommended maximum Spacing Factor value as suggested by ACI 201 2R. A vertical line at 5.25% air content is also added to highlight that mixtures at similar air contents can have very different Spacing Factors. In fact, a mixture with 5.25% air content would meet the current WisDOT specifications for air volume but would not provide a satisfactory Spacing Factor.

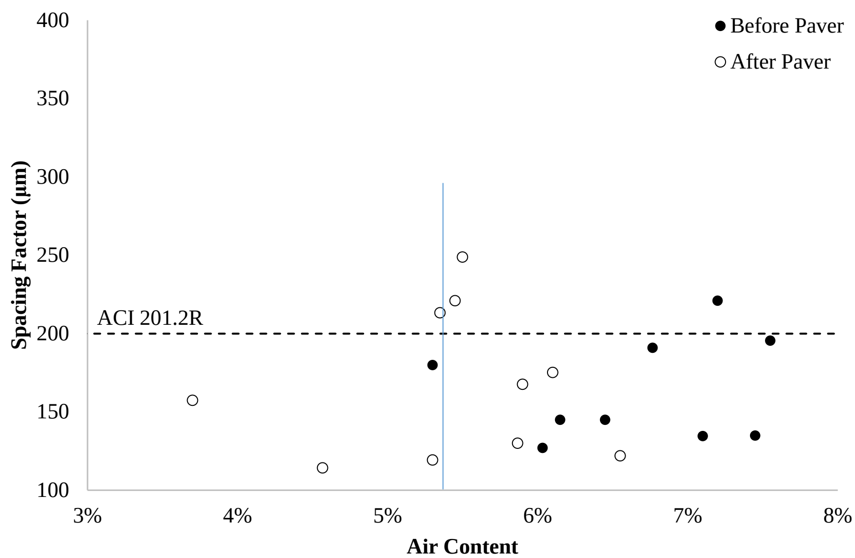


Figure 30: Air content compared to Spacing Factor for the samples investigated with a hardened air void analysis.

Figure 31 shows a comparison of the SAM Number and Spacing Factor. A Spacing Factor of 200 μm is shown for comparison. Two vertical lines are shown for the SAM Number. A SAM Number of 0.30 is shown in red and it is recommended as a field limit for freeze thaw durability. The line shown in black is a SAM Number of 0.20 and it is recommended as a target for design and it is shown in previous research to best correlate to a Spacing Factor of 200 μm. For example, when the SAM Number is < 0.20 then 85% of the data had a Spacing Factor < 200 μm.

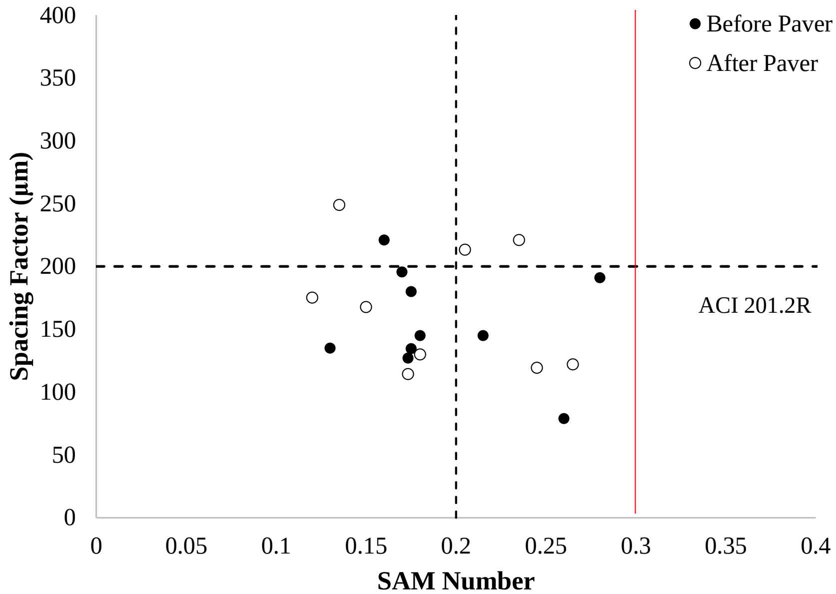


Figure 31: A comparison of the SAM Number and Spacing Factor.

Figure 32 and Figure 33 show the average air content and average SAM Number at the plant, before the paver, and then after being consolidated by the paver. Each data point consists of the average of several measurements with the SAM from several different sessions. The reader should be reminded that the values in Figure 29 and 30 are comparisons from individual measurements. The testing shows that the air content typically dropped from the plant until after the paver by as much as 3.5%. This drop was commonly 1% from the plant to the site and then another 2.5% decrease when comparing the concrete before and after the paver. This created air contents that were close to 4% after the paver. However, Figure 33 shows that there was minimal change in the SAM Numbers when comparing the measurements at the plant, before the paver, and then after the paver for SAM Numbers < 0.28. These mixtures would be expected to have a satisfactory air void distribution of small and well distributed bubbles. However, for the Columbus project, SAM Numbers > 0.30 were observed at the plant. This air void system is not recommended for freeze thaw durability. The SAM Numbers decreased to 0.28 for the concrete in front of the paver and then the values increased sharply after the paver to > 0.40. This means that an air void system with poorly distributed bubbles performed differently under vibration than air void systems that were small and well distributed.

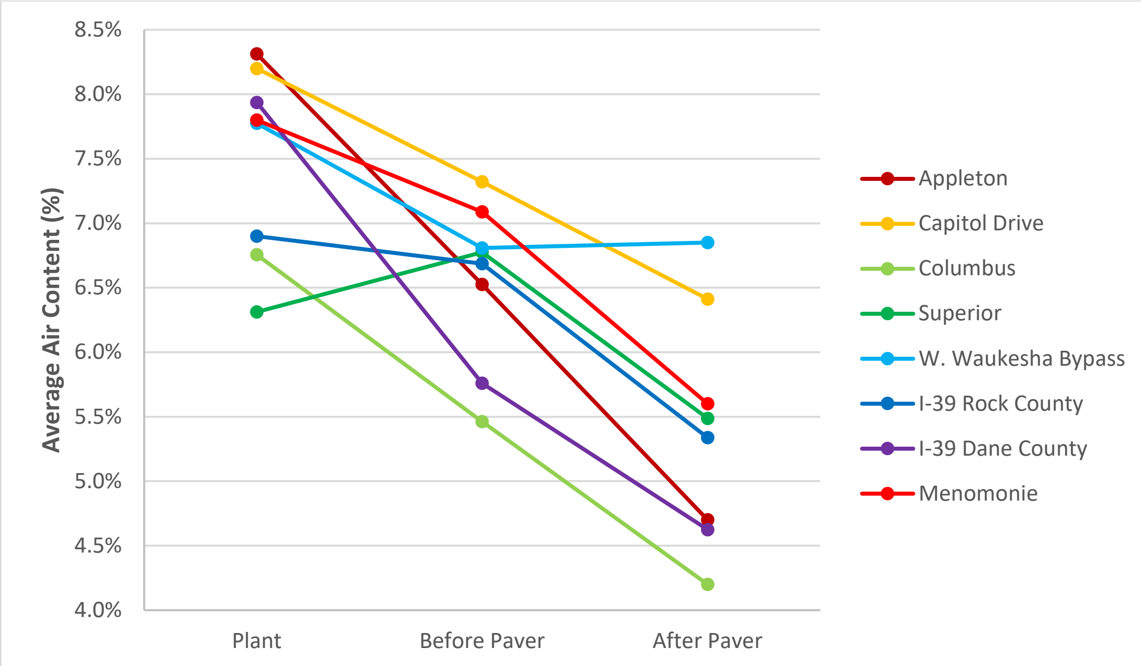


Figure 32: Air content changes throughout production and placement from the plant to before and after the paver.

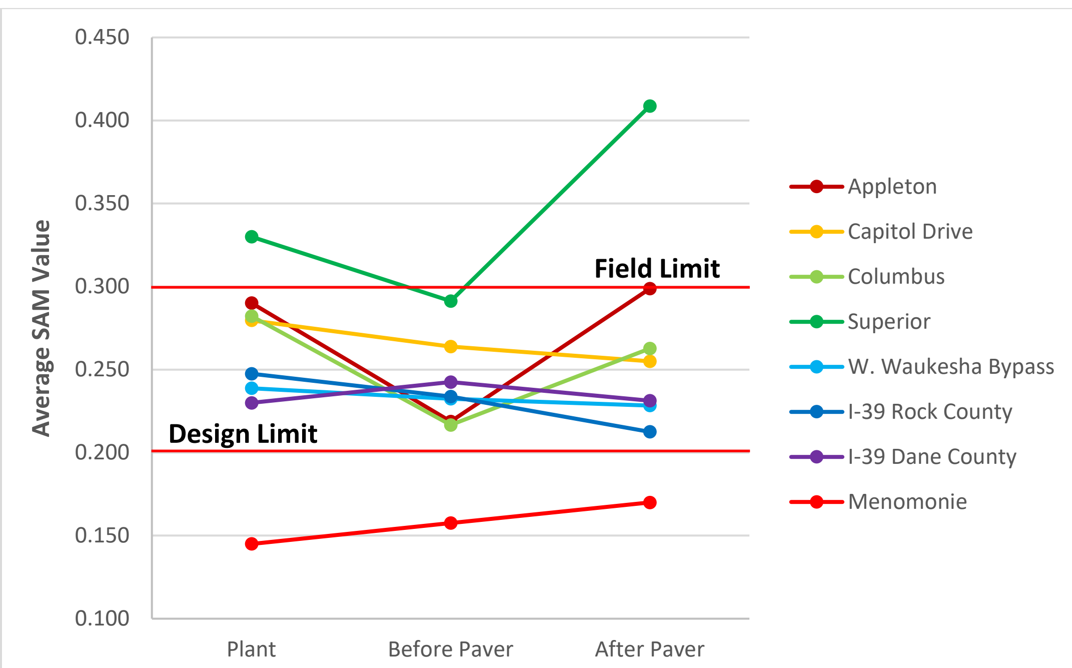


Figure 33: SAM value changes throughout production and placement from the plant to before and after the paver.

An important finding from this work is that the air that is lost from the plant to the job site seems to be largely coarse “entrapped” bubbles. This is shown because the air volume is decreasing but the SAM Number is not changing. Further, when the concrete is vibrated by the paver and the

SAM Number is < 0.27 or made of mainly fine air void bubbles, there was minimal change in the SAM Number despite a significant change in the volume of air in the concrete. This again shows that the air that was lost was large bubbles. However, when the SAM Number is > 0.28 before the paver then it appears the vibration increases the SAM Number. Again, this shows the vibration removes the large bubbles from the matrix.

This shows the importance of using the SAM Number to determine the quality of the air void system of the fresh concrete and not relying on the total air volume in the concrete. Based on the data from the field mixtures, if a concrete mixture has a satisfactory SAM Number either at the plant or before the paver then the concrete would be expected to have a satisfactory air void system in place. This means that sampling concrete behind the paver would not be necessary. This also means that producers should not focus on air volume but should instead focus on obtaining the correct SAM Number and just ensuring the air volume is > 4%. Implementing this would allow the producers to focus on producing a satisfactory air void spacing and measuring that with the SAM instead of focusing on the volume of air in the mixture. It is recommended that a SAM Number < 0.20 and air content > 4% be used for the mixture design and evaluated in the lab. However, in the field it is recommended to use a SAM Number < 0.30 and air content > 4%. Another option would be to have an action limit where the contractor would be required to take action if the SAM Number is between 0.25 and 0.30. This would likely be done by increasing the air content in their mixture.

Figure 34 shows the comparison of the SAM Numbers from different ways to consolidate the concrete. One set of tests used the battery vibrators that were placed within the unit weight bucket and the others used rodding. The results show that the battery-operated vibrators had a much higher variability or error bars and were not similar. However, the samples that were rodded showed much smaller error bars and were very similar. This suggests that an electric vibrator inserted into the unit weight pot should not be used to consolidate the concrete. Further work on this topic is proposed in Phase 2.

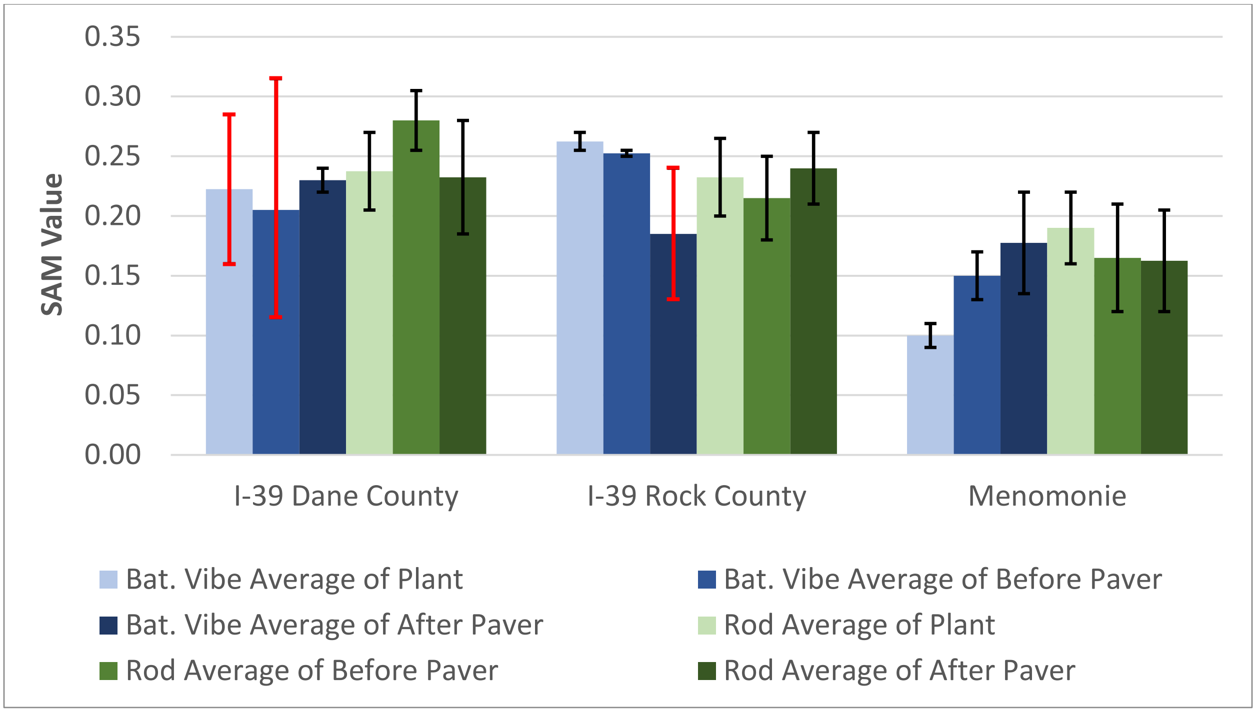


Figure 34: Consolidation method comparison for SAM values by location. Error bars represent the measured low and high SAM values.

4.3.2 Surface Resistivity

The results for the surface resistivity testing are shown in Figure 35. The results match what is expected as the resistivity continued to increase over time. Figure 36 shows the resistivity values in terms of the expected permeability. This range is suggested by the AASHTO T 358 specification in Table 2 and it shows that all the projects are reaching the low permeability value except for Columbus. It is not clear why Columbus did not reach the low resistivity in the same way as the other specimens. Additional testing is needed to better understand this. These results do show that resistivity is a helpful tool to evaluate the concrete. One way to improve the comparison would be to use the Formation Factor which corrects for pore solution.

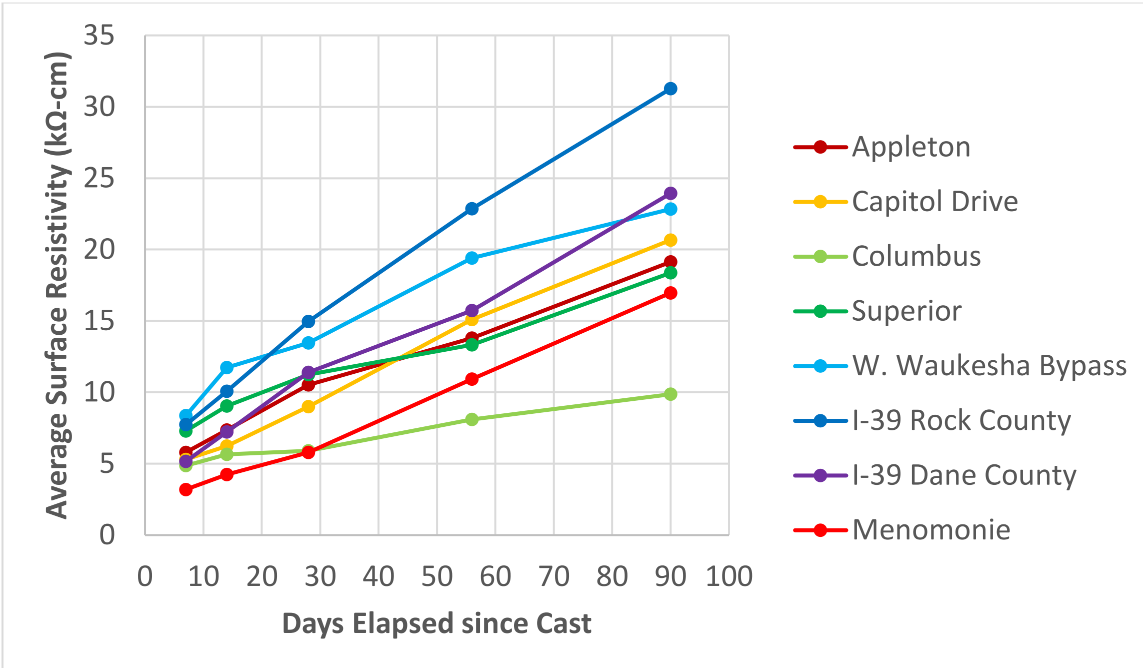


Figure 35: Average Surface Resistivity vs. days elapsed since casting.

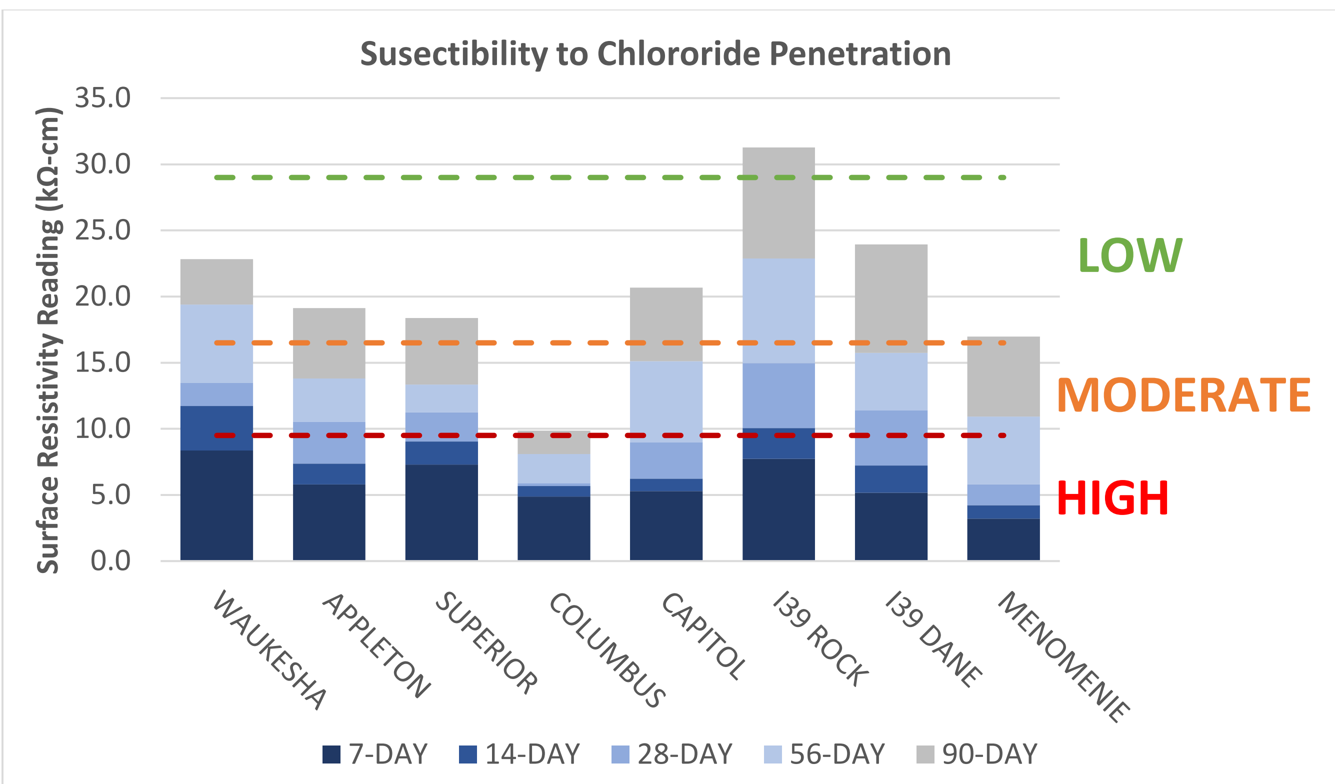


Figure 36: Surface resistivity gain by location with visual comparison.

4.3.3 Porosity and Formation factor

Figure 37 illustrates a summary of results from porosity and formation factor measurements. The tested specimens from three different projects show a similar average porosity value (≈16-17%). However, the specimens from Rock County show the highest formation factor (i.e., lower permeability) when compared to the tested specimens from Dane County and Menomonie. The specimens from Menomonie have the lowest formation factor. The formation factor results are consistent with the results from surface electrical resistivity (Figure 36). In addition, a higher variation exists in the formation factor data measured in Menomonie specimens. This variation can be attributed to the poor consolidation of the samples from Menomonie, as illustrated in Figure 38.

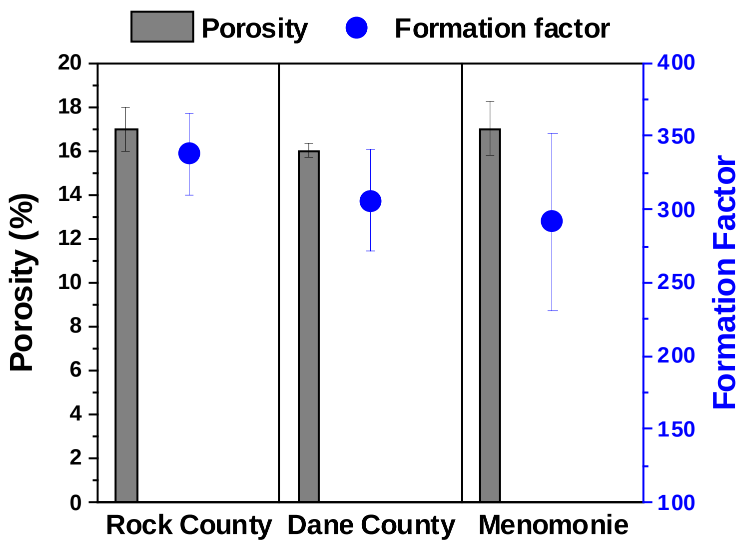


Figure 37: Porosity and formation factor based on bulk electrical resistivity measurement.

Figure 38: Example of specimens from Menomonie with poor consolidation.

4.3.4 Coefficient of Thermal Expansion

Concrete specimens were tested for their coefficients of thermal expansion. The results are shown below in Figure 39, and are arranged by aggregate type. While all of the coefficients were very similar, it is apparent that the primary aggregate types used in the mix have an influence on the coefficient of thermal expansion. Mixtures containing gravels fell somewhere in the middle range of coefficients while exhibiting more variability between project locations. Dolomite containing mixtures also had similar coefficients of thermal expansion to the gravels, but with what appears to be a slightly lower variability between locations. Limestone exhibited, on average, the lowest coefficient of thermal expansion, and Quartzite the highest. Because lower coefficients of thermal expansion are thought to be desirable for their greater volumetric stability under changing temperatures, this would mean gravels and limestones are more ideal aggregate sources for concrete when temperature susceptibility is of primary concern. It is worth noting, however, that the effects of thermal expansion can be mitigated by using thicker concrete slabs in paving applications. In terms of cost savings though, using thicker pavements is not an ideal solution. Therefore, this data shows the importance of aggregate types to thermal properties of concretes.

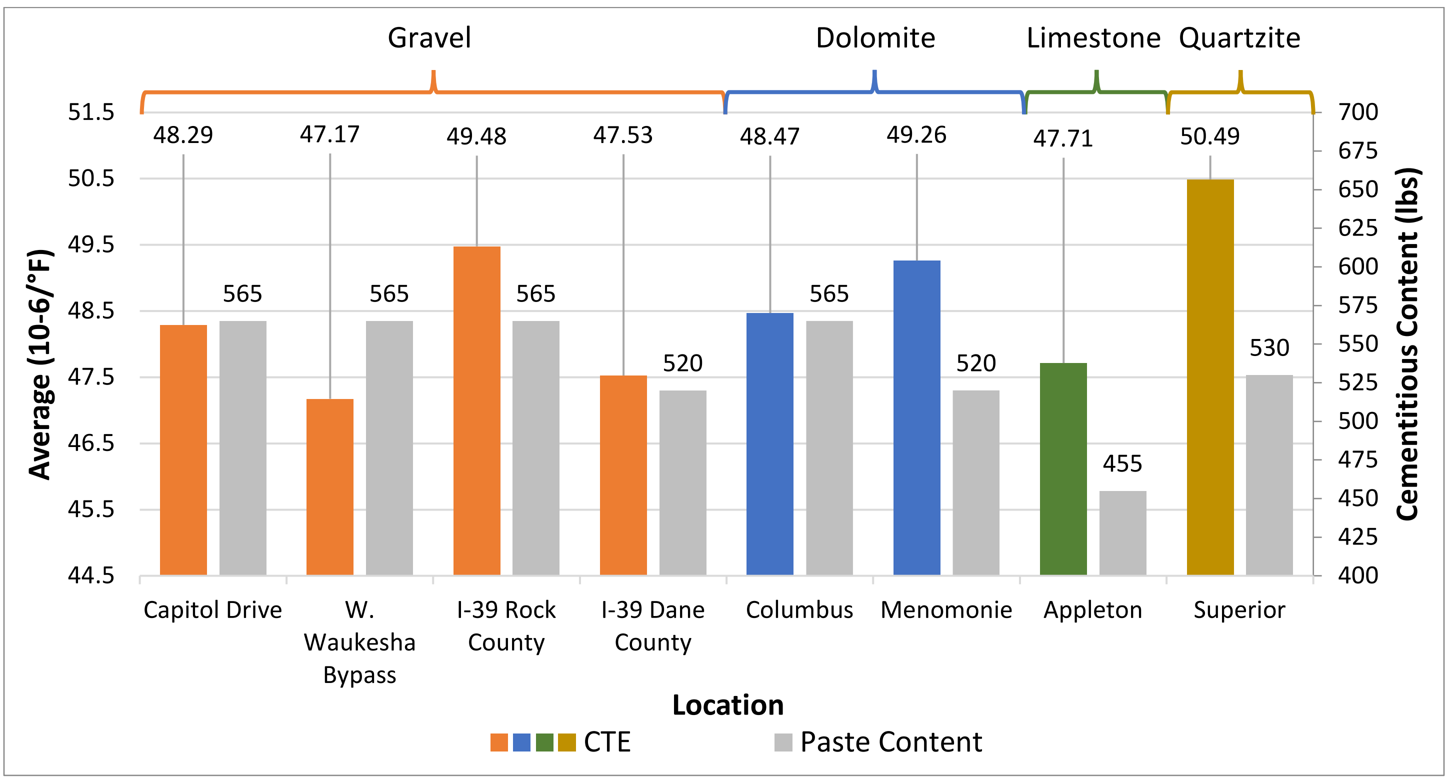


Figure 39: Average Coefficients of Thermal Expansion by Aggregate Type.

4.4 Analysis of Workability Properties

4.4.1 Comparing the Box Test and V-Kelly

Figure 40 shows a comparison of the V-Kelly and the Box Test Number for the values reported in 4.1.9 Mix Design Summary Table

Table 3. The results show that there is general agreement between the two measurements as the lowest V-Kelly measurements did show the highest Box Test values and vice versa however this correlation was not as strong as expected. This demonstrates that the V-Kelly is able to give a rough indication of the plastic concrete's ability to minimize surface voids under vibration, but the box test is a much better indication.

It should also be noted that in the field workability properties varied significantly within certain projects and are demonstrated by the box test photos in Figure 21 and Figure 23. Within these figures it is noted that some samples have significant edge slump while others have almost none. These changes can come from a variety of sources including mix adjustments, change in aggregate moistures, etc. This same trend is also shown in Figure 40 as certain projects had consistent V-Kelly results while other projects had much wider ranges.

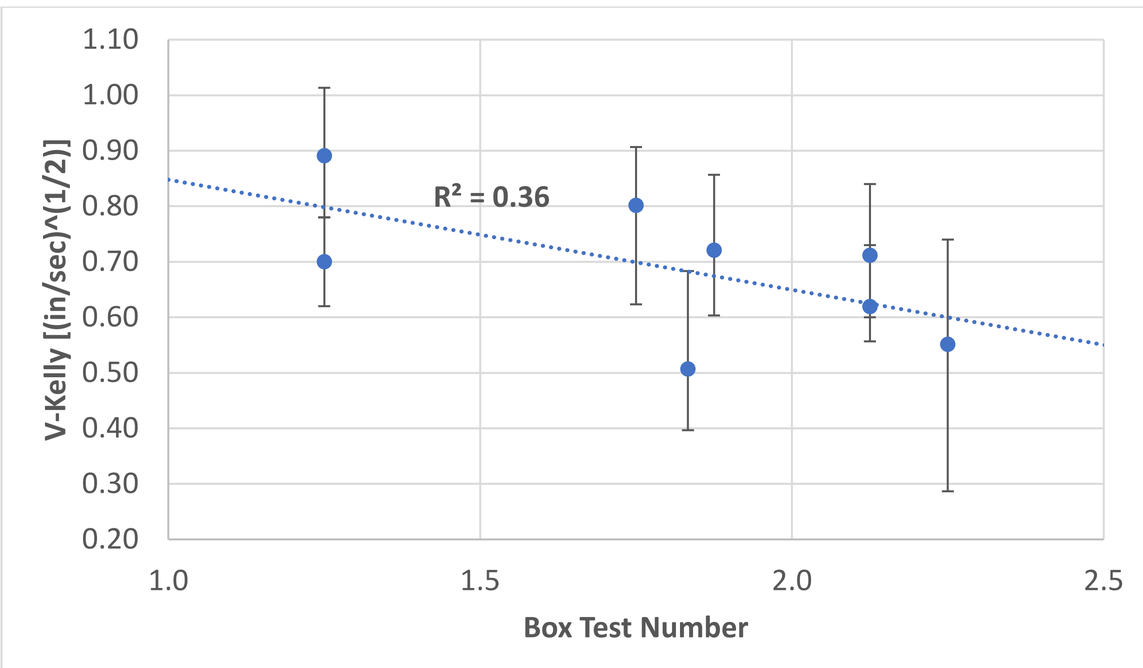


Figure 40: Average Box number vs. Average V-Kelly Index for workability.

*Note: Error bars represent the measured V-Kelly low and high values.

5.0 Summary

5.1 Durability

Several properties of concrete are durability related, these include surface and bulk resistivity, porosity, coefficient of thermal expansion, and the air void system. Surface and bulk resistivity are very similar in nature and measure the same property. The electrical resistance from these tests indicates the susceptibility to water and salt ingress; it can also be used as a reliable check for water content and water/cement ratios. Porosity and air voids are extremely important to freeze/thaw properties of concrete specimens as they allow for the expansion of ice to mitigate expansive stresses induced during freezing which can cause a variety of different failures. The coefficient of thermal expansion is used primarily for volume stability purposes. Concrete, which is a composite material (made up of cement paste and aggregates), can expand and contract with heating and cooling cycles, and the extent to which this occurs is dependent on the composite material properties. The coefficient of thermal expansion is important to factors such as the degree of warping of concrete slabs used on the roadway during normal day-to-day thermal cycling since the slab will have a thermal gradient through its depth which causes the warping.

5.1.1 Air Content

The results show that total air content is not a good indicator of Spacing Factor as several of the samples with the same air content had widely varying Spacing Factors. When the SAM Number is below the recommended design limit of 0.20, 85% of the mixtures has a Spacing Factor < 200 μm. Air content testing shows that the air content typically dropped from the plant until after the paver by as much as 3.5%. This drop was commonly 1% from the plant to the site and then another 2.5% decrease when comparing the concrete before and after the paver. This created air contents that were close to 4% after the paver. There was, however, minimal change in the SAM Numbers when comparing the measurements at the plant, before the paver, and then after the paver for SAM Numbers < 0.28. These mixtures would be expected to have a satisfactory air void distribution of small and well distributed bubbles. An important finding is that the air that is lost from the plant to the job site seems to be largely coarse bubbles. This is shown because the air volume is decreasing but the SAM Number is not changing. This shows the importance of using the SAM Number to determine the quality of the air void system of the fresh concrete and not relying on the total air volume in the concrete.

5.1.2 Surface Resistivity

As expected, with increasing curing time, all concrete specimens exhibited increased surface resistivity. A range is suggested by the AASHTO T 358 specification in Table 2 and it shows that all the projects reached the low permeability value except for Columbus. It is unclear why Columbus did not reach the low resistivity in the same way as the other specimens. Additional testing is needed to better understand this. This means, except for Columbus, that the concrete used for the other project is expected to have good protection from water and salt ingress.

5.1.3 Porosity and Formation Factor

The tested specimens from three different projects show a similar average porosity value (≈16-17%). However, the specimens from Rock County show the highest formation factor (i.e., lower permeability) when compared to the tested specimens from Dane County and Menomonie. The specimens from Menomonie have the lowest formation factor likely due to poor sample consolidation.

5.1.4 Coefficient of Thermal Expansion

The coefficient of thermal expansion/contraction describes how much concrete will expand or contract under changing thermal conditions. Mixtures containing gravels fell somewhere in the middle range of coefficients while exhibiting more variability between project locations. Dolomite containing mixtures also had similar coefficients of thermal expansion to the gravels, but with what appears to be a slightly lower variability between locations. Limestone exhibited, on average, the lowest coefficient of thermal expansion, and Quartzite the highest.

5.2 Strength

Concrete cylinders and beams were broken to determine the compressive and flexural strength respectively. As has been well established for concrete, primary strength gain occurs within the first 7-14 days, and then increases at diminishing rate with time beyond this time. Even though theoretical relationships between compressive and flexural strength have been developed, the mixtures tested in this study with the highest compressive strengths did not always have the highest flexural strengths. This shows that the two measurements are not the same and can't be directly correlated with a simple equation or relationship. These observations are potentially caused by differences in bond strength between the paste and aggregates for the different mixtures. Since concrete pavements are loaded in flexure and the bond between the aggregates and paste is important to observed flexural strength then it is logical to continue to test the flexural strength of the concrete. It is also logical to continue compressive tests for applications in which the concrete is subjected to a compressive load.

5.3 Workability

Both the Vibrating Kelly Ball (V-Kelly) and Box Test attempt to quantify the workability of a concrete mixture. The V-Kelly test uses a quantitative measurement by calculating an index based on the rate of penetration that is measured over 30 seconds. The Box Test is a subjective quantification of workability based on the presence of visible surface voids after fresh concrete has been poured into a box frame and consolidated via vibration. Both tests are subject to variability. The V-Kelly test demonstrated moderate variability even though the test is much more controlled than the Box Test. The Box Test, due to being subjectively measured, has potential for bias and variability depending on the person performing the test. Despite the variability in these two tests, there was general agreement between the results.

One of the primary purposes of using the optimized gradation (Tarantula Curve) is to maintain workability with little to no loss in performance. Having too much or too little sand in a mixture is a very important detail that often is overlooked during mix design, and the aggregate gradations directly affect segregation, ability to finish, edge slumping, and many other mixture issues. The Tarantula Curve was designed in order to place limits on the different aggregate sizes in order to maintain a workable mixture, and in general the box test results were in agreement with whether or not the mix design was within the Tarantula Curve limits. Mixtures that were near or past the warning band but within the upper/lower limits tended to exhibit more surface voids or edge slumping and therefore lower workability and formability. Mixtures that were well within the limitations set by the Tarantula Curves exhibited good workability and formability with few surface defects.

6.0 Recommendations

6.1 Tarantula Curve

WisDOT allows for 1.5” inch maximum aggregate size in its mixtures. The original Tarantula Curve did not have recommendations for 1.5” diameter aggregates. Based on conversations with WisDOT this limit was added based on previous experience and more research data should be generated to support this limit. Previous testing done during the development of the Tarantula Curve showed that the use of aggregates greater than 1” in diameter did not impact the workability of the concrete and that many different aggregate combinations could be used to produce satisfactory concrete mixtures for slipformed pavement applications [27]. Because of this the research team suggests that future research be performed to evaluate mixtures from Wisconsin with these larger aggregates.

It is recommended to fully require optimized gradation for all WisDOT mixtures. As part of using the optimized gradations/Tarantula Curves, we also recommend implementing a warning band that falls 3% below the upper limit, although this value is not a firm recommendation. The warning band should be used for mixture design purposes and allows for variability during production with the goal to maintain a gradation that is within Tarantula Curve limits throughout production.

6.2 Air Void System

Based on the results shown in Figure 33, it is recommended that a SAM Number < 0.20 and air content > 4% be used for the mixture design and evaluated in the lab. However, in the field it is recommended to use a SAM Number < 0.30 and air content > 4%. Another option would be to have an action limit where the contractor would be required to take action if the SAM Number is between 0.25 and 0.30. This would likely be done by increasing the air content in their mixture.

If the SAM Number is < 0.30 then consolidation from the paver is not expected to change the quality of the air void system and so testing is not required after the concrete paver. Based on the results shown in Figure 34, consolidation of concrete by inserting a battery powered vibrator is shown to increase the variability of the SAM results. At this time, it is recommended to use a rod to consolidate the concrete unless a new method of consolidation can be established that shows satisfactory performance. The research team suggests that future research be performed to evaluate the different methods of consolidation with the goal to improve variability.

6.3 Strength Properties

As was observed in Figure 29, mixtures with higher compressive strengths didn’t always have higher flexural strength. Therefore, we recommend that WisDOT continue requiring strength testing depending on the application of the concrete. Compression testing is recommended in applications where concrete will be supporting compressive loads such as in structural columns for bridges; while flexural testing is recommended for applications requiring flexural strength such as roadways or structural girders.

6.4 Workability

While the Vibrating Kelly Ball (V-Kelly) and Box Test both attempt to quantify workability, they are loosely correlated with each other with large variability and bias as shown in Figure 40. Therefore, we do not recommend WisDOT specify or attempt to standardize either of these tests as performance qualifiers. These tests, however, are likely to be valuable to the contractors, who may be more concerned about the workability or ability to finish their mixes before construction as to avoid these types of issues during production. The V-Kelly test may give more insight as to how well a mix will move through a paver, while the Box Test gives a better indication of the ability to finish and potential for issues like edge slumping or large surface voids.

6.5 Bulk and Surface Resistivity

While both bulk and surface resistivity measure the same thing, bulk resistivity is thought to be slightly more accurate. However, more attentiveness is required during testing when measuring bulk resistivity as proper conditioning and appropriate geometric correction factors must be used, whereas surface resistivity is an easier and more straightforward test to perform. We recommend that WisDOT collect resistivity data, especially because results can occur like those seen with Columbus in Figure 36, which still had moderate to high susceptibility to chloride penetration even after 90 days of curing. We do not yet recommend enacting a specification or standard regarding resistivity yet. It is worth mentioning other agencies such as CDOT and the Illinois Tollway are actively collecting resistivity data (for information only), with particular attention paid to resistivity after 28 days.

6.7 Hardened Air Voids

As was shown in Figure 32, air content decreases as it moves from the plant, to before the paver, and then finally after the paver. This isn't necessarily a problem because as the SAM data showed in Figure 33, we can expect there to still be a sufficient air void network. What is actually happening is that the larger entrapped air voids are being removed from the mix, and the small entrained air network remains.

6.6 Coefficient of Thermal Expansion

Due to WisDOT's widespread use of jointed-plain concrete pavements, the coefficient of thermal expansion may be of interest to WisDOT. In applications where there is freedom for movement such as in a jointed concrete roadway, thermal expansion and contraction can cause issues like concave/convex warping. Therefore, we recommend that WisDOT consider collecting more data regarding the coefficient of thermal expansion for further analysis and perhaps subsequent standardization.

7.0 References

[1] P. Kopac, "Making Roads Better and Better," July/August 2002. [Online]. Available: http://www.nrmca.org/sustainability/033000_final.pdf. [Accessed February 2018].

[2] C. H. Goodspeed, S. Vaniker and R. Cook, "High Performance Concrete Defined for Highway Structures," *Concrete International*, vol. 18, no. 2, pp. 62-67, 1996.

[3] C. Ozyildirim, "High Performance Concrete for Transportation Structures," *Concrete International,* vol. 15, no. 1, pp. 33-38, 1993.

[4] M. I. Darter, M. Abdelrahman, P. A. Okamoto and K. D. Smith, "Performance-Related Specifications for Concrete Pavements: Volume I:Development of a Prototype Performance-Related Specification," FHWA-RD-93-042, 1993.

[5] R. M. Weed, "Practical Framework for Performance-Related Specifications," *Transportation Research Record,* vol. 1654, pp. 81-87, 1999.

[6] C. Graveen, W. J. Weiss, J. O. Olek, T. Nantung and V. L. Gallivan, "Comments on Implementation of Performance Related Specifications (PRS) for a Concrete Pavement in Indiana," *Transportation Research Board,* 2004.

[7] Ernst and Sohn Publishers, Fib Model Code fo Concrete Structures, Pg 402, 2010.

[8] American Concrete Institute, "ACI 365.1R00 Service Life Prediction- State of the Art Report," ACI Manual of Concrete Practice.

[9] Taywood Engineering Limited (TEL), "Duracrete/BE95-1347/R4-5 Modeling of Degredation (Task 2)," UK, 1998.

[10] V. Barde, A. Radlinska, M. Coenen and J. Weiss, "Relating Material Properties to Exposure Conditions for Predicting Service Life in Concrete Bridge Decksin Indiana," FHWA/IN/JTPP-2007/27 Joint Transportation Research Program, 2009.

[11] P. Taylor, Y. Ezgi and C. Halil, "Performance Engineered Mixtures for Concrete Pavements in the US," in *Civil Construction and Environmental Engineering Conference Presentations and Proceedings (Paper #24)*, 2014.

[12] R. Spragg, Y. Bu, K. Snyder, D. Bentz and J. Weiss, "Electrical Testing of Cement-Based Materials: Role of Testing Techniques, Sample Conditioning, and Accelerated Curing," *Joint Transportation Research Program,* 2013.

[13] K. C. Hover, "Analytical Investigation of the Influence of Air Bubble Size on the Determination of the Air Content of Freshly Mixed Concrete," *Cement, Concrete and Aggregates,* vol. 10, no. 1, pp. 29-34, 1988.

[14] W. Klein and S. Walker, "A Method for Direct Measurement of Entrained Air in Concrete," *Journal Proceedings,* vol. 42, no. 6, pp. 657-668, 1946.

[15] R. Felice, J. M. Freeman and M. T. Ley, "Durable Concrete with Modern Air-Entraining Admixtures," *Concrete International,* vol. 36, no. 8, pp. 37-45, 2014.

[16] M. T. Ley, R. C. Juenger and K. J. Folliard, "The Physical and Chemical Characteristics of the Shell of Air-Entrained Bubbles in Cement Paste," *Cement Concrete Research,* 2009.

[17] M. T. Ley, J. F. K. and K. C. Hover, "Observations of Air-Bubbles Escaped from Fresh Cement Paste," *Cement Concrete Research,* 2009.

[18] J. LeFlore, "Super Air Meter Test Video," J. LeFlore, 2016. [Online]. Available: https://www.youtube.com/watch?v=xAcHqMz_m3I.

[19] D. Welchel, "Determining the Size and Spacing of Air Bubbles in Fresh Concrete," *Oklahoma State University*, 2014.

[20] M. T. Ley, "The Effects of Fly Ash on the Ability to Entrain and Stabilize Air in Concrete," *ProQuest*, 2007.

[21] U. Jakobsen and a. et, "Automated Air Void Analysis of Hardened Concrete - a Round Robin Study," *Cement and Concrete Research,* vol. 36, no. 8, pp. 1444-1452, 2006.

[22] K. L. Peterson, S. L. and R. M., "The Practical Application of a Flatbed Scanner for Air-Void Characterization of Hardened Concrete," *Recent Advancement in Concrete Freezing-Thawing (FT) Durability. ASTM International,* 2010.

[23] T. C. Powers, "Properties of Fresh Concrete," John Wiley & Sons, New York, 1968.

[24] C. F. Ferraris, "Measurement of Rheological Properties of High Performance Concrete: State of the Art Report," *Journal of Research of the National Institute of Standards and Technology,* vol. 104, no. 5, pp. 461-478, 1999.

[25] P. M. Bartos, M. Sonebi and A. K. Tamimi, "Workability and Rheology of Fresh Concrete: Compendium of Tests," RILEM, France, 2002.

[26] E. Koehler and D. Fowler, "Summary of Concrete Workability Test Methods," University of Texas Austin, ICAR 105-1, 2003.

[27] M. D. Cook, A. Ghaeezadah and M. T. Ley, "Impacts of Coarse-Aggregate Gradation on the Workability of Slip-Formed Concrete," *ASCE Journal of Materials in Civil Engineering,* vol. 30, no. 2, 2017.

Appendix A – Session Testing

Hardened Concrete Testing				
Test	**Session**	**Sample Day**	**Sample Location**	**# of Samples**
Compressive Strength	2	D1 - EVE	Before Paver	10
Flexural Strength	1	D1 - MORN	Before Paver	6
Surface Resistivity	1	D1 - MORN	Before Paver	3
	2	D1 - EVE	Before Paver	3
	3	D2 - MORN	Before Paver	3
Resistivity, Porosity and Pore Solution Resistivity	1	D1 - MORN	Before Paver	2
Hardened Air	1	D1 - MORN	Plant, Before & After Paver	3
	2	D1 - EVE	Plant, Before & After Paver	3
	3	D-2 MORN	Plant, Before & After Paver	3
	4	D-2 EVE	Plant, Before & After Paver	3
Coef of Thermal Expansion	1	D1 - MORN	Before Paver	1
	3	D2 - MORN	Before Paver	1

Plastic Testing				
Test	**Session**	**Sample Day**	**Sample Location**	**# of Samples**
Super Air Meter	1	D-1 MORN	Plant, Before & After Paver	3 (w/2 rep)
	2	D-1 EVE	Plant, Before & After Paver	3 (w/2 rep)
	3	D-2 MORN	Plant, Before & After Paver	3 (w/2 rep)
	4	D-2 EVE	Plant, Before & After Paver	3 (w/2 rep)
Box Test	1	D-1 MORN	Plant	1
	2	D-1 EVE	Plant	1
	3	D-2 MORN	Plant	1
	4	D-2 EVE	Plant	1
V-Kelly Ball	1	D-1 MORN	Plant	1
	2	D-1 EVE	Plant	1
	3	D-2 MORN	Plant	1
	4	D-2 EVE	Plant	1