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TRC1304

Foamed Warm Mix Asphalt Design Issues

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Final Report

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by

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ABSTRACT

The majority of contractors implementing Warm Mix Asphalt (WMA) in Arkansas have elected to use plant-foaming units. However, laboratory mix designs are prepared without foaming. A laboratory-scale foaming device may be necessary for agency verifications of WMA mix designs. In this study, investigations were made using two laboratory foamers to compare laboratory and field foaming techniques, to investigate the temperature sensitivity of foamed asphalt mixes, and to assess additional characteristics such as rutting potential, moisture damage, coating and compactability, dynamic modulus, and binder behavior.

The PTI and Wirtgen laboratory foamers were used, and the PTI more often exhibited properties similar to that of field-foamed mix. The air void content of WMA specimens was relatively insensitive to changes in temperature, however compaction became increasingly difficult as temperatures became excessively low. Temperature sensitivity became more pronounced for mixes containing RAP, suggesting that elevated temperatures may be necessary to “activate” the recycled binder. No significant changes to current mix design procedures were recommended based on the results of performance tests relating to rutting, moisture damage, or stiffness.

It was recommended that a laboratory foamer be used to verify mix designs for WMA mixes involving a temperature reduction (based on the comparable hot mix design) of 50°F or more, and for WMA mixes containing 10 percent or more of RAP and involving a temperature reduction (based on the comparable hot mix design) of 30°F or more.

1. Introduction and Problem Statement

Warm Mix Asphalt (WMA) has quickly become a popular topic in the asphalt industry, and the Federal Highway Administration (FHWA) is actively encouraging implementation of WMA in all states. While a fair assessment plan has been developed with regard to mix design for WMA technologies using additives, a number of questions remain as to the most appropriate method for assessing plant-foamed WMA. There are currently several devices available for simulating the plant-foaming technique in the laboratory, though no data is yet available to determine whether these devices provide a suitable representation of field-produced mixtures.

Data from Project TRC-1004 suggests that a WMA design should not be developed by simply altering a hot mix asphalt (HMA) design by ‘plugging in’ a WMA additive. Thus, it is reasonable that the same would be true of the plant-foaming techniques. AHTD does not currently have a laboratory foamer, and as a result, has no mechanism for approving WMA mix designs that are intended to be generated by a plant-foaming technique. The results of NCHRP Project 9-43 indicated that a laboratory foamer is necessary for all WMA mix designs that will utilize plant-foaming techniques, and those recommendations have led to changes in AASHTO R35 to require a laboratory foamer for the design of such mixes. Thus, an evaluation is necessary to determine how a laboratory foamer could/should be used for the purpose of WMA mix design approval. Additional investigations of WMA and RAP / RAS in laboratory-foamed mixes were also studied.

2. Background and Literature Review

Warm Mix Asphalt (WMA) is a general term used to describe the products and processes that can be used to lower the production temperatures of asphalt mixtures. By reducing temperatures, a number of benefits may be realized, including reduced odors and emissions, energy savings, binder content reductions, less oxidation of the asphalt cement, better working conditions, longer haul distances, and extended paving seasons. Warm mix technology has been used successfully in Europe for a number of years, and was first investigated by the Federal Highway Administration (FHWA) approximately 10 years ago (D'Angelo, 2008). Since that time, WMA has moved to the forefront of the asphalt industry, and is being implemented in many states. Warm mix was also one of the primary components of FHWA's first 'Every Day Counts' initiative.

Warm mix temperatures can be achieved using additives, or by a mechanical foaming process. The available additives include chemical additives, organic wax products, and foaming additives such as synthetic zeolites. Each of these additives affect the asphalt cement by reducing its effective viscosity, or workability, and allow for adequate mixing and compaction at temperatures significantly less than that of hot mix asphalt. According to the American Association of State Highway and Transportation Officials (AASHTO), WMA is an asphalt mixture produced at a temperature of at least 50 °F lower than traditional hot mix temperatures. (AASHTO, 2014). The lower temperatures require less heating, resulting in the potential for significant energy savings. Energy reductions of 20 to 75 percent have been reported, while still achieving acceptable levels of compaction (Dristjansdottir, 2007).

Mechanical foaming processes can also be used to produce WMA, and use a water injection system at the asphalt plant. The tiny bubbles produced by the water injection serve to 'lubricate' the mixture, allowing for increased compaction at lower temperatures. As early as the 1960's, researchers such as Ladis H. Csanyi at Iowa State University were investigating foamed asphalt procedures. Even then, research suggested several benefits of foamed asphalt binder including higher strength and increased freeze-thaw resistance without any other major modifications to the actual mixing procedure.

In the 1990's WMA began to be implemented in Europe, using mostly wax additives or foaming processes (Bonaquist 2011). Wax added to bituminous binder decreased the binder's viscosity to allow increased workability even at low temperatures. Foamed asphalt was produced by several different methods: either with additives, such as Aspha-min or Advera, or by a mechanical process adding water and air to hot binder.

Many of the original laboratory-based WMA research projects in the United States dealt primarily with WMA additives. In 2005, the National Center for Asphalt Technology (NCAT) conducted a study of the effect of Sasobit on both granite and limestone mixes using PG64-22 and PG58-28 binder grades (Hurley and Prowell, 2006). NCAT also performed studies of a synthetic zeolite known as Aspha-Min (Hurley and Prowell, 2005), and the Evotherm chemical additive (Hurley and Prowell, 2006). In general, as compaction temperatures decreased, rutting and stripping potential increased, but were less sensitive to temperature changes than their hot mix counterparts.

More than 20 warm mix products are currently available for producing warm mix, but most contractors in the state of Arkansas who have invested in warm mix applications have chosen to modify their plants with a mechanical foaming process. Mechanical foaming involves the addition of small amounts of water and compressed air to the binder (also known as bitumen). When the water contacts the hot binder, it quickly evaporates and this process, along with the addition of the compressed air, causes the binder to foam and its volume to expand up to 15 to 20 times its original volume (Wirtgen Group 2009). This process is illustrated in Figure 1.

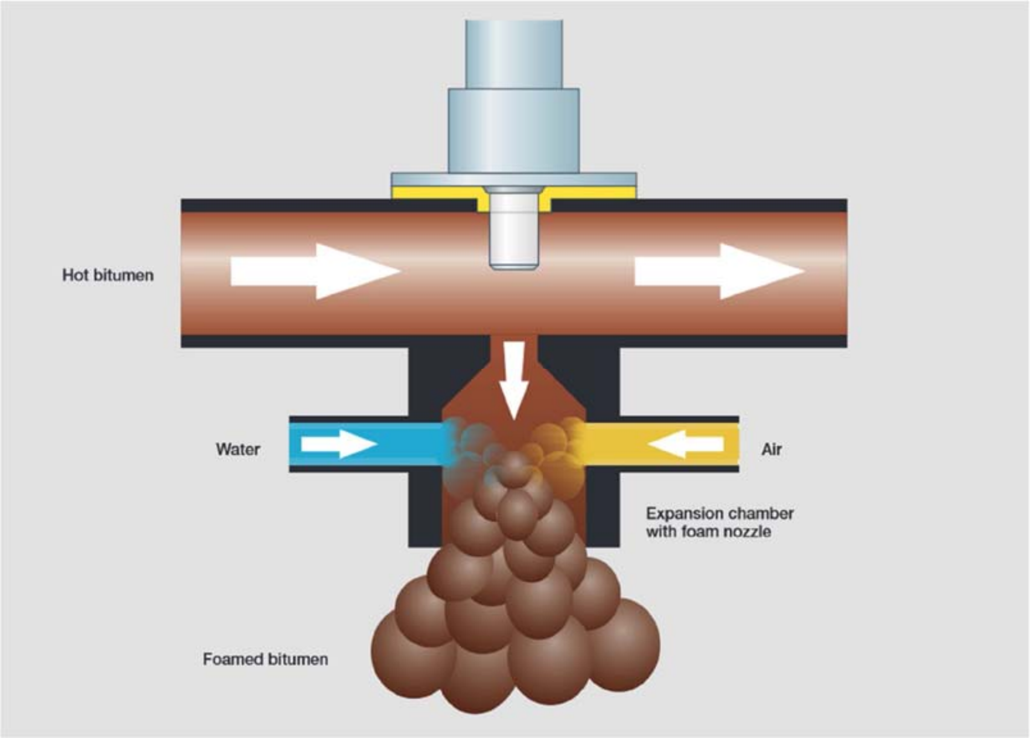

FIGURE 1. Asphalt Foaming Process (Wirtgen Group 2009)

Two of the more locally common mechanical foaming processes are the AQUABlack™ and Double Barrel® Green systems. AQUABlack™ is a foaming process marketed by Maxam Equipment, Inc. This product utilizes a "Microbubble™" foaming technology that injects bubbles at 1000 psi into the binder so that the bubbles will stay in the mix until it is compacted. The AQUABlack™ system comes pre-assembled for quick and easy retrofitting. Once installed, the operator sets maximum tons on a control panel, and the system calculates and sets the amount of water to inject into the binder. Due to the high pressure injection, the water-to-liquid-asphalt ratio during foaming is lower than that of other foaming processes (Maxam, 2010).

The Double Barrel® Green system is distributed by Astec Industries, Inc. This product uses a special apparatus which injects microscopic water bubbles at a rate of one pound per ton of mix into the binder in order to foam the binder to approximately 18 times its original volume. No chemicals are used in this process, and the manufacturer claims that the foaming process allows a drop of about 50°F during production. The apparatus may be used with an Astec Double Barrel® drum mixer/dryer or may be added as a retrofit to existing equipment. (Middleton and Forfylow, 2009 and Astec, 2009)

In 2011, the results of NCHRP Project 09-43 were released, which provided national guidance on mix design practices for Warm Mix Asphalt (Bonaquist, 2011). This study included testing to determine the effects of reheating, binder grade selection, WMA mixtures containing RAP, short-term oven conditioning, and devices used to measure workability. In terms of volumetric properties, it was established that for mixtures having up to 1.0 percent binder absorption, the properties of WMA were essentially the same as their HMA counterparts. However, the compactability, moisture sensitivity, and rutting resistance were often significantly different than for HMA, and so tests for these parameters should become a part WMA mixture design. The two-hour mixture aging used for HMA design was determined to also be adequate for WMA mixture design. However, it was stated that more research will be necessary to determine the additional aging time needed for specimens to be used in performance testing.

One of the primary products of the NCHRP project was a draft appendix to mix design specification AASHTO R 35, ‘Special Mixture Design Considerations and Methods for Warm Mix Asphalt (WMA)’ (Bonaquist, 2011). This draft addresses process-specific specimen fabrication methods, including plant foaming systems. In order to perform a WMA mix design for plant-foaming processes, a laboratory-scale foaming device capable of producing batches of 10 to 20 kg is needed. Because the performance of WMA has been consistently shown to be significantly different from that of HMA mixes, a laboratory-scale foamer must be used for the design and verification of plant-foamed WMA mixtures.

At the time that the NCHRP study was performed, only one laboratory foaming device, a first generation Wirtgen WLB-10, was commercially available. This device was designed for Full-Depth Reclamation foaming technology, which requires much higher water contents than WMA (Wirtgen Group, 2009). Thus, the device was modified to provide the reduced water level. Other problems arose in that the Wirtgen machine was designed to produce large quantities of material (a minimum of 10 kg but optimally designed for 30 kg), making it difficult to generate individual samples for testing that had consistent foam. In addition to the significant expertise required of technicians, another issue involved clogged air lines in the device, requiring frequent disassembly and cleaning (Bonaquist, 2011).

Based on the difficulties noted in the NCHRP study regarding the use of the Wirtgen WLB 10 S foaming device, a second generation of the machine was adapted for WMA. Specifically, the water flow controller was replaced with a smaller, more precise flow controller. This “next generation” foaming device was purchased by the University of Arkansas, as was the corresponding dual shaft pugmill mixer (WLM 30). The WLM 30 is capable of mixing up to 66.1 lbs (30kg) of mix at one time, which provides a sample size adequate for use in the University of Arkansas’s slab compactor, or compaction of multiple gyratory-compacted specimens. At least two other devices have also been developed for making laboratory-foamed warm mix, including ‘The Foamer’, marketed by Pavement Technology, Inc., and the

'Hydro-Foamer', marketed by D&H Equipment, Ltd. Limited data is available for these devices, but to date, the PTI device appears to have been purchased by more research groups.

Other recommendations of the NCHRP 09-43 study were to incorporate testing for coating and compactability. Coating refers to the degree of coverage that the binder applies to the aggregate surfaces after a specified mixing time, which varies according to the type of mixer used. It is noted that appropriate mixing times for bucket mixers or pugmill mixers have not yet been determined. Coating is evaluated in accordance with AASHTO T 195, which is a visual test to determine the percentage of fully-coated coarse aggregate particles in the test sample. The recommended coating criterion is a minimum of 95 percent.

In AASHTO R35, compactability, or workability, is defined as the ratio of the number of gyrations required to achieve 92% density when compacted at design WMA temperature to the number of gyrations required to achieve 92% density when compacted at 30°C lower than the design WMA temperature. The maximum recommended ratio is currently set at 1.25.

Moisture sensitivity and rutting resistance were also recommended as critical steps in the WMA mixture design process. AASHTO T 283 was recommended as the test for determining moisture damage, including a 2-hour mixture conditioning period at field compaction temperature. The chosen test method for measuring rutting resistance was the flow number test described in AASHTO TP 79, including a 2-hour mixture conditioning period at field compaction temperature. This test method is performed using the Asphalt Mixture Performance Tester (AMPT), which is a relatively new "simple" performance test capable of determining dynamic modulus and flow number for asphalt mixtures.

In 2014, the results of Project NCHRP 09-47A were published, which detailed the engineering properties and field performance of WMA technologies (West et. al. 2014). The performance tests included dynamic modulus, moisture susceptibility, Hamburg wheel tracking, fatigue, thermal cracking, and flow number.

In this study, 13 WMA mixtures were evaluated. In all cases, the mixes were first designed as HMA designs, and then the WMA technologies were simply "dropped in". Mix design verifications were then performed and the binder contents were adjusted to identify optimum binder content for each WMA mix. Overall, the design binder contents were an average of 0.27 less for WMA mixes as compared to their HMA counterparts. One possible explanation for this was that binder absorption was, on average, 0.12 percent less for a WMA mix than for a comparable HMA mix, meaning that more effective binder was available for coating and compaction of the WMA mixes. However, after 1 to 2 years, the absorption levels had approached (and sometime surpassed) that of the HMA mixes, suggesting that the HMA-designed optimum binder content was, in fact, appropriate for the WMA mixes. While rutting potential had been a concern for these seemingly 'over-asphalted' WMA mixes, field performance of the 13 mixes was approximately the same as the HMA mixes, resulting in the conclusion that WMA mixes do not need reduced design binder contents. The WMA technology was believed to serve as a compaction aid, which was consistent with the larger proportion of the unabsorbed binder in the WMA mixes. If design binder contents were to be reduced for WMA based on this difference in absorption, then the compaction benefits of WMA could be negated.

One specific issue arose regarding the use of laboratory foaming devices for mix design purposes. It was noted that the full-scale foamers were able to provide better coating than laboratory-scale foamers, and that the laboratory foamers were not considered accurate enough for mix design. It was recommended that in order to perform mix designs, the binder should be foamed into a separate container, and then weighed externally for inclusion in the mix design samples. A heated container was suggested for minimizing foam collapse during the weighing process. The research findings included a recommendation that WMA mix designs be performed initially without the WMA technology, but that additional performance checks, coating, compactability, moisture sensitivity, and rutting resistance could be completed using either laboratory- or plant-produced WMA. Due to potential differences in laboratory- and plant-scale foaming, it was recommended that moisture damage susceptibility testing be tested using plant-foamed WMA.

Additional performance testing of WMA has also been recommended, but further study is suggested for the determination of appropriate mixture aging times. Specific performance test methods suggested as alternatives include the development of dynamic modulus master curves, low-temperature creep compliance and strength testing, torsion bar testing, and the Semi-Circular Bend Test (SE(B)). The dynamic modulus, creep compliance, and torsion bar are all indicators of rutting and permanent deformation of asphalt concrete, while the SE(B) fracture test is an indicator of cracking characteristics. Dynamic modulus (AASHTO TP 62) is a primary input for mechanistic-empirical pavement design, and quantifies the fundamental linear viscoelastic characteristics of asphalt concrete (Underwood *et al*., 2001). Creep compliance (AASHTO T 322) is also an indicator of rutting behavior (White *et al.,* 2002). Therefore, it is important to understand the performance of the WMA in these two tests. A newer test, with the ability to run on a standard Dynamic Shear Rheometer (DSR) device (with additional fixtures), is a torsion bar test (Reinke and Glidden, 2005). This test can also indicate the rutting susceptibility of asphalt concrete using small samples sizes on a piece of equipment available in most asphalt concrete laboratories (Dave and Koktan, 2011). The Semi-Circular Bend test is a simple fracture test that quantifies the cracking resistance of asphalt concrete. A mixture with higher fracture energy indicates stronger resistance to cracking (Molenaar *et al*., 2002).

In addition to analyzing the properties of WMA mixtures, the characteristics of the asphalt cement with no aggregate should be understood. Understanding the workability, or viscosity (units Pa-s), of foamed asphalt cement is important, as capturing the proper mixing temperatures for WMA is critical to its success. Ideally, the aggregate structure provides the load carrying capacity of the pavement, but if the asphalt cement is prone to rutting, permanent deformation can occur in a single or multiple pavement layers. Since asphalt is a viscoelastic material, it displays both viscous and elastic behavior, depending on the loading rate and testing temperature (Asphalt Institute, 1995). The viscous and elastic behaviors determine the total resistance of a material to deformation. The $G^*/\sin\delta$ (units kPa) is an important parameter for measuring the stiffness of asphalt cement, or the resistance of asphalt cement to deformation under loading (ASTM D 7175). Asphalt binders behave like elastic solids at lower temperatures (generally below freezing), but behave like viscous fluids at higher temperatures (generally above typical in-service pavement temperatures). The elastic deformation is recoverable, while the viscous deformation is not recoverable. Normal pavement temperatures generally lie between a pure elastic and pure viscous state. By measuring G* and sin δ, the effect of foaming of asphalt cement on asphalt binder grade can be determined (Roberts *et al.,* 1996). There is a strong possibility that by foaming the asphalt cement, a shift of grade may occur. Figure 2 demonstrates this possibility.

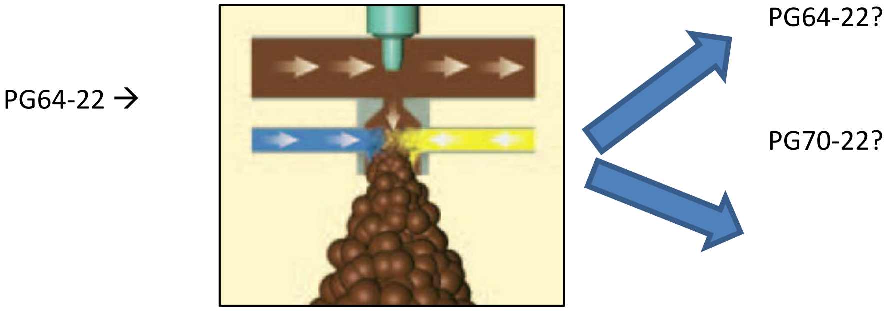

FIGURE 2. Potential Grade Modification Due to Foaming (picture from Wirtgen Group, 2010)

In addition to exploring the effect of foaming on binder grade and G*/sin δ specifications, understanding the G* and sin δ parameters can lead to building asphalt cement master curves. Master curves are a collection of data points that measure the stiffness of asphalt cement over various temperatures (or frequencies). By understanding the stiffness of asphalt cement, a better prediction of the potential of rutting can be made. If the foaming of asphalt cement increases the stiffness of the asphalt cement, it may be more resistant to rutting. Figure 3 shows some theoretical master curves, with the mixtures showing higher stiffness as the G* value increases.

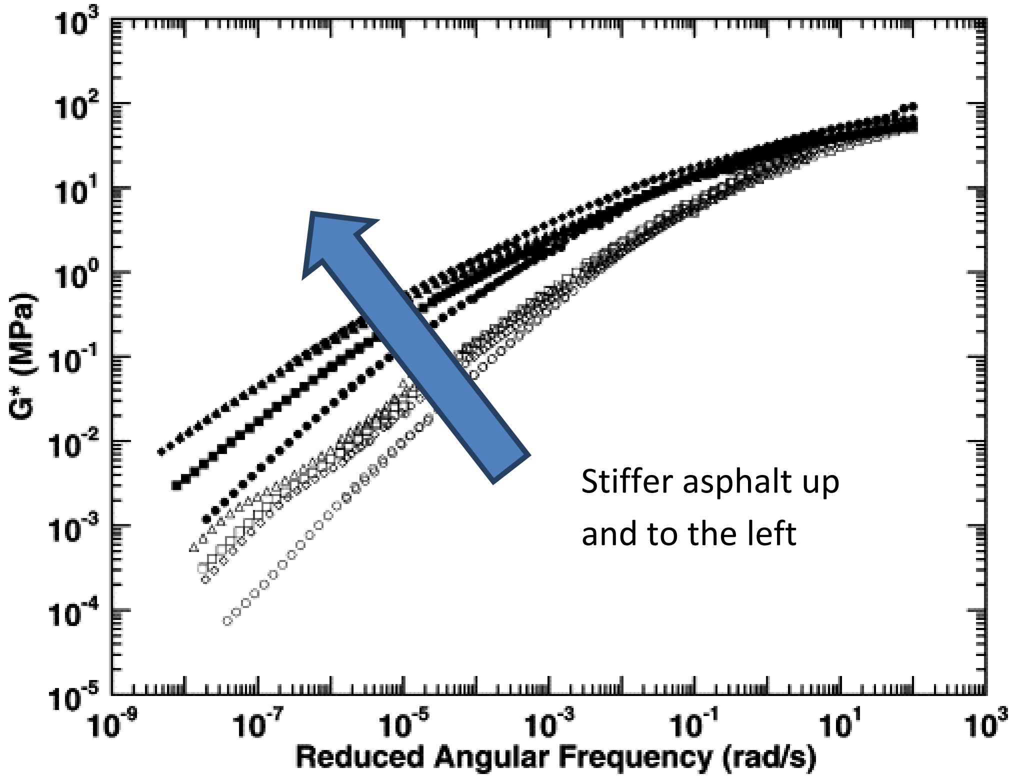

FIGURE 3. Master Curves of Asphalt Cement (Ruan *et al.*, 2003)

Unfortunately, and especially when working with polymer modified asphalt cements, capturing G* and sin δ has not done a good job of predicting actual rutting performance of asphalt concrete (Delgadillo *et al.,* 2006). In these cases, lab data and field rutting data have shown a poor correlation, especially when examining polymer modified asphalts. In addition, some manufacturers of unmodified asphalt cement are able to modify their products in such a way where the G* and sin δ data will indicate a polymer is in the asphalt cement, but in fact, the asphalt cement is not polymer modified (D'Angelo et al., 2007). While some states have gone to a SHRP+ program to identify the presence of polymer modification, these tests simply identify the presence of polymer, but do not properly categorize the potential performance of the polymer modified asphalt cement. In order to remedy this, instead of using the traditional cyclic loading, it has been proposed to capture the repeated creep and recovery. This testing mechanism is also more representative of traffic flowing over an asphalt concrete surface. During the test, there is a deformation, but also time for recovery. In the late 2000s, there was significant work in developing this concept, with a new parameter being developed, J_{nr} (D'Angelo, 2010; units kPa). J_{nr} is a parameter captured by the Multi-stress Creep and Recovery (MSCR, ASTM D 7405), and stands for the non-recoverable creep compliance, or the amount of asphalt cement deformation that will not return to its original form. Figure 4 shows data collected from a J_{nr} test. In the G* and sin δ test, a sinusoidal load is constantly applied, whereas in the J_{nr} test, the load is applied and relaxed on the sample.

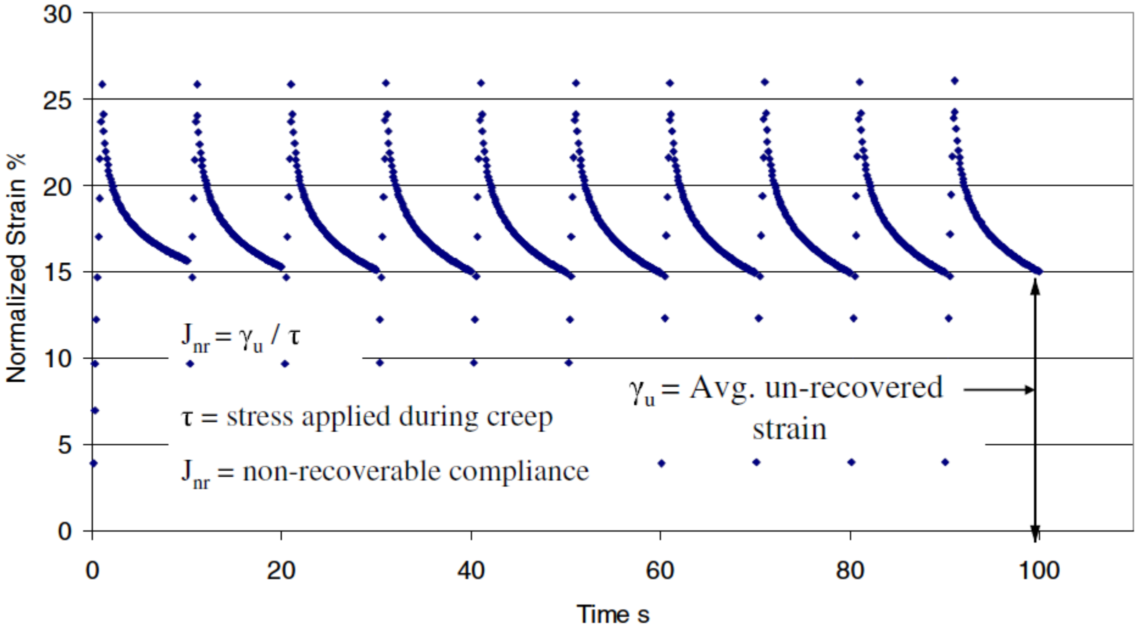

FIGURE 4. J_{nr} Data Collected During Testing (D'Angelo *et al.*, 2007)

From Figure 4, it is anticipated that larger J_{nr} values indicate a higher chance of rutting. J_{nr} is a function of two measurements, the stress applied to the sample (τ) and the average un-recovered strain (γ_u). By taking the ratio of these two values, the non-recoverable creep compliance can be determined. It is believed that in the future, J_{nr} will be the primary asphalt cement test that can capture rutting potential. Currently, however, an understanding of G*/sin δ is still essential to the pavement community, in order to correlate new data with data collected in the past. Both the G*/sin δ and J_{nr} parameters can be measured using the Discovery Hybrid Rheometer, utilizing the traditional parallel plate equipment.

3. Research Objectives

The primary objectives of this research effort were to thoroughly evaluate laboratory foaming techniques used to generate WMA mixture designs, and to determine the most advantageous plant-foamed WMA mix design approval process for the AHTD to implement. Specific objectives included:

Purchase a laboratory foaming device. At least three laboratory devices were available for producing specimens of foamed WMA in the laboratory. These devices were investigated and considered. One was chosen for purchase, for the purpose of completing laboratory evaluations for the project.

Compare field- and laboratory-foamed WMA. One of the most significant anticipated problems relating to foamed WMA was the potential for inconsistencies between field- and lab-produced WMA mixtures. Thus, plant-produced mixtures were obtained, and compared to equivalent mixtures produced in the laboratory.

Evaluate the sensitivity of plant-foamed WMA to changes in temperature. One of the most important features of the WMA design is temperature. Thus, plant foamed WMA was studied to determine its sensitivity to changes in production and compaction temperature. Also, greater differences in production and compaction temperatures were investigated in order to determine the effects of temperature on haul times.

Investigate fluctuations in binder content. Binder content is another important mix design feature that was considered. Previous research has shown that for WMA produced using additives, the WMA designs are no more sensitive than HMA mixtures to changes in binder content. This effect was investigated for foamed WMA.

Assess the effects of moisture content of foamed WMA. Because WMA mixtures are produced at lower temperatures than HMA, there was some concern that moisture trapped in the aggregate may not be completely evaporated prior to mixing with the asphalt cement binder. This effect could significantly affect performance, and could lead to issues regarding plant speed. The effects of moisture content were investigated with respect to coating.

Evaluate the coating and compactability of foamed WMA. In addition to the traditional volumetric properties and performance tests typically used for HMA mixture design, coating and compactability are believed to be important characteristics for WMA mixture designs. These features were evaluated as a means for quantifying the effects of the reduced temperatures used in WMA.

Perform advanced testing of WMA binders and mixtures. The behavior of the asphalt binder, when foamed, is the determining factor in the compactability of the mixture. Thus, testing of the asphalt cement was performed in order to establish properties relating to this behavior. These tests included workability and stiffness. Additional advanced tests were also performed on selected mixtures, including dynamic modulus, creep compliance, torsion bar, and the semi-circular bend fracture test, in order to better understand the rutting and cracking characteristics of foamed WMA.

Investigate combinations of WMA with RAS and RAP combinations. The potential performance issues of WMA, primarily rutting and moisture damage, could be offset by the stiffening properties of recycled asphalt shingles (RAS) and reclaimed asphalt pavements (RAP). Thus, the performance of WMA with RAS and/or RAP combinations was investigated.

4. Data and Analysis

The first task of the project was to investigate the available laboratory foaming devices, and to purchase the equipment. The Foamer, produced and marketed by Pavement Technology, Inc., was selected as the most advantageous item for purchase. The Wirtgen WLB 10 S was also included in the study. The Wirtgen device, already owned by the University of Arkansas, was the second generation foamer adapted for use with WMA. Both laboratory foamers are shown in Figure 5.

FIGURE 5. The PTI Foamer (left) and the Wirtgen WLB 10 S (right)

FIELD VS. LABORATORY

The next task was to compare mixes produced by a plant-foaming device, each of the two laboratory foamers, and hot mix. The ultimate goal was to identify a way to produce a foamed mixture in the laboratory that best represented the characteristics of the mix in the field. To do this, three field mixes were sampled from the plant after foaming, and then the raw materials were obtained in order to recreate those mixes in the lab as a hot mix (HMA), as a warm mix foamed in The Foamer (PTI), and as a warm mix foamed in the Wirtgen (WTG). This process was replicated for 3 different binder grades, including PG76-22, PG70-22, and PG64-22. All three mixes had a nominal maximum aggregate size (NMAS) of 12.5mm, were comprised of a limestone/sandstone combination, and had similar gradations. For each mix, multiple specimens were produced for assessing mixture volumetrics, rutting resistance, and moisture susceptibility. A summary of volumetric test results is given in Table 1, including bulk specific gravity (Gmb), air void content, absorption, voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and percent density at $N_{initial}$ (%Gmm@N_{ini}). Each result in the table represents the average of four tests.

TABLE 1. Summary of Volumetric Properties Comparing Field and Lab Compacted Specimens

		Gmb	Air Voids (%)	Absorption (%)	VMA (%)	VFA (%)	%Gmm@N_{ini}
PG64	HMA	2.233	7.5	1.8	18.8	60.3	81.6
	PTI	2.230	7.9	1.5	18.9	58.3	81.6
	WTG	2.229	6.0	1.7	18.9	68.4	82.0
	Field	2.320	5.1	0.8	15.6	67.5	83.6
PG70	HMA	2.255	5.9	1.6	17.7	66.8	83.0
	PTI	2.304	5.6	0.8	15.9	65.4	82.9
	WTG	2.274	6.7	1.1	17.0	60.9	82.3
	Field	2.325	4.5	0.7	15.1	70.1	84.2
PG76	HMA	2.308	4.0	0.8	16.1	75.0	85.4
	PTI	2.265	5.8	1.5	17.6	67.4	84.0
	WTG	2.300	4.3	0.9	16.4	73.8	85.0
	Field	2.294	5.9	0.7	16.6	64.6	82.7

The first comparisons aimed to determine whether there were statistically significant differences in the volumetric properties of the mixes when prepared by different methods (plant-foamed, PTI-foamed, WTG-foamed, and HMA). The first analysis focused on the air void content of the specimens, and sought to identify overall trends in the data for this property. Statistically, when the differences due to PG grade were separated, the effects of mixing method were only marginally significant, with the Analysis of Variance (ANOVA) results indicating a p-value for mixing method of 0.09. These results are shown graphically in Figure 6.

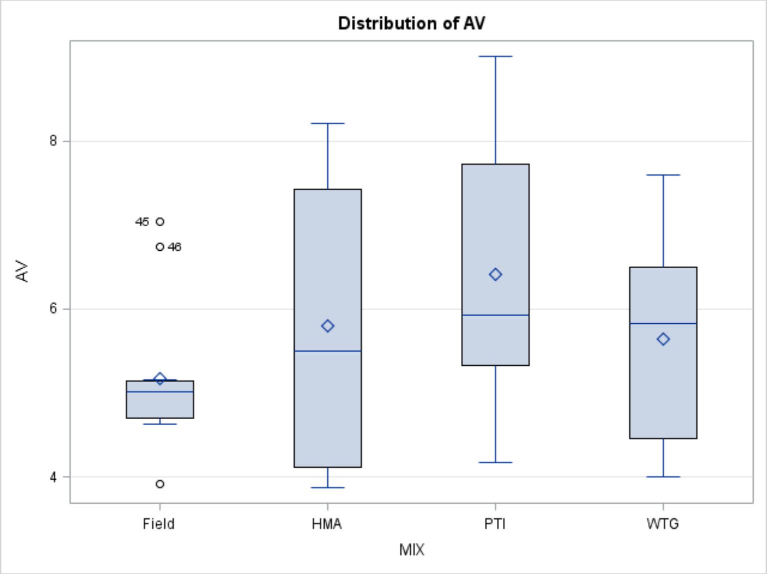

FIGURE 6. Mixing Method vs. Air Voids (%)

Next, each PG grade was analyzed individually, and the results are shown in Figures 7, 8, and 9. The PG76-22 mix was the first to be sampled from the field, and was sampled on two different days of production. Differences in sampling day were believed to contribute to the relatively large range of air voids. The field and PTI samples had similar average air voids, while the HMA and WTG were significantly lower.

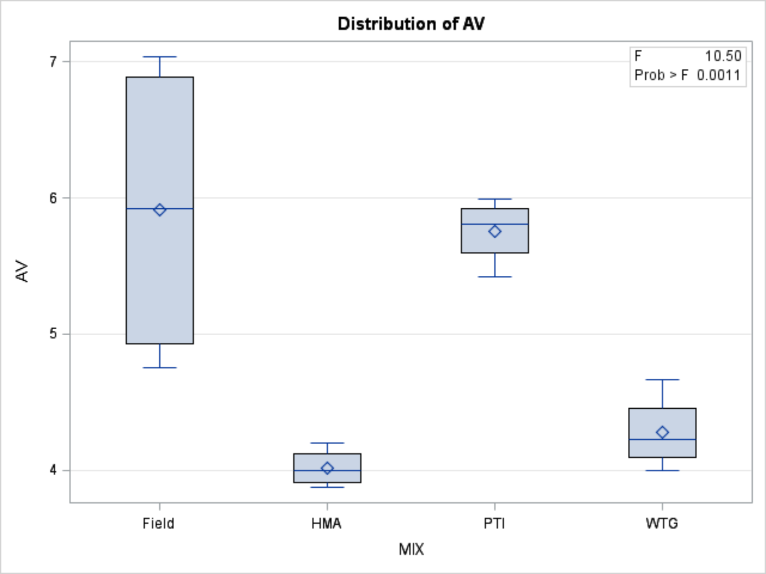

FIGURE 7. PG76-22 - Air Voids for Varying Mixing Methods

Next, the PG70-22 mix was analyzed, and the results are shown in Figure 8. For this field mix, results were more consistent than for the PG76-22 mix, which is reasonable since all samples were sampled and compacted on the same day. The average air void content was lowest for the field samples, followed by the PTI, then HMA, with WTG being highest. Again, the PTI samples were most similar to the field specimens.

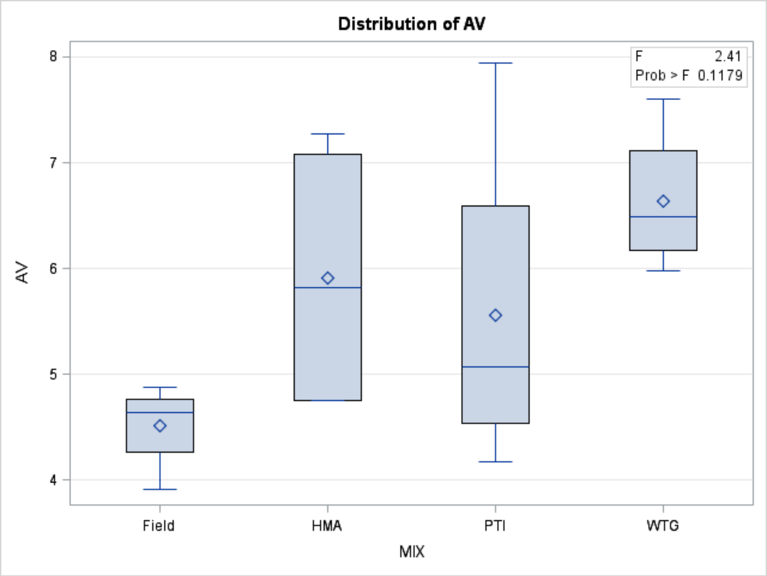

FIGURE 8. PG70-22 - Air Voids for Varying Mixing Methods

Finally, the PG64-22 mixes were analyzed for air voids, and the results are shown in Figure 9. In this case, the field mix was again most consistent, having a small range of air voids. For this mix, the WTG mixing method produced air voids most similar to the field, while the HMA and PTI were significantly higher.

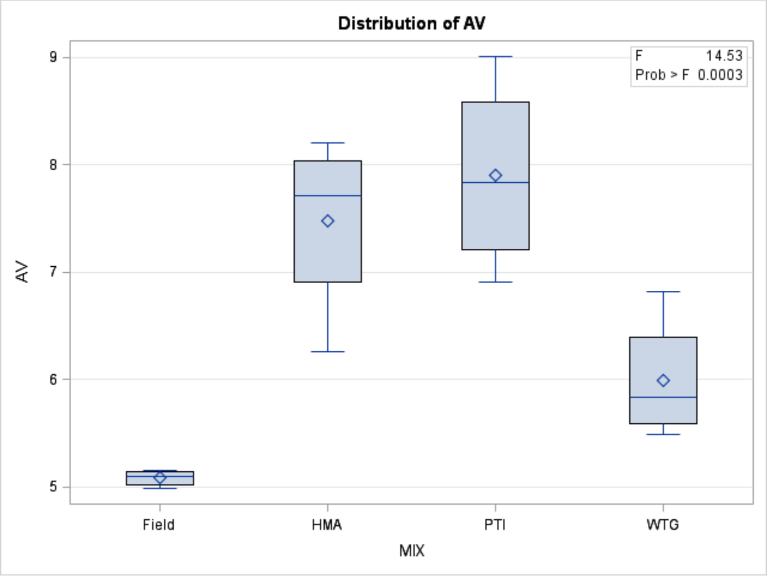

FIGURE 9. PG64-22 - Air Voids for Varying Mixing Methods

Statistically, the HMA was similar to the field mix in only 1 of 3 cases, meaning that HMA is not an adequate representation of a field-produced WMA. Also, the WTG was only similar to the field mix in 1 of 3 cases, so this method is not likely to provide the best approximation of a field-produced WMA. The PTI was similar in 2 of 3 cases, showing the best correlation to the field mixes.

Similar analyses were performed for the volumetric characteristics of absorption capacity. In general, no clear trends were present regarding PG grade, though this parameter did create significant variability in the data. The primary finding in the analysis of absorption capacity was that the field mixes exhibited lower levels of absorption than their lab-mixed counterparts. This was true for all PG grades, as shown in Figures 10, 11, and 12. For the PG64-22 mix, there was a statistically significant difference between laboratory- and field-compacted mixes. However, no differentiation was detected between the HMA and WMA mixes with respect to absorption. For the PG70-22 mix, no statistically significant differences were noted between mixing methods, although the field-mixed specimens had the lowest absorption values. For the PG76-22 mix, the field-mixed specimens again had the lowest absorption values, though there was no statistically significant difference between the field-mixed and HMA specimens.

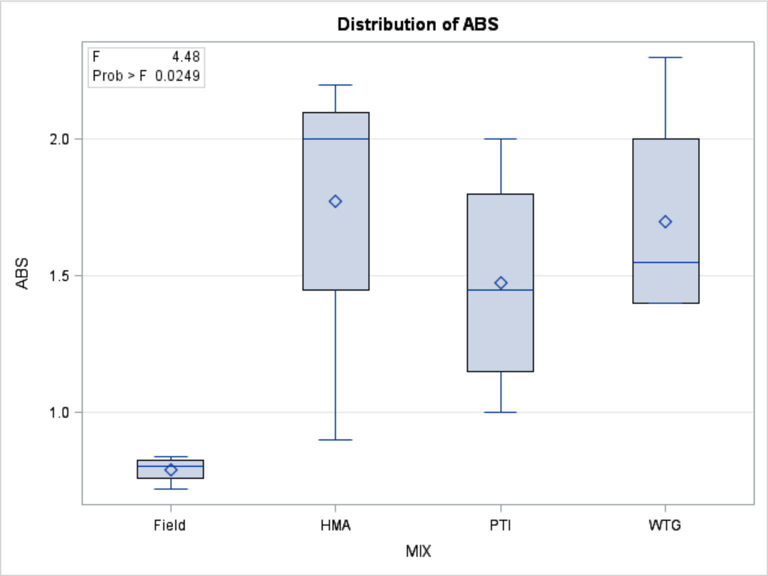

FIGURE 10. PG64-22 – Absorption (%) for Varying Mixing Methods

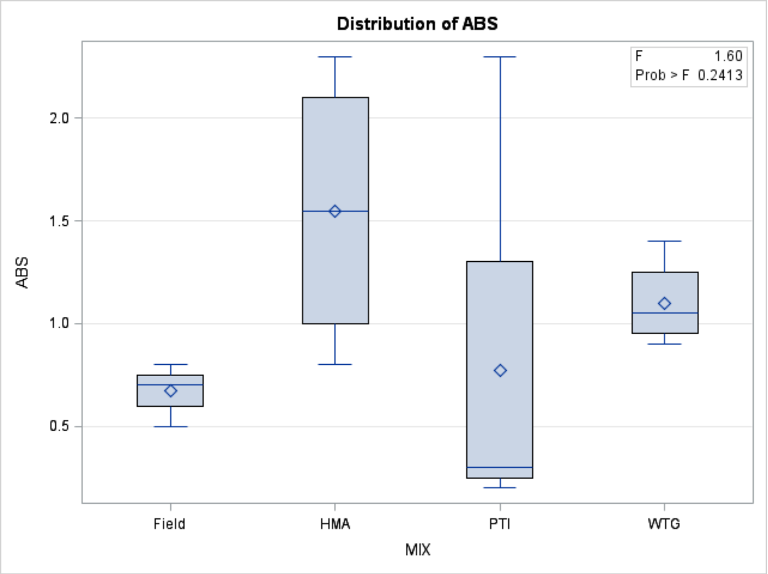

FIGURE 11. PG70-22 – Absorption (%) for Varying Mixing Methods

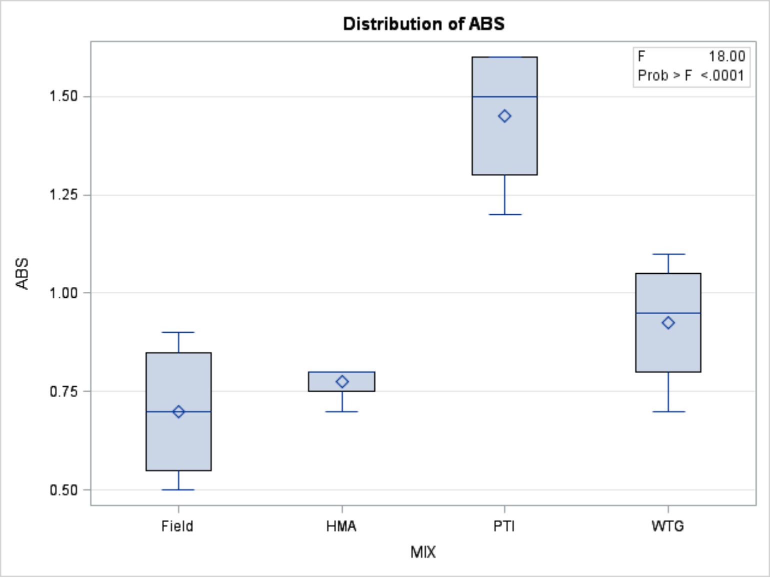

FIGURE 12. PG76-22 – Absorption (%) for Varying Mixing Methods

Additional analyses were performed for the properties of bulk specific gravity, VMA, VFA, and percent density at $N_{initial}$, however no other notable trends were observed.

TEMPERATURE SENSITIVITY

Temperature sensitivity of the foamed mixes was evaluated using mix designs comprised of two aggregate sources. Both were primarily limestone (referred to herein as Limestone #1 and Limestone #2), and each of the mix designs contained a sandstone component. Each aggregate source was used in mix designs containing PG64-22, PG70-22, and PG76-22 binders. For Limestone #1, mixes were produced in the laboratory using no foaming (HMA), with foam using the Foamer (PTI), and with foam using the Wirtgen foamer (WTG). For the Limestone #2 mixes, all three laboratory mixing methods were used, as well as field-produced plant-foamed field mix for each binder grade. Specimens of each mix design were short-term aged at the design compaction temperature, and then the temperature was reduced incrementally for more than 100°F. Although several volumetric properties were determined, air void content was chosen as the parameter of greatest interest and was used in the statistical analyses.

In Figure 13 the relationship between compaction temperature and air voids is shown for the entire dataset. While there is a slight trend of decreasing air voids with increasing temperature, this trend was statistically insignificant and likely confounded by other factors.

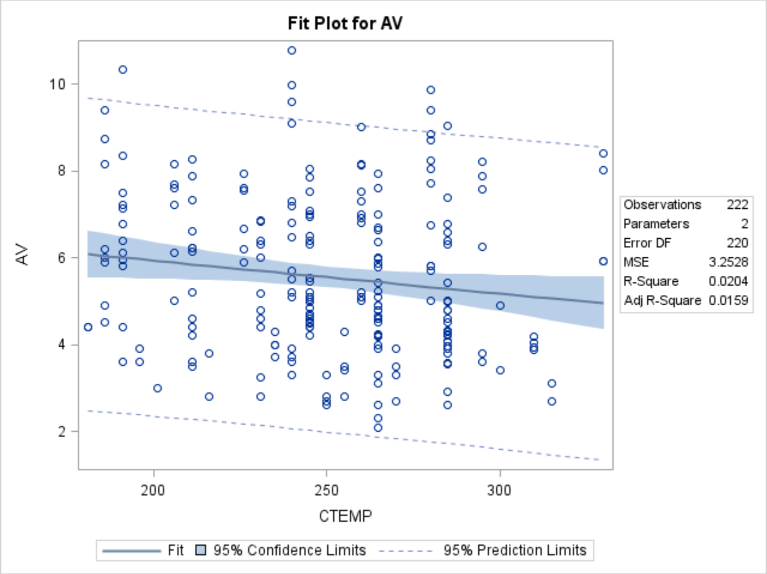

FIGURE 13. Relationship of Compaction Temperature (°F) and Air Voids (%)

In order to more thoroughly consider the data, the results for each mix design were plotted separately as shown in Figures 14 - 19. For the Limestone #1 mixes, no field mix was available, though fair agreement was present between the PTI and WTG specimens. In some cases, a slight increase in air voids was evident for the lower compaction temperatures. Some air voids were also elevated at the higher temperatures, suggesting an optimum compaction temperature for a mix. For the Limestone #2 mixes, an upward trend was present at lower temperatures, which was evident for both laboratory and field-produced mixes.

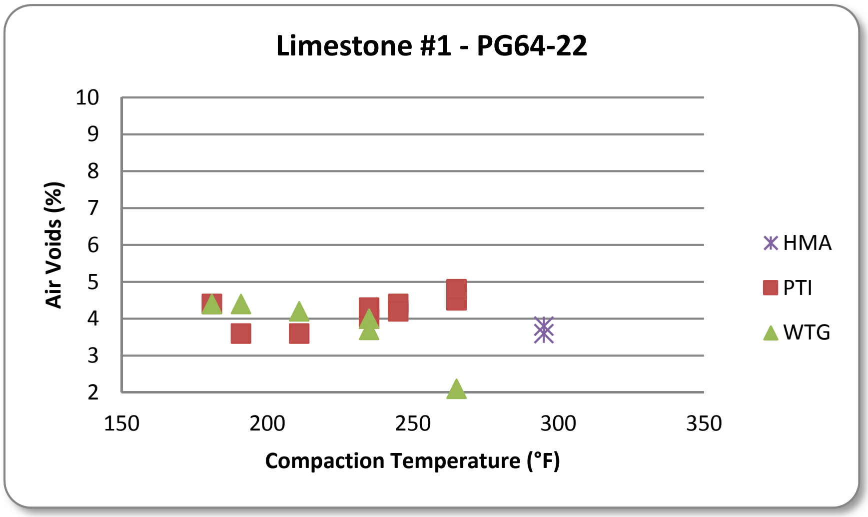

FIGURE 14. Compaction Temperature vs Air Voids for Varying Mixing Methods (Limestone #1 PG64-22)

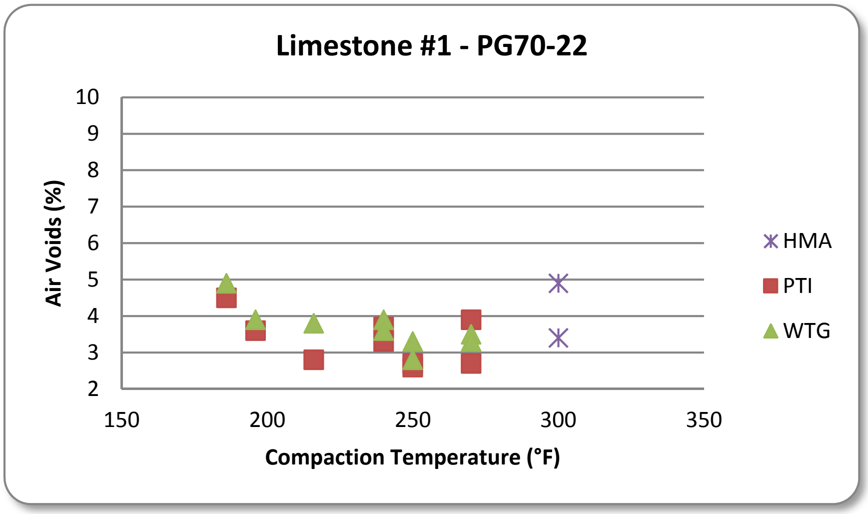

FIGURE 15. Compaction Temperature vs Air Voids for Varying Mixing Methods (Limestone #1 PG70-22)

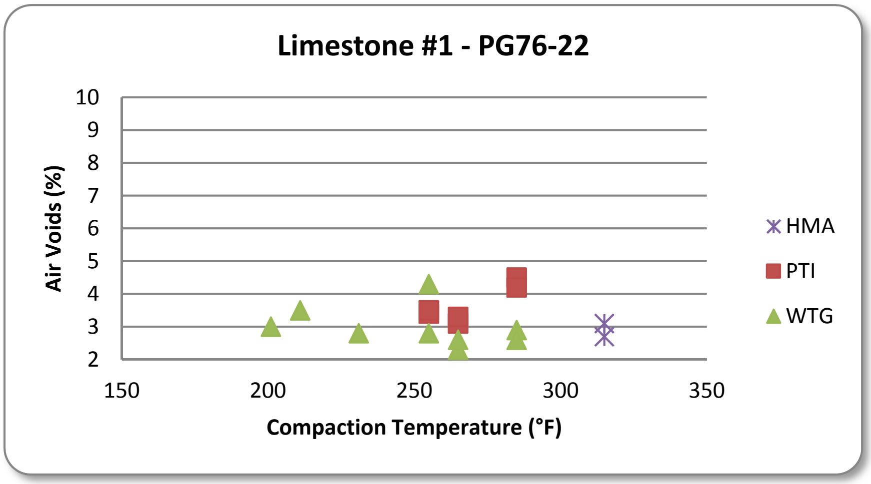

FIGURE 16. Compaction Temperature vs Air Voids for Varying Mixing Methods (Limestone #1 PG76-22)

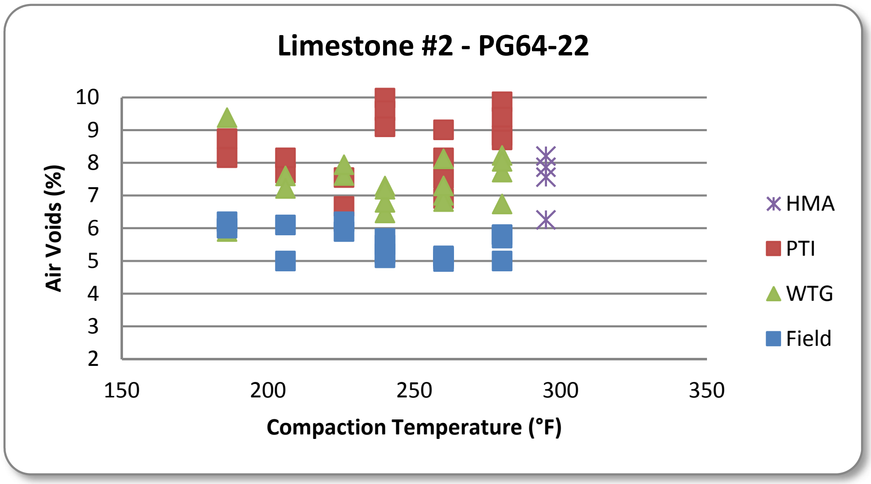

FIGURE 17. Compaction Temperature vs Air Voids for Varying Mixing Methods (Limestone #2 PG64-22)

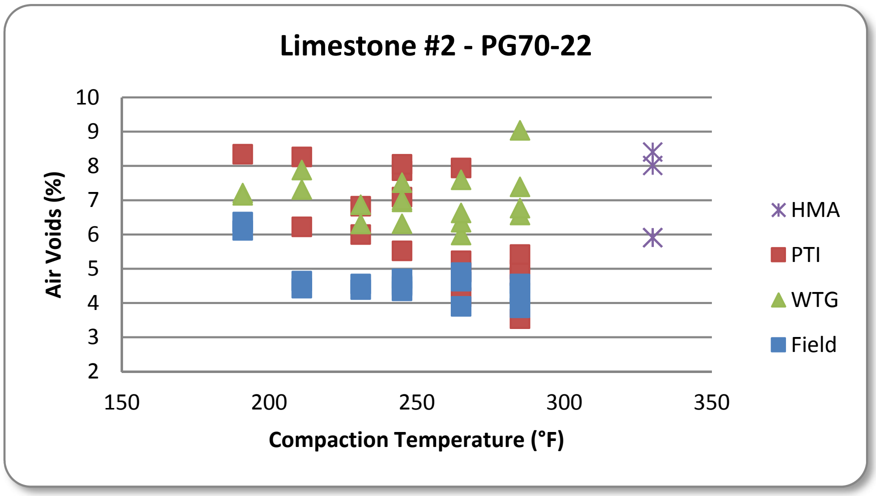

FIGURE 18. Compaction Temperature vs Air Voids for Varying Mixing Methods (Limestone #2 PG70-22)

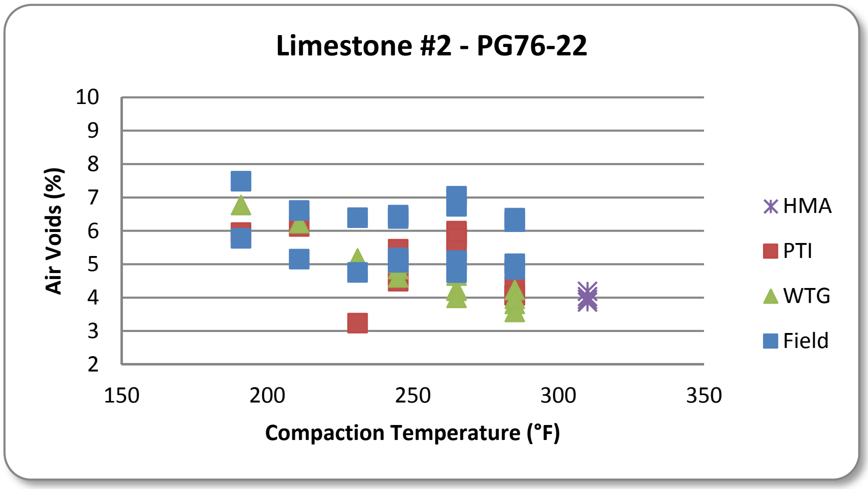

FIGURE 19. Compaction Temperature vs Air Voids for Varying Mixing Methods (Limestone #2 PG76-22)

Although some trends were visible, consistent relationships were not prevalent, requiring further investigation. Because each mix design had a different design compaction temperature, it was believed that a consideration of the deviations in temperature could provide greater insight. Thus, the field data was next considered using temperature categories rather than numerical values. The medium temperature (M) represented the design compaction temperature for the WMA, while low (L) and high (H) represented 20°F below and above design, respectively. The overall relationship between air voids, temperature category, and PG grade is shown in Figure 20. The lowest overall air voids were associated with the PG70-22 mix, which was also the mix with the greatest reduction in design compaction temperature (65°F reduction from HMA to WMA). It was expected that the mix with the least temperature reduction would also have the least air voids, but this was not the case. Although the interaction appeared to be related to PG grade, it was noted that other differences were present in the designs that could have also caused this interaction.

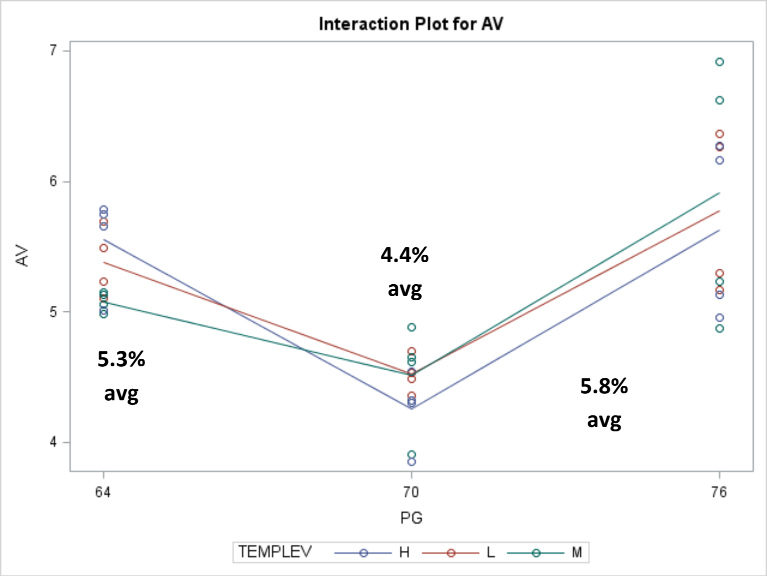

FIGURE 20. PG Grade vs. Air Voids for Varying Temperature Levels

Each of the Limestone #2 mixes contained a percentage of reclaimed asphalt pavement (RAP). The PG64-22, PG70-22, and PG76-22 mixes contained 20%, 10%, and 15% RAP, respectively. It was believed that since the PG70-22 mix contained the lowest RAP percentage, this mix was least affected by differences in temperature, allowing for greater compaction and lower air void contents. Mixes with higher RAP contents had a lesser potential for the RAP binder to become activated at warm mix temperatures, reducing the effective binder and increasing air void content. In other words, higher RAP mixes may require additional heating in order to activate the RAP binder such that it properly contributes to the overall binder content of the mix. Similar results were noted for recycled asphalt shingles (RAS) in project TRC-1004.

Another anomaly was that the mixing and compaction temperatures for the PG70-22 binder were higher than that of the PG76-22, which seemed unusual. The results of research project TRC-1004 indicated that higher binder grades can be more sensitive to warm mix technologies (i.e., achieve greater benefits in temperature reduction). In this case, the PG70-22 mix achieved the greater temperature reduction and lower air void contents, and this was considered reasonable given the higher mixing and compaction temperature ranges.

COMPACTABILITY

Additional samples were prepared for the purpose of evaluating compactability, based on the workability ratio analysis. The basic premise of this analysis was to determine whether, when the mix is compacted at a temperature of 30°C lower than the target compaction temperature, it can still be compacted with relative ease. Using volumetric properties along with the height data collected during gyratory compaction, the degree of compaction (or relative density) was calculated for each gyration using Equation X2.6 from AASHTO R35-12 X2.8.3.7.

$$\%Compaction = \%G_{mm_N} = 100\left(\frac{G_{mb} \times h_d}{G_{mm} \times h_n}\right)$$

$\%G_{mmN}$ = *relative density at N gyrations*
G_{mb} = *Bulk Specific Gravity*
G_{mm} = *Maximum Theoretical Specific Gravity*
h_d = *Final height after* N_{des} *gyrations*
h_n = *Height at n gyration*

This equation allowed for a determination of the gyration at which each sample reached 92% compaction, a necessary input for analyzing the workability index. The workability ratio was then determined using the number of gyrations to reach 92% compaction at the warm mix temperature and the number of gyrations to reach 92% compaction at the corresponding mixture 30°C below the WMA temperature.

$$Workability\ Ratio = \frac{(N_{92})_{T-30}}{(N_{92})_T}$$

Ratio = workability ratio
$(N_{92})_{T-30}$ =*gyrations to reach 92% relative density* 30^oC *below design temperature*
$(N_{92})_T$ = *gyrations to reach 92% relative density at design temperature*

AASHTO R35-12 recommends that for a mix design to be considered adequately “workable” this ratio should be less than or equal to 1.25. A workability ratio greater than 1.25 suggests that the mix will not compact adequately in the field and can also be an indicator of when a mix is sensitive to temperature decrease. The results of this analysis follow in Table 2, where acceptable ratios are shaded in green, and excessive ratios are shaded in pink. It should be noted that the PG76-22 binder specified for use in Limestone #1 PG76-22 mix design became unavailable before the completion of this research study. Thus, it was not possible to determine workability for this mixture using the PTI Foamer as current supplies were exhausted before completion.

TABLE 2. Workability Ratios

Mix ID	Foam	Compaction Temp	Average N92 Values		Ratio
			N92(T)	N92(T-30)	
Limestone #1 PG64-22	PTI	295	37.5	28	0.75
		265	35	28	0.80
		245	33	32	0.97
	WTG	295	32	30	0.94
		265	30.5	33	1.08
		245	30.5	28	0.92
Limestone #1 PG70-22	PTI	270	35.5	29	0.82
		250	30	35	1.17
		240	35	40	1.14
	WTG	270	35.5	36	1.01
		250	32.5	36	1.11
		240	37.5	45	1.20
Limestone #1 PG76-22	PTI	285	50	-	-
		265	40.5	-	-
		255	40.5	-	-
	WTG	285	37	33	0.89
		265	32.5	37	1.14
		255	42	28	0.67
Limestone #2 PG64-22	PTI	280	95	62	0.65
		260	75	75	1.00
		240	103	84	0.82
	WTG	280	70	71	1.01
		260	65	66	1.01
		240	59	74	1.25
	Field	280	44	32	0.72
		260	39	44	1.12
		240	43	49	1.15
Limestone #2 PG70-22	PTI	285	68	46	1.48
		265	88	59	1.49
		245	125	77	1.63
	WTG	285	76	70	0.92
		265	71	90	1.26
		245	77	80	1.05
	Field	285	41	42	1.02
		265	43	44	1.04
		245	42	65	1.54
Limestone #2 PG76-22	PTI	285	42	33	0.76
		265	63	68	1.08
		245	49	64	1.30
	WTG	285	41	52	1.28
		265	44	71	1.60
		245	50	82	1.64
	Field	285	68	96	1.41
		265	75	103	1.37
		245	71	131	1.86

The workability ratios of the Limestone #1 mixes were acceptable in all cases, however some ratios for the Limestone #2 PG70-22 and PG76-22 mixes were excessive. While the mixes having ratios exceeding the maximum were not consistent for all mixing methods, all methods were able to identify potentially troublesome mixes for some temperatures. The mixes that did not meet the recommended 1.25 criteria were the Limestone #2 mixes, which contained RAP, and the workability ratios increased as temperature decreased. Thus, the lower temperatures may not have activated the RAP binder, limiting the workability of the mixture.

MOISTURE AND COATING

Because the aggregates in WMA are not heated as much as HMA aggregates, there was concern that aggregates in plant-mixed WMA may not be heated enough to remove residual moisture, thereby affecting the ability of the binder to coat the aggregate surfaces. To assess the effects of this moisture, laboratory samples were prepared using 1% and 2% moisture. A half-wet procedure, as described in AASHTO R35, was used to introduce the moisture into the samples prior to mixing. At 2% moisture, mixing was difficult, and coating was very poor. The coated percentage was determined according to AASHTO T195, and was compared to the recommended minimum of 95%, as stated in AASHTO R35. With 2% moisture, the PG76-22 mix achieved 67% coated while the PG64-22 mix achieved only 3% coated. Compaction was not achievable at this low coating percentage. The moisture content was then reduced to 1%, resulting in 74% coating for the PG76-22 mix and 86% for the PG64-22 mix. Though the mixing process was somewhat improved with 1% moisture, the mix was still not considered to be acceptable. An example of a 1% mix is shown below in Figure 21. It was determined that excess moisture, even in small percentages would be visually evident by a lack of coating.

FIGURE 21. PG64-22 Mix – 1% Moisture Added

RUTTING SUSCEPTIBILITY

Rutting susceptibility was assessed using the Asphalt Pavement Analyzer (APA) device. Field-compacted specimens representing the Limestone #2 mix were compacted at varying temperatures for each of the 3 binder grades. Comparisons were also made at design compaction temperature for the field, PTI, WTG, and HMA mixing methods. A summary of results is shown in Table 3, and the mixing method comparison is shown graphically in Figure 22. Statistically, rut depths were not significantly affected by mixing method or compaction temperature, but did vary with air voids, such that higher air voids generally correlated with higher rut depths, as shown in Figure 23.

TABLE 3. Summary of Rutting Susceptibility Results (average values shown)

	Mixing Method	Compaction Temperature Level	Air Voids (%)	Rut Depth (mm)
PG76-22	Field	Low	5.35	1.764
		Design	5.7	1.596
		High	5.4	1.857
	PTI	Low	N/A	N/A
		Design	7.2	1.669
		High	6.9	1.599
	WTG	Low	7.8	2.111
		Design	6.8	2.126
		High	6.7	1.962
	HMA	Design	7	3.203
PG70-22	Field	Low	9.75	4.021
		Design	8.95	3.603
		High	9.2	4.336
	PTI	Design	7	2.489
	WTG	Design	7.2	2.805
	HMA	Design	7.3	1.523
PG64-22	Field	Low	7.1	3.712
		Design	7.05	3.408
		High	7	3.421
	PTI	Design	7.4	3.470
	WTG	Design	6.8	3.805
	HMA	Design	6.8	2.995

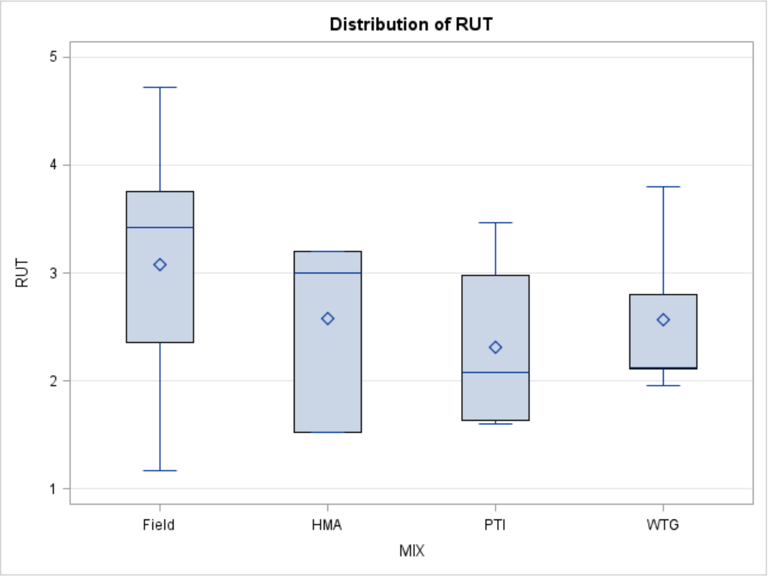

FIGURE 22. APA Rut Depths for Various Mixing Methods

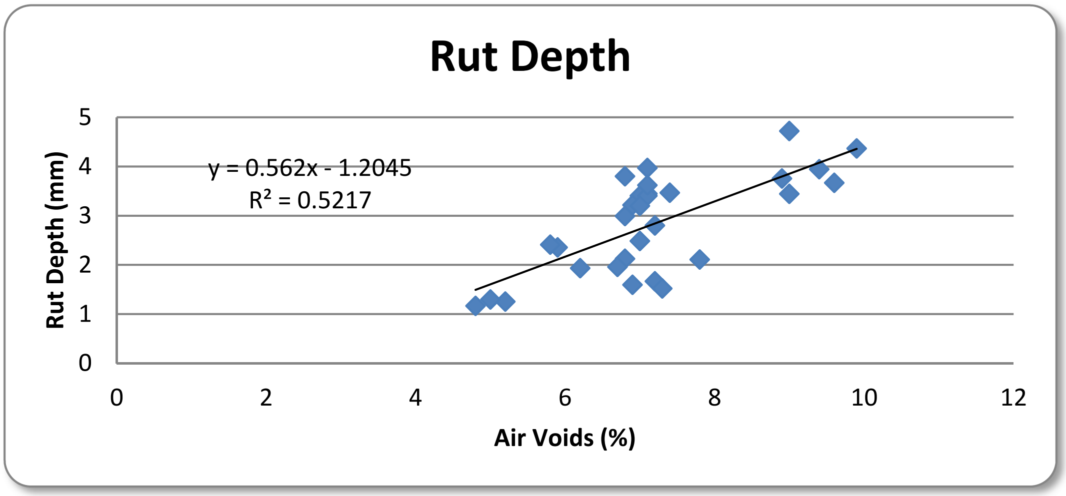

FIGURE 23. Air Voids (%) vs. APA Rut Depths (mm)

MOISTURE DAMAGE

A selection of mixes was prepared and tested for moisture damage susceptibility according to AASHTO T283, and the tensile strength ratio (TSR) results are shown in Table 4. For the Limestone #2 PG76-22 field mix, three different compaction temperatures (design, design - 20°F, and design + 20°F) were used to prepare test specimens. There was very little difference in TSR results. Based on this conclusion, and the lack of significance in other parameters due to temperature, further comparisons for varying temperature were not performed. Additional testing was completed for field mixes, HMA, and PTI-foamed mixes, for the three binder grades using the Limestone #2 aggregate source. Overall, the HMA mixes were the best performers, followed by the field mix, and then the PTI mixes.

TABLE 4. Moisture Damage (TSR) Results

Binder Grade	Mixing Method	Tensile Strength Ratio (TSR)
PG64-22	HMA	0.95
	Field	0.82
	PTI	0.77
PG70-22	HMA	0.86
	Field	0.86
	PTI	0.81
PG76-22	HMA	0.99
	Field	1.00
	PTI	0.81
PG76-22	Field (design – 20°F)	0.97
	Field (design)	1.00
	Field (design + 20°F)	1.02

The lower TSR values being associated with the laboratory-foamed mix suggests that foamed warm mix may be more susceptible to moisture damage than traditional HMA mixes. However, the field results did not support this conclusion for the polymer-modified binders. For the PG70-22 and PG76-22 mixes, the field and HMA results were essentially the same, while the PTI results were lower – especially for the PG76-22 mixture. For the PG64-22 mix, the field and PTI results were somewhat similar, while the HMA mix showed greater resistance to moisture damage. This is consistent with the findings of project NCHRP 9-49, which determined that in general, moisture susceptibility of laboratory-foamed WMA can be detected; however, the field performance of those mixes was typically better than expected.

SHORT-TERM AGING

The effects of short-term aging were investigated using laboratory-prepared specimens tested for maximum theoretical specific gravity (Gmm). One mix (12.5mm Limestone #1, PG64-22) was prepared and aged at 3 different temperatures (235, 265, and 295 °F), according to 3 different mixing methods (HMA, PTI, and WTG). Duplicate specimens were tested after aging for 2-hour and 4-hour periods. Three metrics (response variables) were obtained, including maximum theoretical specific gravity (Gmm), effective specific gravity of the stone (Gse), and percent of absorbed binder (Pba). A summary of results is contained in Table 5.

TABLE 5. Summary Results for Aging (average values shown)

Aging Time (hrs)	Aging Temp (°F)	Mixing Method	Gmm	Gse	Pba (%)
2	295	HMA	2.398	2.625	2.21
		PTI	2.394	2.620	2.14
		WTG	2.389	2.614	2.05
	265	HMA	2.393	2.618	2.11
		PTI	2.386	2.608	1.97
		WTG	2.376	2.596	1.79
	235	HMA	2.388	2.612	2.02
		PTI	2.383	2.606	1.93
		WTG	2.373	2.593	1.74
4	295	HMA	2.407	2.636	2.38
		PTI	2.406	2.634	2.36
		WTG	2.397	2.623	2.19
	265	HMA	2.380	2.601	1.86
		PTI	2.396	2.622	2.17
		WTG	2.394	2.620	2.13
	235	HMA	2.396	2.622	2.18
		PTI	2.392	2.617	2.10
		WTG	2.382	2.604	1.91

In the complete ANOVA, no interactions were present, but the three factors of aging time, aging temperature, and mixing method were significant. For each of the response variables, the following trends were noted:

- As aging time increased, Gmm, Gse, and Pba also increased
- As temperature increased, Gmm, Gse, and Pba also increased
- HMA and PTI specimens were similar, while WTG specimens revealed statistically lower values

More specifically, HMA specimens prepared at design conditions were compared to the WMA methods at varying temperatures and aging times. For all response variables, no statistically significant difference was found between the HMA mix and PTI specimens. However, the WTG specimens required longer aging times and/or higher aging temperatures in order to be considered similar to the HMA specimens. Thus, the 2-hour aging period appears to be acceptable when preparing WMA specimens in the lab using the PTI foamer. However, further research is necessary to determine whether changes to the aging procedure would be necessary for specimens prepared by the WTG foamer.

ADDITIONAL PERFORMANCE TESTING

Further performance testing was completed in an effort to discover the more fundamental differences between WMA and HMA mixes. Testing was performed on both asphalt mixtures and asphalt cement. The Brookfield Rotational Viscometer and Dynamic Shear Rheometer were used to test the asphalt cement, while mixture testing included dynamic modulus, creep compliance, and cracking information. The dynamic modulus and creep compliance was collected from the indirect tension configuration on cylindrical samples, dynamic modulus was collected from the torsion bar configuration, and cracking information was found with the Semi-Circular Bend [SC(B)] test.

Brookfield Rotational Viscometer

One of the challenges with quantifying behavior in the Brookfield Rotational Viscometer (RV) is determining when to record the viscosity measurement. In ASTM D4402 (Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer), the asphalt cement sample must be allowed to equilibrate at the desired temperature within thirty minutes, and equilibrate at the desired temperature for at least ten minutes before taking any measurements. Another five minutes passes after starting the motor rotation for equilibrium. After these equilibrium time periods, the viscosity is measured at one minute intervals for a total of three minutes. However, immediately after foaming, foamed asphalt cement begins to collapse.

The most common method for characterizing foamed asphalt is via the expansion ratio (ER) and half-life (HL) of the foamed asphalt. The ER of foamed asphalt is the initial volume of a sample of asphalt binder after foaming divided by the final volume of that sample of binder (or the initial volume before foaming). HL is a measure of the time required for a sample of foamed asphalt to reach half of its maximum volume. Some recommendations are that the HL be at least 6 seconds and that the ER be at least 8:1 for foamed warm-mix (Ozturk, 2013). This method of optimizing half-life and expansion ratio requires testing a matrix of possible water contents, binder temperatures, and air/water pressures (Wirtgen, 2008). Some research has shown that these parameters can be dependent on the operator, so some research is being done on how to use lasers or video cameras to measure these parameters more accurately (Ozturk, 2013). However, based on conversations with Wirtgen, this method was developed to aid in Full-Depth Reclamation mix design, and has not been verified to contribute to Warm Mix Asphalt mix design. Another method of characterizing foamed asphalt binder is to use liquid nitrogen to freeze foamed asphalt samples and use x-ray imaging to count the number of bubbles inside as well as measuring the diameter of each bubble (Kutay and Ozturk, 2012). Two different research groups followed the standard ASTM D4402 to measure the viscosity of foamed asphalt and saw no change or an insignificant change in the viscosity of foamed binder vs. original binder (Hanz *et al.*, 2010; Olga *et al.*, 2012). These groups looked at final viscosity of the foamed asphalt at temperatures near 160°C. The attempt in this research was to use standard asphalt lab equipment already readily available to characterize foamed asphalt. In order to achieve this, four metrics [FVf/OBV (final foamed viscosity/original binder viscosity), AAOB (area above original binder viscosity and below foamed binder viscosity), ABOB (area above foamed binder viscosity and below original binder viscosity), and TTI (time to intersection of foamed asphalt binder viscosity and original binder viscosity)] were created solely for the purpose of characterizing foamed asphalt binder.

The current method for measuring the viscosity of asphalt binder is to follow ASTM D4402. The viscosity given by the rotational viscometer is the ratio between the applied shear stress and the rate of shear and can be calculated from the following equation. Typically the RV measures torque in a percent (0 to 100), divides this torque by the RPM, and multiplies it by a series of constants based on the spindle used:

$$\eta = \frac{\tau}{\gamma} \qquad \tau = \frac{\mathrm{T}}{2\pi R_S^2 L} \qquad \gamma = \frac{2\omega R_C^2 R_S^2}{x^2(R_C^2 - R_S^2)}$$

Where:

$\eta = dynamic\ viscosity\ (Pa * s)$

$\tau = shear\ stress\ \left(\frac{N}{cm^2}\right)$

$\gamma = shear\ rate\ (s^{-1})$

$\mathrm{T} = \mathrm{torque}\ (\mathrm{N} * \mathrm{m})$

$L = effective\ spindle\ length\ (m)$

$R_s = spindle\ radius\ (m)$

$R_c = container\ radius\ (m)$

$\omega = rotational\ speed\ (\frac{radians}{second})$

$x = radial\ location\ where\ shear\ rate\ is\ being\ calculated$

An important note when using the rotational viscometer is that there are no air bubbles inside the liquid being tested. Using this equipment is straightforward when using unfoamed asphalt binder, which has no air bubble. However, foamed asphalt does have air and is an unstable substance, meaning that the volume of a sample of foamed asphalt is constantly changing from the instant the water and air mix with the asphalt binder until such a time that all the water and air has escaped the binder. There are several observations about foamed asphalt that can be recorded in relation to trying to obtain a viscosity measurement in a rotational viscometer:

- At the end of the foaming process, there may be a slight continued increase in volume until the maximum expansion is reached and the foam starts to collapse.
- If any heat is added to the foam, such as placing the sample in a temperature controlled thermo-cell in a rotational viscometer, the foam continues to expand as the air bubbles inside the foam are heated.

- If the foamed asphalt is introduced to the thermo-cell at the same temperature as the foaming process was set, then the asphalt may expand outside of the sample chamber. As the foam collapses, the height of the foamed asphalt cement may decrease to below the required height.
- At some temperatures, the viscosity of a foamed and unfoamed binder are nearly equal if using the standard testing procedure

These observations, among others, lead to the creation of a new testing procedure that would allow foamed asphalt to be easily tested in a viscometer at a wide range of temperatures. This testing procedure would record the observed viscosity over time so that the influence of the bubbles over time could be observed.

The first task was to create a test method that allows different results to be recorded for foamed asphalt vs. unfoamed binder while using a rotational viscometer. Typically two temperatures such as 135°C and 160°C are used to test asphalt binders for Superpave testing (Harman *et al.*, 1999). According to specifications, asphalt binder must have a viscosity of less than 3 Pa*s at 135°C. The viscosity at these two temperatures is used to create a line to find the mixing and compacting temperature zones on a temperature-viscosity chart. The spindle, sample chamber, and thermo-cell are preheated to the testing temperature and asphalt is poured in at that temperature. If this exact procedure is followed with foamed asphalt, two things occur. First, the foamed asphalt expands in the thermo-cell, overflowing out of the sample chamber and thermo-cell. After the foam collapses, the amount of asphalt cement left in the sample chamber is inadequate. Second, if enough time passes for the foamed sample to stabilize, the foamed nature could not be observed.

Foamed asphalt isn’t a stable substance, so a new method was established to measure viscosity over a period of time instead of at a single data point. In this method, viscosity was recorded at one minute intervals until three measurements in a row recorded the same viscosity value. This allowed for a viscosity versus time curve to be constructed for each foam sample. An example of these curves can be seen in Figure 24. The viscosity measurements taken for the foamed asphalt is called “observed viscosity” as an effort to highlight that the measurement isn’t a true viscosity of the asphalt binder but a reading that the Brookfield is giving based on the combination of binder and air bubbles inside the sample. Figure 1 shows three PG graded binders in a foamed and unfoamed (original binder) condition. The unfoamed viscosities were an average of three readings over a three minute period but are extended graphically across the graph to provide a better reference baseline with which to analyze the foamed observed viscosity. The whiskers shown are a 95% confidence interval based on 3 replicates. There seemed to be a wider distribution of data in the first portion of the test and as the test progressed, the variability decreased.

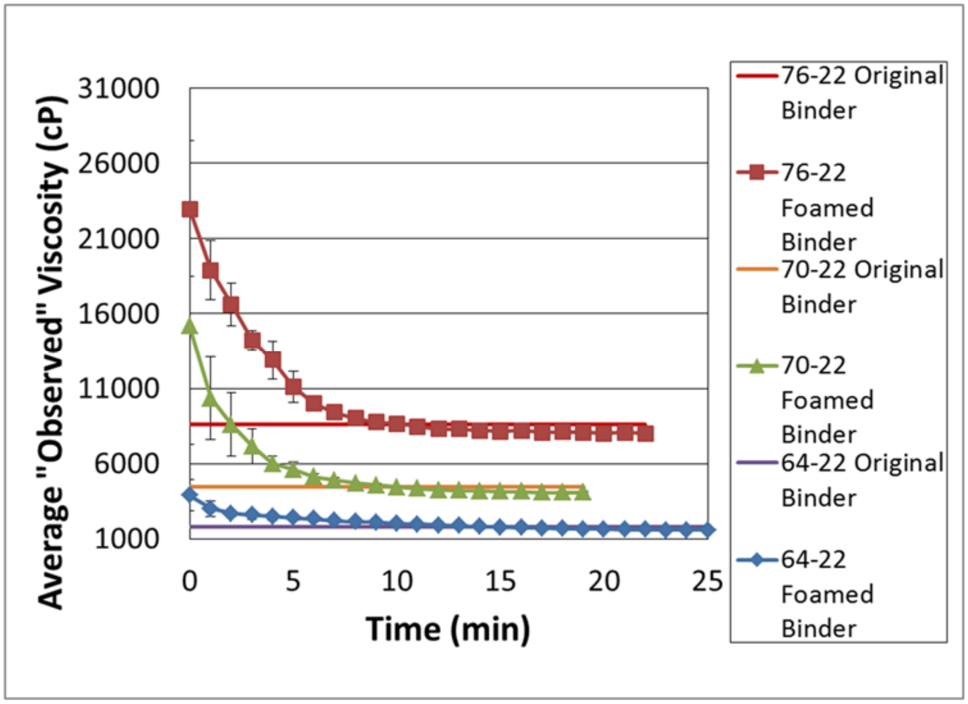

FIGURE 24. Example of Viscosity Curves

The initial testing phase in Table 6, called Phase 1, was executed to give a broad overview of the behavior of foamed asphalt in the rotational viscometer. For simplicity, during the first phase of testing only the Wirtgen WLB 10s and PG64-22 binder were utilized. In addition, the four foaming temperatures were 160°C, 145°C, 130°C and 115°C. These temperatures were chosen to obtain a range of temperatures that resemble possible foamed warm-mix mixing temperatures. The thermo-cell temperatures are listed as “foam temp – XX” such that if the foaming temp was 160°C the possible thermo-cell temps would be 150°C, 140°C, and 130°C. Since each spindle requires a specific range of viscosity, the spindle needed to be changed a few times in this round of testing due to the viscosity dropping out of the initial spindle’s (spindle 21) testing range.

TABLE 6 – Phase 1 Testing Matrix

Factor	# of levels	Levels
Foaming Temperature	4	160°C 145°C 130°C 115°C
Thermo-cell Temperature	3	Foam Temp - 10°C Foam Temp - 20°C Foam Temp - 30°C
Spindle Number*	3	21 27 28
Binder type	1	Lion Oil 64-22
Foamer type	1	Wirtgen WLB 10S

Based on the results from Phase 1, it was decided to continue testing as many of the foaming temperatures as possible but to only use the thermo-cell temperature drop of -30°C. This was chosen so that the thermo-cell would not warm any of the samples up higher than the temperature that they were placed into the thermo-cell. Foam exiting the Wirtgen foamer ranged anywhere from 5°C to 25°C cooler than the temperature to which the Wirtgen was set. It is believed that this temperature drop occurred because the water enters the foamer at room temperature but quickly absorbs heat from the asphalt as it is mixed together. The change in these temperature drops in the different foaming temperatures can be explained by poorer mixing as the foaming temperature goes down. The water isn't distributed as well so it does not absorb as much heat from the asphalt. A summary of this phenomenon can be seen in Table 7.

TABLE 7. Exit Foam Temperature from the Wirtgen Foamer

	Wirtgen set temperature			
	160°C	**145°C**	**130°C**	**115°C**
Sample	**Temperature Measured with Probe**			
1	134	133	115	109
2	133	121	117	111
3	139	137	115	111
avg.(°C)	135	130	116	110
Change(°C)	25	15	14	5

Phase 2 of testing used three binders (PG64-22, PG70-22 polymer modified, and PG76-22 polymer modified) and two foamers (Wirtgen WLB 10s and Pavement Technology Inc./PTI "The Foamer"). At this stage, only one spindle was used for further testing because changing the spindle (and thus the spindle geometry) affected how the bubbles were allowed to escape the foam sample during testing. The wider the spindle geometry, the quicker the bubbles were forced out of the sample. Therefore, it was deemed more important to keep the geometry constant versus keeping the spindle number consistent. Table 8 shows the testing matrix for Phase 2.

TABLE 8. Phase 2 Testing Matrix

Factor	# of levels	Levels
Foaming Temperature	1	160°C
Thermo-cell Temperature	1	Foam Temp - 30°C
Spindle Number	1	28
Binder type	3	Lion Oil 64-22 Lion Oil 70-22 PM Lion Oil 76-22 PM
Foamer type	2	Wirtgen WLB 10S PTI "The Foamer"

As a full-factorial testing matrix was not feasible, not all of the temperature/binder/foamer combinations were executed. Table 9 shows the combinations foamed and tested and which were unable to create foam. If an asphalt cement was not able to foam at certain temperature, "no foam" is indicated on the table. In Phase 2 testing, the two foamers were being compared to each other as well as the binder grades being compared to each other.

TABLE 9. Phase 2 Matrix, Expanded Showing Impossible Combinations (*means temp raised to 165°C)

Foamer & Binder Grade	Foaming temperature			
WTG	160°C	145°C	130°C	115°C
PG76-22	tested	tested	no foam	no foam
PG70-22	tested	tested	tested	no foam
PG64-22	tested	tested	tested	tested
PTI	160°C	145°C	130°C	115°C
PG76-22	tested at 165°C	no foam	no foam	no foam
PG70-22	tested	no foam	no foam	no foam
PG64-22	tested	tested	no foam	no foam

In order to quantify trends of the observed viscosity curves created in Phase 2, four different metrics were created to attempt to characterize the foamed asphalt binder. These metrics were:

- FVf/OBV (final foamed viscosity/original foamed viscosity)
- AAOB (area above original binder viscosity and below foamed binder viscosity)
- ABOB (area above foamed binder viscosity and below original binder viscosity)
- TTI (time to intersection of foamed asphalt binder viscosity and original binder viscosity)

FVf/OBV is the ratio of the final foamed viscosity divided by the original binder viscosity. It is the only metric with no time dependency and is represented graphically in Figure 25 by the two double ring circles. AAOB is the area above the original binder line and below the foamed binder curve. It has units of min*cP and is represented in Figure 25 by the double line triangular section. Due to the high variability of the observed viscosity in the first minute, the area bound by time zero minute and time one minute was not factored into the area of AAOB. AAOB is represented by the double line triangular shape in Figure 25. ABOB is the area below the original binder line and above the foamed binder curve with the units of min*cP. The last data point used to create this area is the first of the three replicate observed viscosity readings representing the end of the test. ABOB is represented by the dashed line triangular shape in Figure 25. TTI is the time to intersection of the foamed binder curve and the original binder line. It is calculated by simple line-slope algebra using the first observed foam viscosity data points to either side of the original binder line and is represented by the single ring circle in Figure 25.

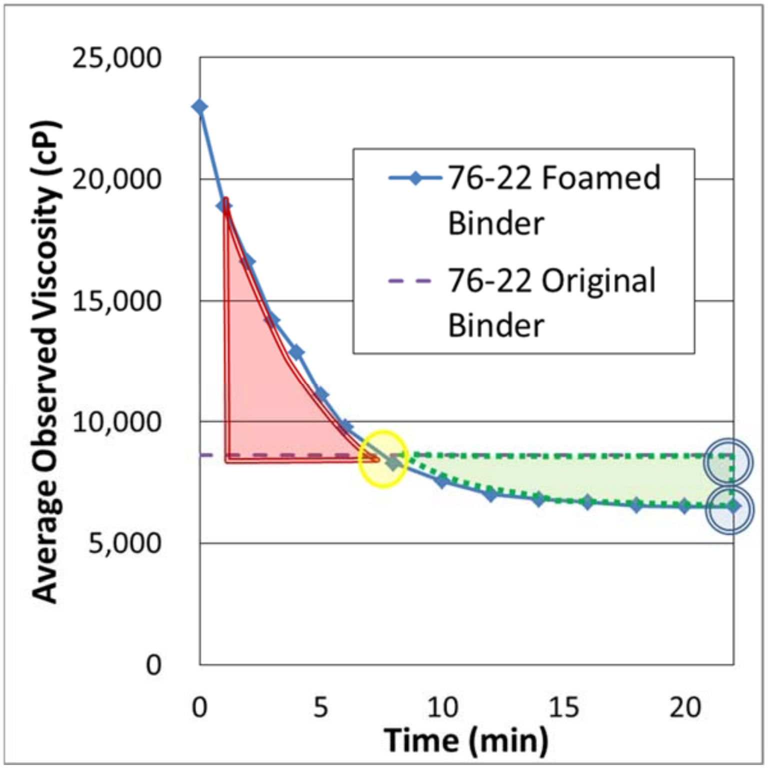

FIGURE 25. Example of Observed Viscosity Curve Showing Where the Four Metrics Are Defined

The results of the thirteen possible binder/foamer/temperature combinations are shown together in Figure 26. All the curves start with a relatively high observed viscosity which decrease as the tests progress with all tests finishing by 30 minutes except for 64W115 and 70W130. The end of the test was defined as three consecutive equal observed viscosity readings. In Figure 26, the naming convention is as follows: the first number designates the PG grade (76-22 “76”, 70-22 “70”, 64-22 “60”), the middle letter represents the foamer (WTG “W” or PTI “P”), and the last number represents the foaming temperature (160,145, 130, or 115°C). As shown in Figure 26, the shape of the observed viscosity curve was dependent on the PG grade. PG64-22 began with lower observed viscosities but the curve continued for a longer time period, whereas the PG76-22 began with the largest slopes but leveled out quickly, with the PG70-22 in between. However, the PG64-22, WTG, at 115°C (64W115) foamed asphalt cement shows an opposite trend than all other curves. It is believed that this phenomenon is caused by temperature. Since the initial foaming temperature was so low (115°C), the water may not have mixed thoroughly with the asphalt binder. Therefore, the temperature of the binder did not cool as much as the higher foaming temperatures. When this sample was inserted into the thermo-cell, it was still much warmer than the 85°C that the thermo-cell was set. It is hypothesized that a lower temperature limit for foaming may have been reached where proper foam does not occur, but this theory would need more evaluation before any strong conclusions can be made.

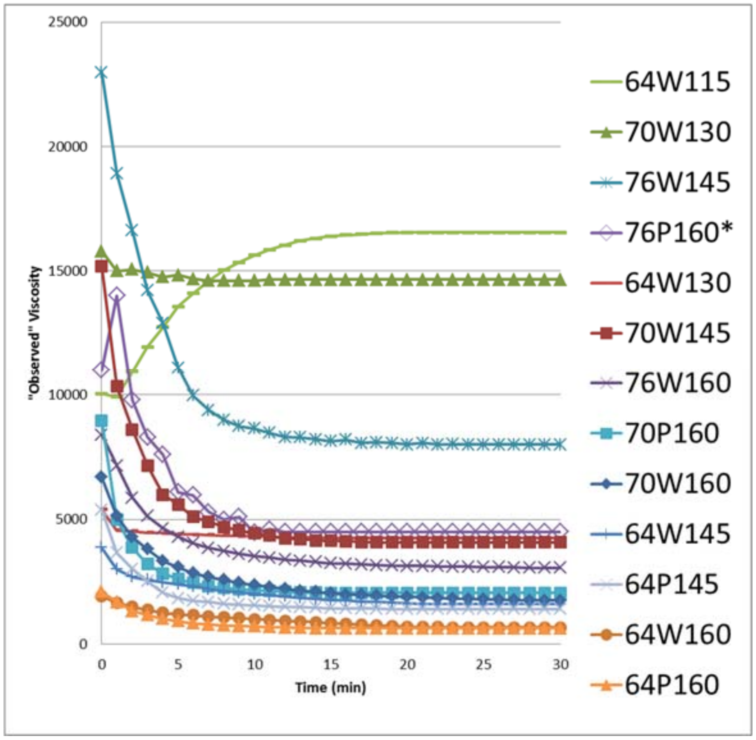

FIGURE 26. Phase 2 Data (all 13 curves)

The first foaming metric examined was the FVf/OBV data. Figure 27 shows the FVf/OBV data. As the foaming temperature decreases, so does the ratio. The ratio decreases at a set temperature as the PG grade decreases. At 160°C the PTI and WTG have similar ratios for all PG grades. The PTI data has a bigger decrease from a foaming temperature of 160°C to 145°C.

When looking at the FVf/OBV data, the lower ratios incurred by lowering the foaming temperature are most likely from micro bubbles in the asphalt that are unable to escape due to the lower temperature but are small enough to not cause friction between the sidewall of the sample chamber and the spindle thus increasing the observed viscosity. Interestingly, the PTI experienced a significant drop from 160°C to 145°C (~100% to ~80% as compared to ~98% to ~90% with the WTG). This is probably explained by the different processes of foaming used by each foamer. The WTG pumps the asphalt and water through the system and forces the foam out a nozzle whereas the PTI uses gravity to feed the asphalt binder and lighter pressure to force the water and air to mix with the asphalt binder. It is possible that this softer foaming process may allow more bubbles to stay immersed in the asphalt binder at lower temperatures. Also the lower the PG grade the lower the ratio which is explained by the smaller bubbles being able to form in the softer asphalt binder.

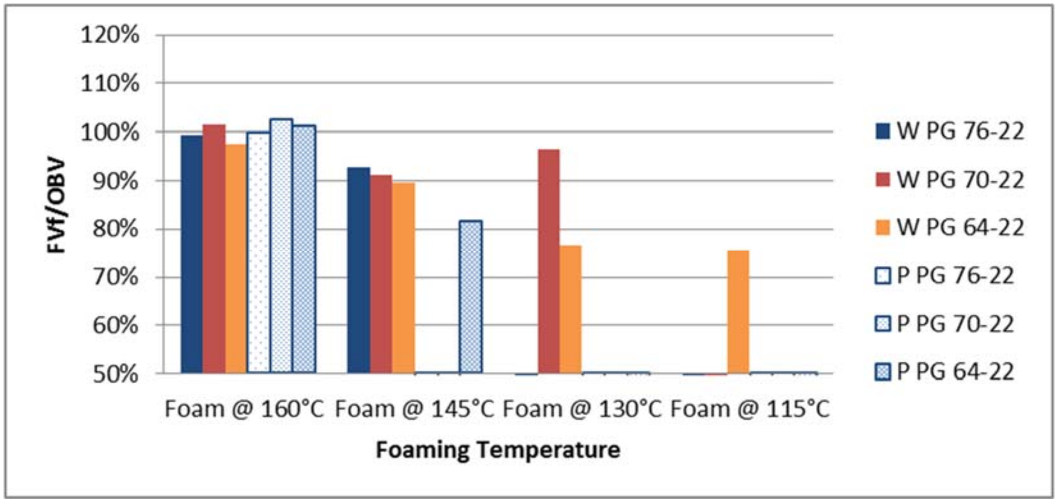

FIGURE 27. FVf/OBV Data

The next metric to be considered was the AAOB metric or the area above the original binder and below the foamed viscosity lines. Figure 28 shows the AAOB data collected. The AAOB area goes down as the PG grade increases for both foamers. PTI values are generally slightly lower than their WTG counterparts. PG64-22 has much lower values than both PG70-22 and PG76-22.

When the AAOB data is examined, AAOB goes down as the PG grade decreases. This could be explained by the softer PG grades allowing the larger bubbles to pop faster, which was visually observed during testing. The three data points that are zero for AAOB can be explained by a combination of temperature and poor foaming. The foaming temperature was so low that the foam exiting the foamer is cooling off at a slower rate compared to the higher temperatures (see Table 7) so the -30°C isn't as close to the actual temperature of the foam as with the higher foaming temperatures and this is affecting the shape of the curve. The foam isn't foaming and mixing as well either because of the lower temperature. It appears that the asphalt does not want to mix with the water as readily, so not as many large bubbles are forming to cause a spike in the viscosity reading.

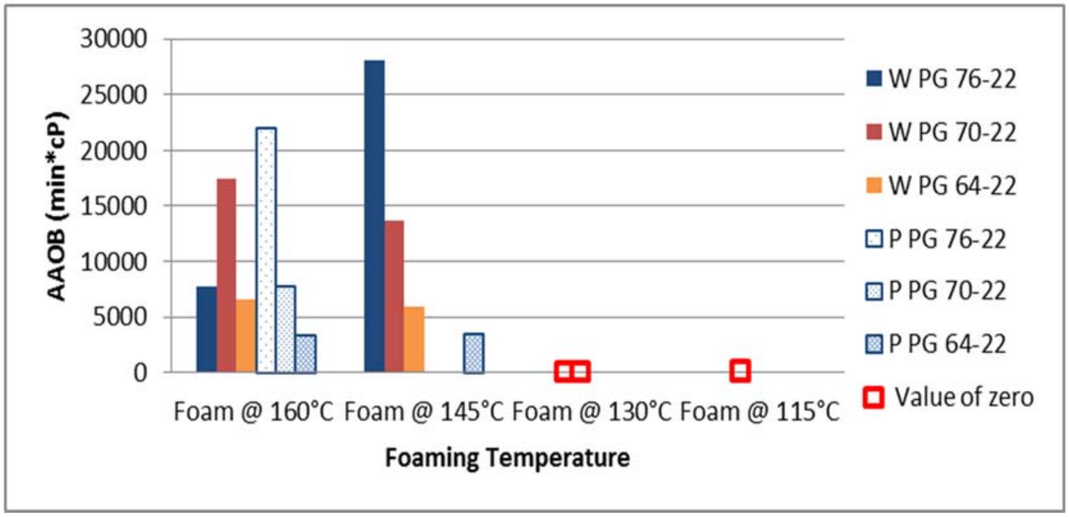

FIGURE 28. AAOB Data

The third metric to be analyzed is ABOB, which is similar to AAOB but represents the tail end of the data and is the area below the original binder and above the foamed binder viscosity lines. Figure 29 shows the data for ABOB. It is clear that at foaming of 160°C, ABOB was not captured. The foam's observed viscosity did not dip below that of its original binder counterpart. As the temperature of foaming decreases, ABOB appears and at 115°C it is eight times bigger than at 130°C. The polymer modified PG70-22 is less affected than the unmodified PG64-22.

Further analysis showed that the ABOB metric is zero for all of the 160°C tests. At higher temperatures the foamed asphalt started at a very high observed viscosity due to the large bubbles. Since the material is at a high temperature, both large and small bubbles were free to escape the asphalt returning the binder back to its original viscosity. For lower temps however, the smaller bubbles couldn't escape and ABOB started to rise. At 115°C, the temperature again affected the results. ABOB for PG64-22 jumps by a factor of eight from 130°C to 115°C (16,500 to 132,000). This could be because that lower temperature sample was significantly higher than the thermo-cell's temperature setting, so a longer time period is necessary before the sample achieves the proper temperature.

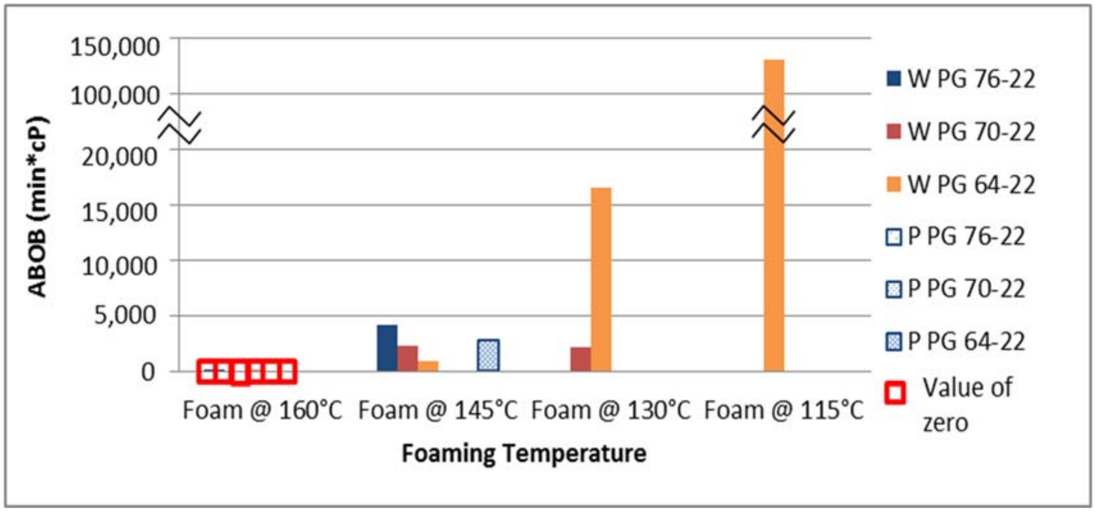

FIGURE 29. ABOB Data

The last metric to be analyzed was TTI, which is the time to intersection of the foamed viscosity and original binder viscosity lines. Lowering the foaming temperature allowed the intersection of foam binder and original binder viscosities to occur more quickly. Values of zero represent samples that started below and never reached their original binder viscosity. Generally, the lower the PG grade, the longer it takes to reach the intersection point.

PG64-22 took the longest of the PG grades to reach the intersection point. PG64-22 is the softest binder so it would seem logical that the opposite trend would hold true. PG64-22 had the least AAOB area but took the longest to actually cross the original binder line. This means that the PG64-22 binder could be creating a larger quantity of midrange bubble size than the higher 70-22 and 76-22 PG grades; indicating that larger bubbles pop quickly. This rapid decrease dropped the observed foam viscosity quickly but keeping the observed viscosity just above the original binder for a longer period of time as the medium bubbles pop. When the medium bubbles pop, the smallest bubbles remain which allow the viscosity to drop below the original binder viscosity. Again, the bubble sizes were based simply on observations made during the testing process.

Based on material availability, the method of testing foamed asphalt in a rotational viscometer outlined above is different and unique in that it uses equipment readily available in most asphalt cement laboratories, and the data collected is relatively simple and reproducible. There are several conclusions about the viscosity of foamed asphalt based on observation and the four metrics designed for foamed asphalt outlined above:

- Higher foaming temperatures tended to have higher initial viscosities and the lower foaming temperatures had lower final viscosities as compared to original binder counterparts.
- ABOB was hard to compare to the other 3 metrics because of the lack of comparable data at 160°C foaming temperature. The other three show trends of becoming smaller as the foaming temperature decreased.

- While FVf/OBV and AAOB decreased with decreasing binder grade, TTI increased with decreasing binder grade.
- When comparing the WTG to the PTI, the PTI generally had lower numbers which is reflected in the visual assessment of the foam created by both foamers. The PTI took longer to create foam and didn't look as mixed as the WTG foamer. The WTG allowed more flexibility when testing different binders and temperatures. The gravity fed design of the PTI limits how well it can foam by how the binder needs to be to flow easily through its system.

Dynamic Shear Rheometer

The next asphalt cement test explored was the Dynamic Shear Rheometer. ASTM D7175 (Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer) was followed as closely as possible when running the asphalt foamed samples. Tests were run at 64°C on a PG64-22, with a foaming temperature of 155°C. For the first step, asphalt cement samples were foamed in the WTG and poured into a silicon mold immediately. After approximately 5-10 minutes, the samples were placed in the DSR and the temperature was stabilized to 64°C. In order to preserve as many bubbles as possible, only five minutes passed before the test was run. As seen in Figure 30, the asphalt foam samples had values of G*/sin δ from 1520-1530 Pa (1.52-1.53 kPa) over a strain rate from 9-15%, while the straight run binder had G*/sin δ from 1940-1960 Pa (1.94-1.96 kPa) over the same strain rate range. Therefore, foaming the asphalt cement reduced G*/sin δ values approximately 25%. Higher G*/sin δ values tend to indicate a stiffer asphalt cement, so it appears that the asphalt foam reduces the stiffness of the material. It is also worth noting that both the foamed and straight binder pass specification with values greater than 1.00 kPa at a target strain value of 12%.

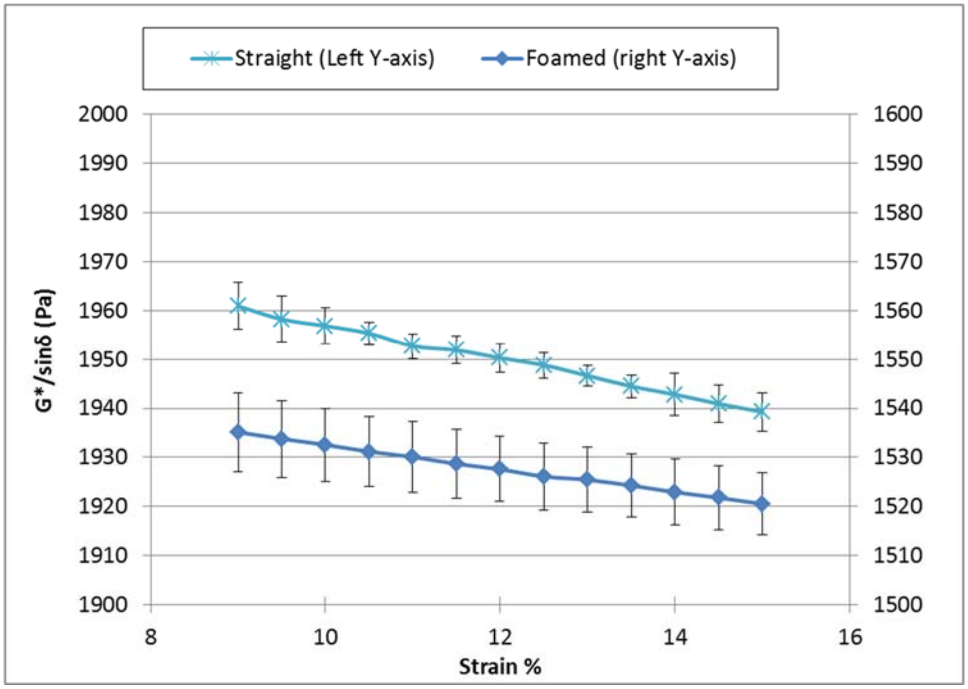

FIGURE 30. Single Cycle G*/sin δ Trends for Wirtgen Foam and Straight Binder

The next step was to explore how the foamed asphalt cement behaved over multiple strain cycles immediately after foaming. As the plates rotate, it was anticipated that the asphalt foam would collapse over time, and there would be a trend of increasing G*/sin δ as the binder went from a foamed stage to an unfoamed stage. However, the foam did not show an increasing trend, but instead showed a decreasing trend of G*/sin δ followed by an increasing trend, as seen in Figure 31. After approximately 30 cycles, the foamed asphalt went from approximately 1.425 kPa down to 1.400 kPa, and then returning to approximately 1.420 kPa. This is a very similar trend observed to straight PG64-22 asphalt cement as seen in Figure 32. During this testing, the difference between the straight asphalt cement and foamed asphalt cement was even greater, with the foaming reducing the strain values over 50% (2.685 kPa versus 1.410 kPa). These initial trends, however, went outside of the scope of research for this project, but are recommended to look at in more detail in future research.

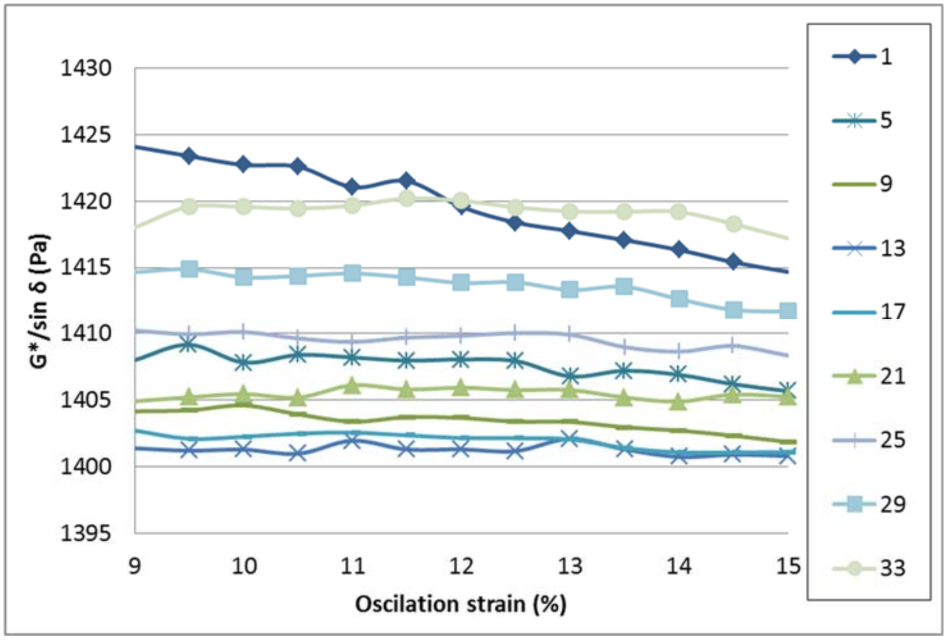

FIGURE 31. Wirtgen Foam, Multiple Strain Sweep Data, Cycles 1 Through 33

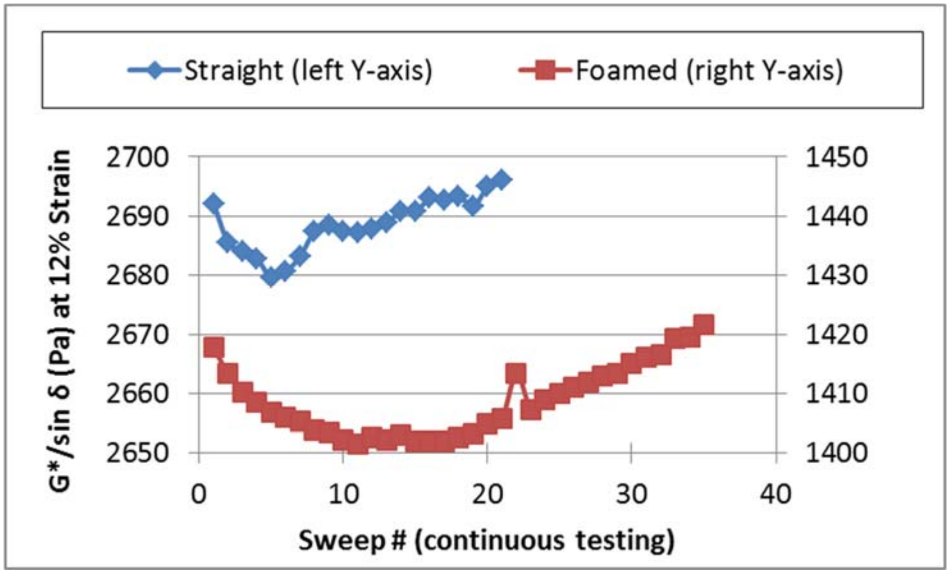

FIGURE 32. Multiple Strain Sweeps for Wirtgen Foam and Straight Binder. 12% Strain is Shown to Emphasize Sweep # - G*/sin δ Relationship

All of the G*/sin δ shown above was run using the WTG foamer. To finish the G*/sin δ data collection, the Wirgten foamer was compared to the PTI foamer, examining PG76-22, PG70-22, and PG64-22 asphalt cement binders, foamed at up to four different foaming temperatures. Figure 33a shows the PG64-22 data, 33b PG70-22, and 33c PG76-22. The measurements were taken at 12% strain, and tested at the proper PG testing temperature.

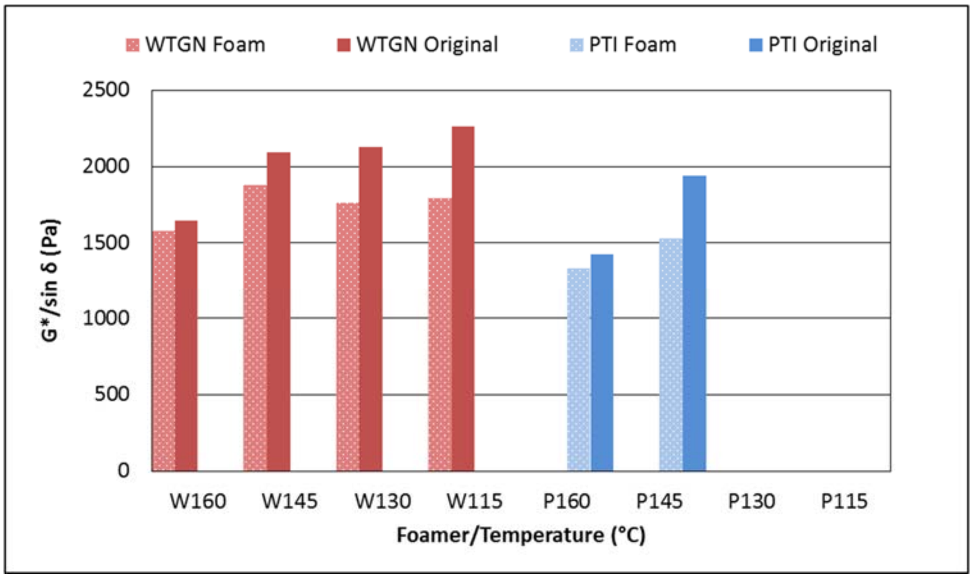

FIGURE 33a. PG64-22, Wirtgen (WTG, W) and PTI (PTI, P) G*/sin δ at Four Foaming Temperatures

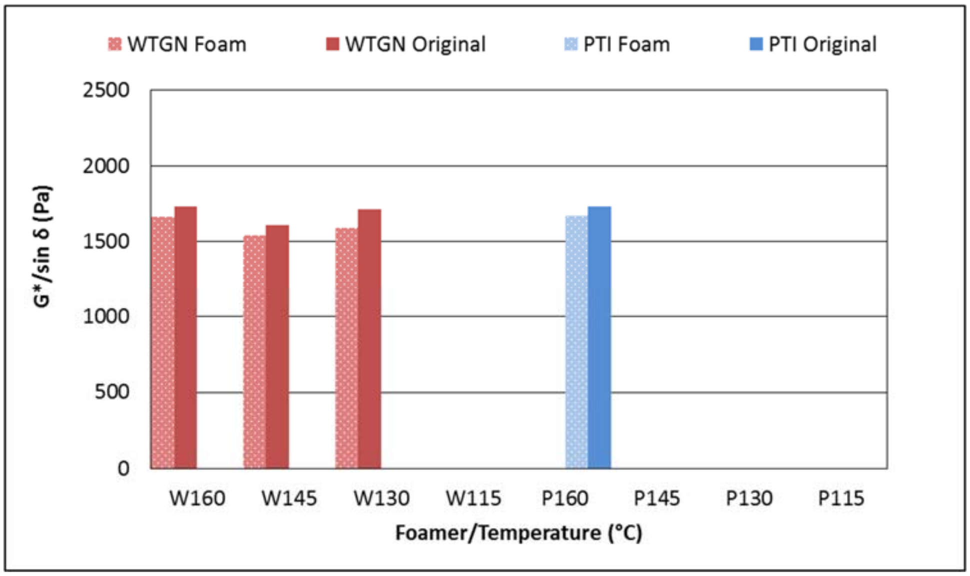

FIGURE 33b. PG70-22, Wirtgen (WTG, W) and PTI (PTI, P) G*/sin δ at Four Foaming Temperatures

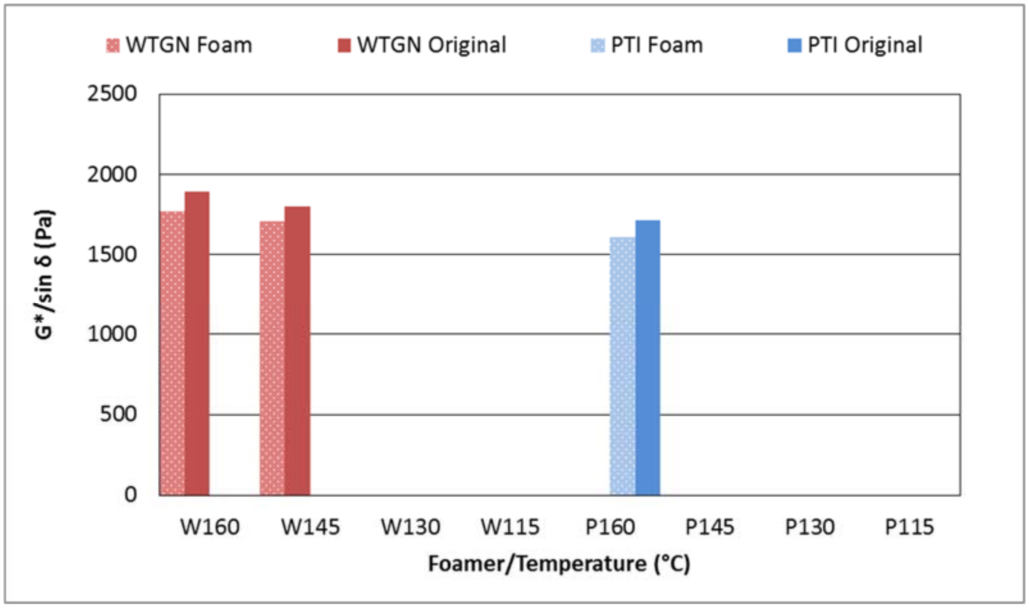

FIGURE 33c. PG76-22, Wirtgen (WTG, W) and PTI (PTI, P) G*/sin δ at Four Foaming Temperatures

As seen in Figure 33, if the foaming machine was physically able to make foam, it appeared that all of the G*/sin δ values were slightly lower than the original binder G*/sin δ. In addition, it did not appear that there was a significant difference when changing the foaming temperature. This was most likely due to the fact that the temperature needs to stabilize in the DSR, so this stabilization period negated any change in foaming temperature. However, similar to the viscosity data, both the WTG and PTI were not able to foam at lower temperatures as the PG grade increased. However, with all three binders, the WTG was able to foam at more temperatures than the PTI. All values fell well above the minimum 1.0 kPa limit in ASTM D4402. However, because there was not a significant difference of G*/sin δ observed between the two foamers, the four foaming temperatures, and the three asphalt cement binder grades, it was decided not to continue on with the J_{nr} testing, as it was deemed that no pertinent information would be available from the additional testing.

Dynamic Modulus

AASHTO TP 62 was used to collect and analyze the data for the dynamic modulus testing. Dynamic modulus is a primary input into the Pavement ME Design software and quantifies the fundamental linear viscoelastic characteristics of asphalt concrete. There are two primary outputs for dynamic modulus, the stiffness master curve (E*) and the shift factor relationship to temperature. Figure 34 below shows the stiffness curves for the Hot Mix Asphalt mixture, the Wirtgen foamed mixture, and the field foamed mixture. Note, we were unable to run E* tests on the PTI due to continued difficulties with foaming the PG76-22 on the PTI foamer.

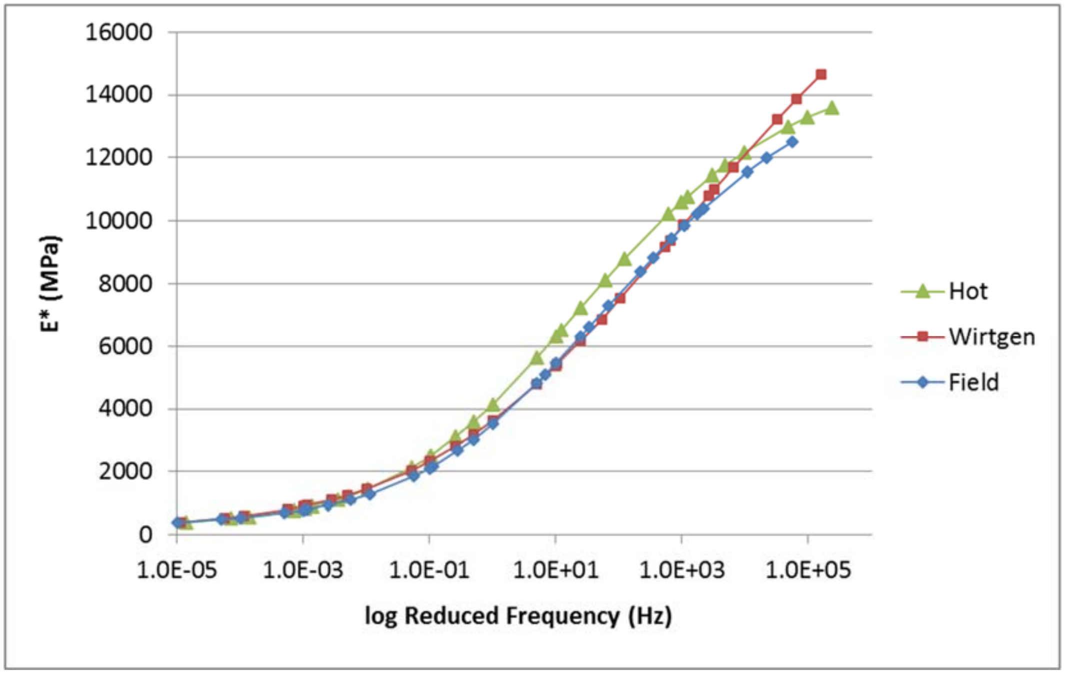

FIGURE 34. Dynamic Modulus Curves for Hot Mix Asphalt, Wirtgen Produced Warm Mix Asphalt, and Field Produced Warm Mix Asphalt

As seen in Figure 34, the lower frequencies were all quite similar for the three mixtures. This indicates that at higher temperatures or slower loads, the mixtures all had similar stiffnesses. As the temperature decreased, or the load speed increased, however, the hot mix became stiffer than the two foamed mixtures. This could be attributed to the fact that the asphalt cement went through more of an aging process with the hot mix, during the mixing, aging, and compacting at the higher temperatures. The two warm mixtures, however, did not have that high level of aging. Interestingly, at very low temperatures, or very fast loads, the Wirtgen warm mix diverged from the field warm mix, and in fact became stiffer than the hot mix. As of this time, a reasonable explanation for this phenomenon has not been identified. The master curve in Figure 34 was constructed by shifting data from the actual frequency tested to either a higher or lower frequency. In order to shift the data, shift factors were developed, and are shown in Figure 35.

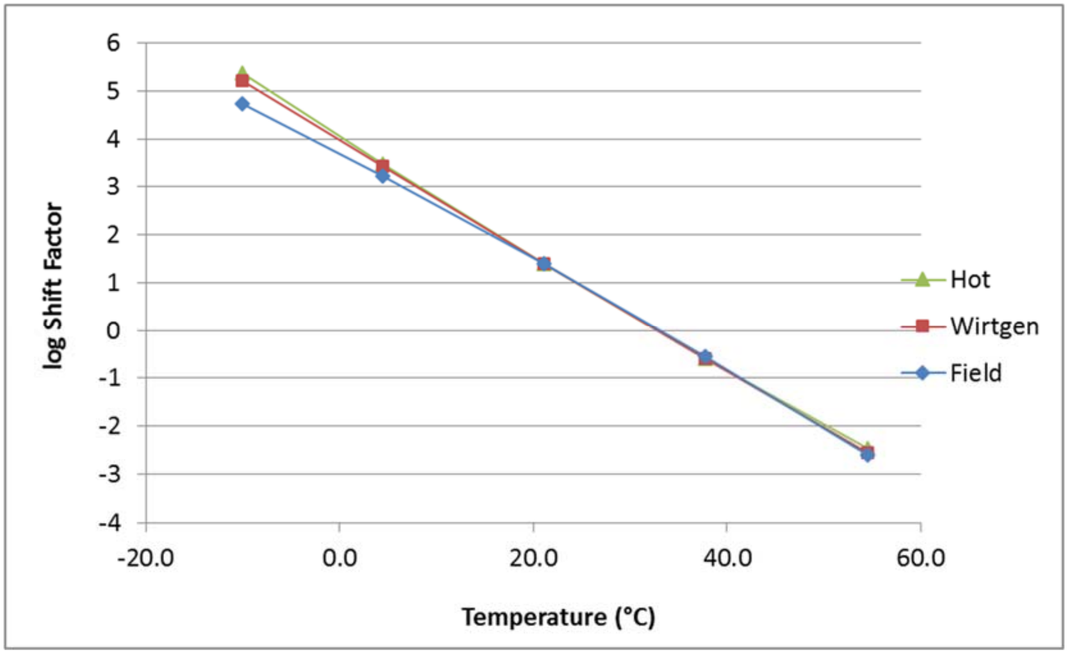

FIGURE 35. Dynamic Modulus Shift Factors for Hot Mix Asphalt, Wirtgen Produced Warm Mix Asphalt, and Field Produced Warm Mix Asphalt

In Figure 35, the shift factors for -10, +4.4, +37, and+54°C are plotted for the three mixtures, with the test at +21°C used as the reference factor (hence, a shift factor of one). It is important to note that the shift factors are essentially identical, except at the lowest temperature. That indicates that the relation between performance is the same for all three of the mixtures, except the field mixture at the lowest temperature.

Creep Compliance

Creep compliance (AASHTO T322) is an indicator of rutting behavior. In general, mixtures with a higher creep compliance indicate a higher susceptibility of rutting. Creep compliance is generally run at three temperatures, 0, -10, and -20°C. This allows for an understanding of material behavior over a range of temperatures. Figures 36-38 show the creep compliance of the four warm mix asphalt mixtures at 0, -10, and -20°C respectively, with three replicates for each curve. In Figure 36 below, the WTG, PTI, and field mixtures all performed almost identically, while the HMA showed a significantly higher amount of creep compliance at 0°C. This was not expected, as the HMA, in theory, should have a lower creep compliance, as it is a stiffer material compared to the WMA as more oxidation occurs in the mixing and compacting. However, it is encouraging that the three WMA techniques provided very similar results.

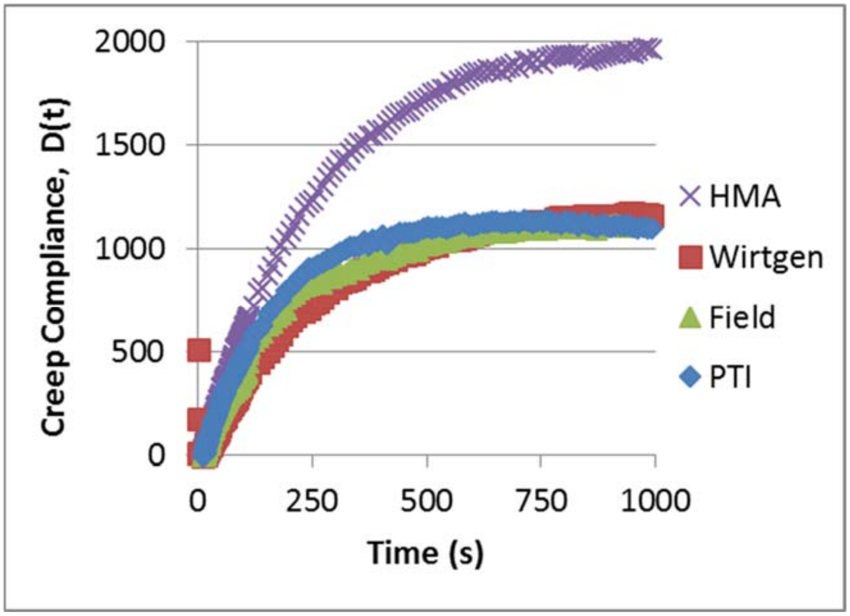

FIGURE 36. Creep Compliance at -20°C for Hot Mix Asphalt, Wirtgen Produced Warm Mix Asphalt, and Field Produced Warm Mix Asphalt

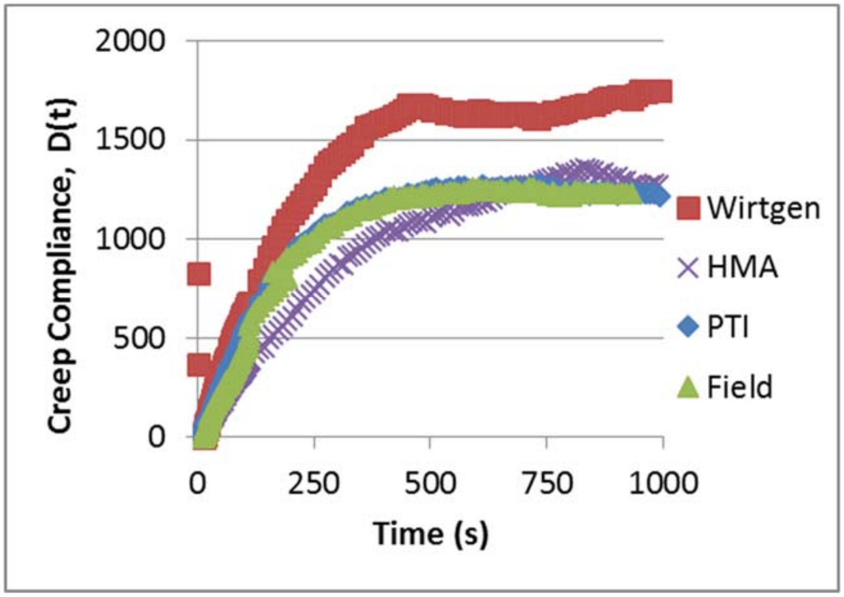

FIGURE 37. Creep Compliance at -10°C for Hot Mix Asphalt, Wirtgen Produced Warm Mix Asphalt, and Field Produced Warm Mix Asphalt

Results were not as consistent at -10°C, as seen in Figure 37. Here, the HMA, PTI, and field showed similar creep curves, with the PTI and field mix almost on top of each other. However, the Wirtgen mixture showed a higher creep compliance, indicated a softer material at -10°C. Lastly, Figure 38 shows the creep data at -20°C. Here, it appears that the temperature is low enough where all four mixtures behave in a very similar fashion. This indicates that the binder has reached the glass transition temperature, and behaves as more of an elastic material, eliminating differences between the four different materials.

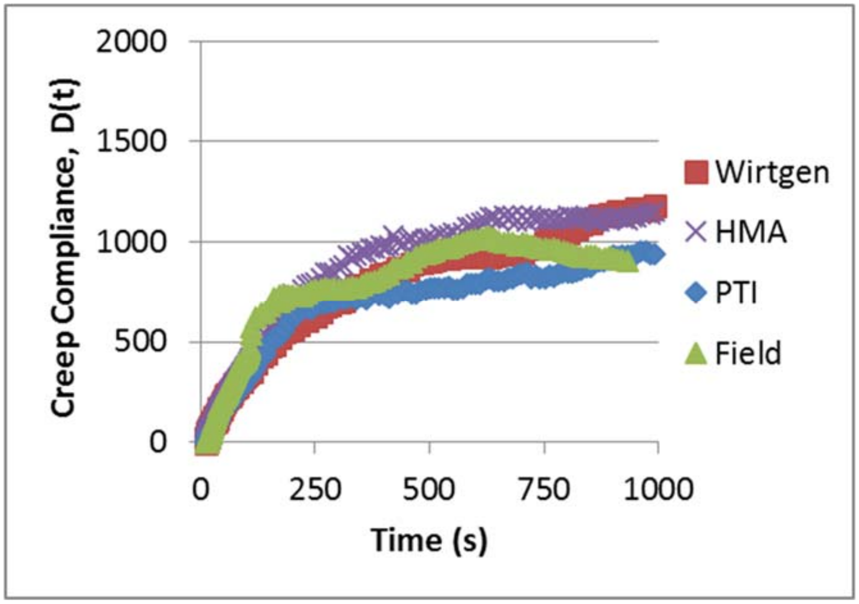

FIGURE 38. Creep Compliance at 0°C for Hot Mix Asphalt, Wirtgen Produced Warm Mix Asphalt, and Field Produced Warm Mix Asphalt

While the general trend of creep decreased as temperature decreased, as expected, overall, the trends did not provide clear guidance on which laboratory machine mimics the field performance most closely.

Torsion Bar

A newer method of collecting creep compliance data, developed by Reinke and Glidden (2005), has the advantage of using smaller sample sizes in order to collect creep data. Creep data can be an indication of the rutting susceptibility of asphalt concrete. In the torsion bar test, a ranking can be developed that can directly comparing the rutting susceptibility of mixtures. Figure 39 shows the torsion bar creep data.

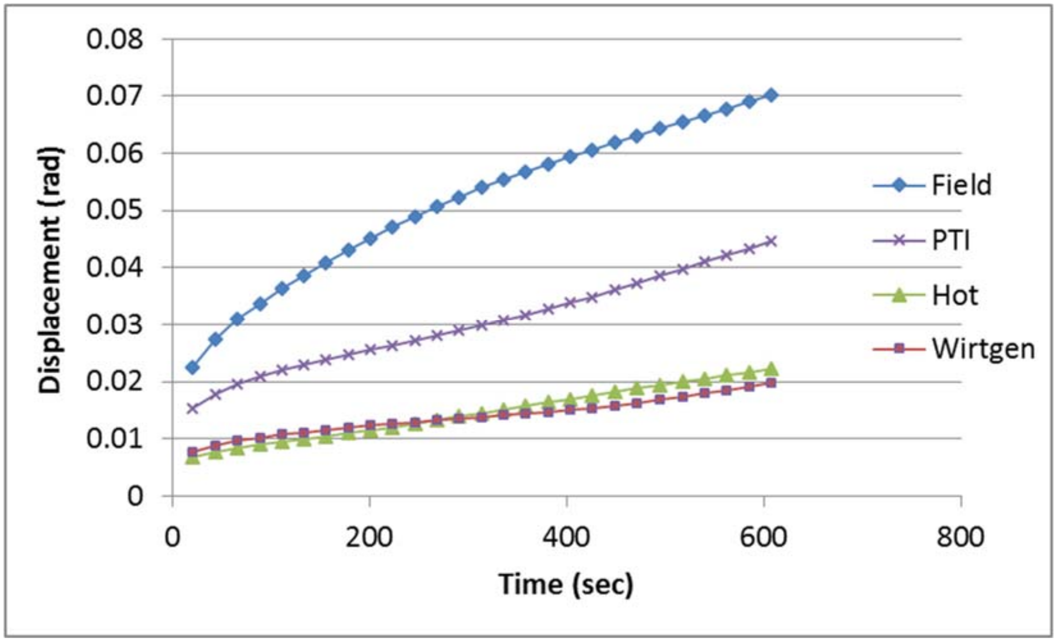

FIGURE 39. Torsion Bar Creep at Ambient Temperature for Hot Mix Asphalt, Wirtgen Produced Warm Mix Asphalt, and Field Produced Warm Mix Asphalt

In Figure 39, there are much clearer trends in the data than with the traditional creep compliance data. The Wirtgen mix and hot mix had very similar creep behavior, with the lowest torsional displacement of the four mixtures. The PTI mix demonstrated approximately twice as much creep behavior as the Wirtgen and hot mix, while the field mix had almost twice as much creep again. This indicates that the mix generated by the Wirtgen machine creates a mix that displays approximately ¼ the creep behavior in the lab as field mix, and the PTI machine creates a mix that displays approximately ½ the creep behavior in the lab as the field mix. This indicates that the two pieces of lab equipment do not do a significantly strong job of mimicking the field foaming performance in terms of torsion bar creep.

<u>SC(B) fracture</u>

The final performance test run was the Semi-Circular Bend, or SC(B), fracture test. This test is a simple fracture test that quantifies the cracking resistance of asphalt concrete. A mixture with higher fracture energy indicates stronger resistance to cracking (Molenaar *et al*., 2002). Figure 40 shows the results from the SC(B) fracture test for the four mixtures.

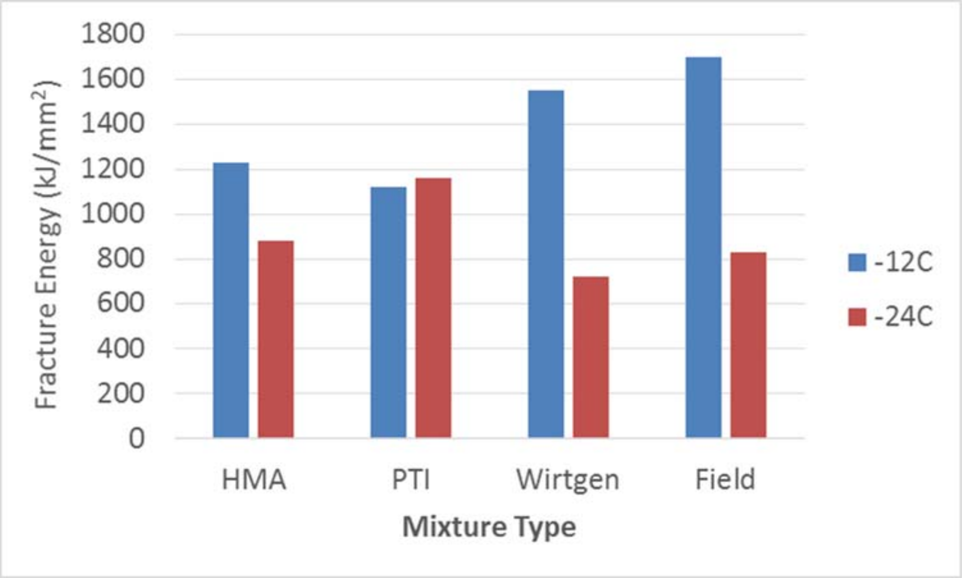

FIGURE 40. SC(B) Fracture Data for Hot Mix Asphalt, Wirtgen Produced Warm Mix Asphalt, and Field Produced Warm Mix Asphalt

In Figure 40, two test temperatures were run. One temperature was -12°C, which is the same temperature of the Bending Beam Rheometer test. The second temperature, -24°C, was two low temperature PG grades below the BBR testing temperature. This created a range of testing temperatures that bracketed the glass transition temperature, providing an opportunity to observe the cracking behavior of the samples when the material behaves in an elastic manner and a viscoelastic manner. Interestingly, the PTI mixtures did not appear to be sensitive to testing temperature, while the Wirtgen and field mixes behaved as expected, and quite similar, with higher temperatures providing higher cracking resistance. The Wirtgen and field mixes were more crack resistant at the higher testing temperature, but less crack resistant at the lower testing temperature. This indicates that perhaps the foaming warm mix technology may not be as resistant to thermal cracking as traditional HMA. Finally, Marasteanu *et al.* (2012) suggest a 400 kJ/mm2 is sufficient for the asphalt concrete to resist to thermal cracking, at the BBR testing temperature. For this material, the BBR testing temperature is -12°C, and all of the mixes were easily above the 400 kJ/mm2 limit, indicating that these four mixtures would not be susceptible to thermal cracking.

Overall, there were significant strides made with advanced performance testing. Several innovative metrics were developed in order to quantify the viscosity characteristics of foamed asphalt cement, and differences were seen with G*/sin δ behavior between unfoamed and foamed binder. In short, it appears that the traditional Superpave binder tests could be used with foamed asphalt cement. However, the mixture tests were not as clear. The dynamic modulus did not provide conclusive results, nor did the traditional creep compliance test. While the torsion bar test did provide a clear ranking, it was only run at one temperature. Finally, while all four mixtures passed the recommended fracture energy value, indicating that they would all be able to withstand low-temperature cracking, the results between testing temperature and mixture type were not conclusive. Overall, the single mixture examined here did not provide conclusive results toward choosing the Wirtgen over the PTI foamer. However, since the PTI foamer struggled producing foamed material with polymer modified asphalt cements, the Wirtgen seems to be the stronger laboratory foaming machine.

FIELD PROJECT DATA

In order to further assess the differences in WMA and HMA, SiteManager records for all AHTD asphalt projects during the years of 2011 through early 2015 were obtained. These records included lot and sublot data for the properties of percent air voids, binder content, percent compaction, specific gravity of the mix, and voids in the mineral aggregate.

Anecdotally, WMA is reportedly used to assist with mixture coating and as a compaction aid. Improved coating allows for particles to become adequately coated more quickly, potentially increasing plant production speeds. Improved compaction characteristics improve contractor confidence, and may require fewer roller passes to achieve desired compaction levels. With this in mind, in-place density would be the characteristic most likely to reveal differences between WMA and HMA. Thus, this property was investigated first. Summary statistics are shown in Table 10, and the distribution of data is given in Figure 41.

TABLE 10. Summary statistics for In-Place Density of Field Projects 2011 – 2015

	Warm Mix	**Hot Mix**
Average (%)	93.1	93.1
Standard Deviation	1.17	1.02
Coefficient of Variation (%)	1.26	1.09
# of Data Points	2489	11878

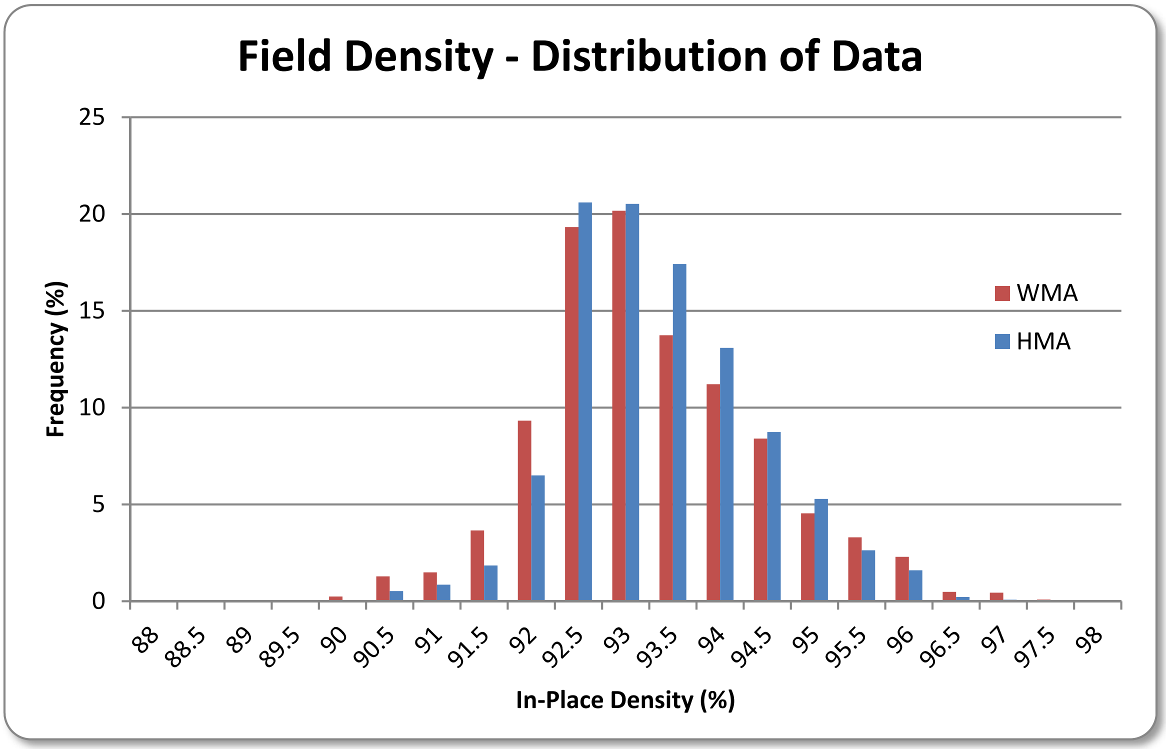

FIGURE 41. Distribution of Field Density Data – Field Projects 2011 – 2015

For all available data, the average in-place density was 93.1% for both the HMA and WMA mixes, indicating no difference in the two types of mixes. The data appeared to be approximately normally distributed with a sharp increase at the 92% level – not surprising since this is the lower specification limit. The overall variability of densities for the WMA was slightly greater than that of the HMA, however the sample size was also smaller. Since WMA is often used as a compaction aid, it was expected that the WMA data would include slightly higher densities than the HMA, but this was not the case. More likely, rolling patterns were adjusted to achieve the desired density, resulting in no significant difference in WMA and HMA. A more enlightening comparison might be possible if rolling pattern information were available for each mix. If fewer roller passes were necessary to achieve the desired compaction level for WMA, then claims of WMA's benefits as a compaction aid could be confirmed.

Next, air voids were considered. Summary statistics are shown in Table 11, and the distribution of data is shown graphically in Figure 42.

TABLE 11. Summary statistics for Air Voids (%) of Field Projects 2011 – 2015

	Warm Mix	Hot Mix
Average (%)	3.96	3.95
Standard Deviation	0.59	0.55
Coefficient of Variation (%)	14.9	13.9
# of Data Points	2526	12474

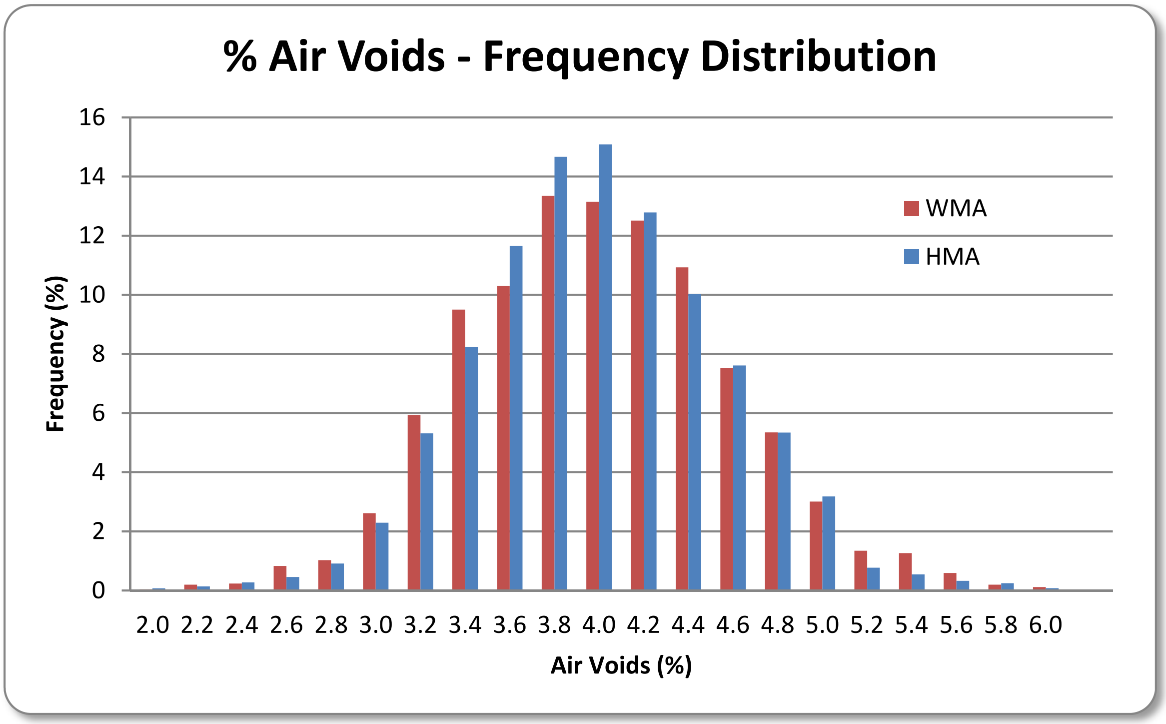

FIGURE 42. Distribution of Field Density Data – Field Projects 2011 – 2015

Again, the average values for WMA and HMA mixes were nearly identical, being 3.96 and 3.95 percent, respectively. And again, the variability of the WMA data was slightly larger, though the sample size was also considerably smaller. No statistically significant difference was noted between the two mixture types.

COST

According to information gathered in Project NCHRP 9-47A, WMA mixes may or may not provide a significant cost savings over HMA. Most monetary benefits are related to energy usage reductions at the plant, the potential for receiving increased pay (either by gaining incentives or avoiding disincentives) resulting in greater compaction levels, greater haul distances, and the potential for extensions in the paving season. However, there is also a cost associated with the production of WMA.

Additives represent a recurring unit cost ranging from \$2.00 to \$3.50 per ton, while mechanical foaming units create a one-time capital investment ranging from \$30,000 to \$80,000, or an additional expense of approximately \$0.08 per ton.

Energy savings vary depending on the type of fuel used, fluctuations in fuel prices, and the temperature reduction achieved. Recycled fuel oil used with a mechanical plant foaming system and a 25 °F temperature reduction resulted in a calculated savings of \$0.39 per ton, while the same system using natural gas achieved a savings of approximately \$0.16 per ton. Coupled with the cost of producing WMA, a savings of less than \$0.10 per ton should be expected.

While no data was available to estimate actual energy savings on the Arkansas field projects included in the SiteManager analysis, some anecdotal evidence does exist, which is favorable to the WMA foaming process. In general, WMA producers in Arkansas do not attempt to achieve significant temperature reductions (i.e., greater than 50°F). Therefore, energy savings are likely minimal, simply offsetting the cost of the plant modification. More commonly, milder temperature reductions of 20 to 30°F are used with the foaming process, with the primary goals of improving aggregate coating and mat compaction. Warm mix is also advantageous in that haul times can be increased, allowing projects in remote areas to be constructed without the need for moving and setting up an asphalt plant. This results in the potential for reduced mobilization costs, as well as a greater number of available contractors who can feasibly bid on a given project, increasing competition and lowering prices.

Field data suggests that WMA and HMA mixes have consistently achieved nearly identical characteristics with respect to in-place density and air voids. Thus, no significant cost savings are anticipated with regard to those pay items when comparing WMA and HMA. Greater contractor confidence with coating and compaction should, over the long term, lead to fewer pay reductions, and in turn, more accurate bid prices. With a competitive bidding process, the savings associated with foamed WMA should be translated to the agency.

5. Conclusions and Recommendations

For a number of mixes produced as a hot mix, plant-foamed warm mix, and laboratory-foamed warm mix (by two laboratory foamers), mixing method, temperature sensitivity, workability, coatability, rutting potential, moisture damage susceptibility, and viscosity were investigated in order to determine the best course of action for implementing the use of a laboratory foaming device in mix design verification. The following conclusions were made:

- <u>Comparison of mixing method</u>: In general, the effect of mixing method on air voids was marginally significant. Although relationships varied by mix, the variability of the laboratory mixing methods was generally greater than that of the plant-foamed mix. While no laboratory method consistently replicated the plant-foamed mixes, the PTI Foamer most often provided the closest match.

Recommendation: The PTI is adequate for verification of WMA mix designs, although other laboratory-scale foamers are also capable of producing specimens for design.

- <u>Temperature Sensitivity:</u> The air void content of WMA specimens was relatively insensitive to changes in temperature. This was true for all mixing methods; however, when individual mixes were considered, there was a trend of increasing air voids as the temperature reached low levels. This follows conventional thought in that when the temperature is excessively low, air void content will exceed the desired range.

Recommendation: A laboratory foamer should be used to verify that acceptable air void contents are achievable at the target field compaction temperature.

- <u>RAP / RAS:</u> Mixes containing greater percentages of RAP were more sensitive to changes in temperature than those with little or no RAP. Previous research has shown similar findings to be true for mixes containing RAS.

Recommendation: Mixes containing RAP / RAS may require higher mixing temperatures in order to "activate" the available binder. Thus, mix designs should be verified at the target design temperature with the recycled material source to verify mixture compcatability.

- <u>Workability Ratio:</u> The workability ratio, as described in AASHTO R35 was used to gain a measure of the relative compactability of a mix at its target compaction temperature, and at 30°C below the target compaction temperature. This measure was capable of identifying mixes that may be more sensitive to decreases in temperature, particularly if there was a RAP component in the mix.

Recommendation: The workability ratio of laboratory-foamed WMA specimens should be determined, and caution should be exercised if the ratio exceeds 1.25, meaning that the compaction temperature may be too low.

- Moisture and Coating: When moisture was intentionally added to the laboratory-produced WMA specimens, thorough mixing became difficult and coatings were visibly deficient. At moisture contents as low as 1%, coating was significantly and adversely affected.

Recommendation: Field mix should be visually examined for complete coating. If there is a question or suspicion regarding incomplete coatings, AASHTO T195 should be performed to ensure a minimum coating of 95%.

- Rutting Potential: Rut depths, as measured in the Asphalt Pavement Analyzer (APA), were not significantly affected by mixing method or compaction temperature.

Recommendation: The rut testing currently required for HMA mix design verification is considered adequate for screening foamed WMA mixes.

- Moisture Damage Susceptibility: Laboratory-foamed mixes showed a greater potential for moisture damage than either HMA or field-produced WMA. Other research has discovered this same discrepancy, and it is possible that the issue is related to aging of the warm mix. Thus, field-produced mix that was placed in the spring and aged during a summer will be less susceptible to moisture damage than one that is placed in the fall and not aged.

Recommendation: Current methods for assessing moisture damage potential are adequate for laboratory-foamed WMA designs.

- Short-term Aging: Laboratory-foamed mixes were prepared and compared to laboratory-prepared HMA mixes for varying aging temperatures and aging times. Maximum theoretical specific gravity (Gmm), effective specific gravity (Gse), and binder absorption (Pba) of the PTI-foamed mixes were similar to that of the HMA mixes. The WTG-foamed mixes required longer aging times and/or higher aging temperatures to achieve properties similar to that of the HMA.

Recommendation: Current short-term aging times are acceptable for PTI-foamed specimens. However, aging times for other foamers may require additional study.

- Foamed Binder Viscosity: Four metrics were developed for assessing laboratory-foamed binders using the Brookfield Rotational Viscometer. While unfoamed binders maintained a constant viscosity level at a given temperature over time, the foamed binders experienced a reduction in viscosity, achieving a final viscosity level within 30 minutes or less. Polymer-modified binders (PG70-22 and PG76-22) displayed a greater reduction than the unmodified (PG64-22), which is consistent with previous observations that polymer-modified binders can achieve greater temperature reductions with warm mix technologies.

Recommendation: No test methods using the Brookfield rotational viscometer are recommended at this time. Further research is necessary to determine the appropriate applications of the data generated.

- Dynamic Modulus, Creep Compliance, SC(B) Fracture: Dynamic modulus testing was performed for 3 mixing methods, including HMA, WTG, and Field. All three performed in a very similar manner, with the hot mix exhibiting slightly greater stiffness at lower temperatures or higher testing frequencies. At three testing temperatures, creep compliance overall exhibited expected trends of decreasing compliance with decreasing temperature, and while the three warm mix samples behaved in a relatively similar fashion, the trends compared to the hot mix were not consistent. The full-scale creep compliance, however, provided more reasonable data than the torsion bar data. Finally, using the SC(B) fracture testing, it was established that none of the mixtures tested were susceptible to thermal cracking.

Recommendation: No test method changes are recommended based on the results of the dynamic modulus, creep compliance, and SC(B) fracture testing. However, it is noted that these tests may provide additional insight into the behavior of materials.

- Field Data: Field data, specifically in-place density and air voids in the compacted mix, revealed no significant differences between HMA and WMA. Thus, no adverse effects should be expected with respect to mixture type.

Recommendation: No test method changes are recommended based potential impacts during compaction.

Based on the results of this research project, it is recommended that a laboratory-foaming device be incorporated into the mix design verification process for warm mixes, particularly when a substantial temperature decrease (from hot mix) is targeted. The warm mix design can be adapted directly from an accepted hot mix design, and should be submitted as follows:

Approval of a warm mix design will require the contractor/mix designer to submit an accepted hot mix design job mix formula along with the desired WMA production temperatures (both mixing and compaction temperatures). The target mixing temperature for the aggregate need not be the same as the target mixing temperature of the binder, as some binders do not foam well at significantly reduced temperatures. If mixing temperatures for the binder and aggregate are different, both should be reported, though the aggregate mixing temperature will serve as the dominant mixing temperature.

Materials must be submitted for verification, including blended aggregates and binder adequate for producing 4 replicate gyratory-compacted specimens and a Rice (Gmm) specimen for volumetric analysis, as well as moisture damage susceptibility testing.

After submittal, AHTD will perform laboratory foaming of the binder, then will mix and compact two specimens at the target compaction temperature, and two specimens at a compaction temperature of 30°C below the target compaction temperature. The maximum theoretical specific gravity will also be determined using a specimen mixed with foamed binder. The average properties of the two specimens compacted at the design temperature will be used to calculate volumetric properties, and the average of the two compacted at the reduced temperature will be used to calculate the workability ratio. Typical procedures will be used to prepare additional specimens for moisture sensitivity analysis, with the exception that the binder will be foamed. Volumetric and moisture sensitivity properties shall meet current HMA design requirements, and the workability ratio shall not exceed 1.25.

The following implementation strategies are recommended:

1) Require the additional WMA verification procedures for WMA mixes involving a temperature reduction (based on the comparable hot mix design) of 50°F or more.
2) Require the additional WMA verification procedures for WMA mixes having RAP contents of 10 percent or more and a temperature reduction (based on the comparable hot mix design) of 30°F or more.

Mix temperature at the time of placement of all warm mixes should be monitored in the field.

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