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Temperature Sensitivity of Foamed Warm Mix Asphalt

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TEMPERATURE SENSITIVITY OF FOAMED WARM MIX ASPHALT

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By

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Abstract

Foamed warm mix asphalt (WMA) is a technology that is beginning to be utilized across the United States. Often, producers are placing foamed WMA at decreased temperatures without fully understanding the properties of this relatively new product. By studying the volumetric properties of laboratory produced foamed WMA, this study sought to better understand the temperature sensitivity of foamed WMA and the potential factors that contribute to this sensitivity. Two mix designs containing primarily limestone aggregate were tested using differing binder grades. It was determined that binder grade, binder source and potentially the inclusion of recycled asphalt pavement all influence how sensitive a mixture will be to temperature changes. More specifically, this research concluded that foamed WMA using polymer modified binder is more sensitive to changes in temperature than binders that are not polymer modified.

It was also determined that mixtures either have an optimum compaction temperature or a minimum allowable compaction temperature. For the first limestone mixture tested it was concluded that the compactability of the foamed WMA was maximized at a 50^{o}F below hot mix asphalt (HMA) temperatures. For the second limestone mixture tested it was determined that temperature could be decreased a maximum of 50^{o}F to still achieve adequate compaction. Research should continue in this area to determine if other performance properties are optimized at these temperatures.

Department of Civil Engineering

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Introduction

Warm Mix Asphalt (WMA) is defined by The American Association of State Highway and Transportation Officials (AASHTO) as an asphalt mixture produced at a temperature of at least 50^{o}F lower than those temperatures typically used for hot mix asphalt (HMA). It can also be used to generally describe the group of methods used to lower the viscosity of bituminous asphalt binder to allow for lower production temperature. WMA offers the benefit of lower production and compaction temperatures, meaning reduced energy usage and therefore increased energy cost savings, as well as decreased environmental impact of asphalt production. Some jobs implementing WMA have shown between 20 and 75 percent reduction in energy costs compared to HMA (Chowdhury and Button 2008). In addition, the lower temperatures mean working conditions are improved, cold weather paving is much more feasible and hauling distances can be increased. However, all these benefits are centered on the concept that WMA maintains the same performance properties as HMA. This study sought to better understand whether this assumption is true, specifically in the area of the temperature sensitivity of WMA. Determining a minimum temperature at which WMA can be produced will lead to a better understanding of the economic, environmental and procedural implications.

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.

There are four generally accepted procedures for producing warm mix asphalt in the United States today: WMA additives added to the binder, WMA additives added to mixture, wet aggregate mixtures, and plant foaming processes. Because WMA is such a popular topic in the asphalt industry and is being implemented so rapidly, there is a large amount of research that has been conducted in recent years and that is currently taking place. WMA additives such as Aspha-min, Sasobit and Evotherm are some of the most widely used products. While all of these products show increased workability, even at extremely reduced temperatures, they do not always maintain the same performance characteristics as their HMA equivalents.

One study investigating the effects of Aspha-min, Sasobit and Evotherm showed improved workability and compaction at compaction temperatures as low as 190^{o}F with all three additives. While the addition of these additives themselves did not adversely affect the resilient modulus or rutting potential, the likelihood of rutting or moisture damage was increased when paired with temperature decrease. (Hurley and Prowell 2006)

Some researchers believe that because aggregate is not heated to HMA temperatures, more moisture remains in the aggregate at mixing. This extra moisture can lead to decreased tensile strength as well as increased susceptibility to moisture damage. Hadley, Hudson and Kennedy completed an extensive study in 1969 evaluating different factors that impact the tensile strength of asphalt materials. Pertinent to this study, Hadley et al. studied the effect of temperature decrease. It was noted that at decreased temperatures, the asphalt binder had increased viscosity making it more difficult for the binder to be absorbed by the aggregate. This decreased absorption and bonding was believed to cause WMA to perform at a lower level than its HMA equivalent.

However, even these results are not consistent across all research projects. As discussed, research has shown that decreased temperatures likely lead to increased moisture susceptibility but research performed by Kennedy et al. showed increasing temperature will actually lead to increased moisture damage (Kennedy 1984). While lab results indicate more water remains in the mixture of WMA, field cores have shown no increased moisture damage (Chowdury and Button 2008). Because of these important and sometimes contradicting results, research must continue on how temperature affects WMA. Researchers must explore even further what possible performance characteristics are modified by temperature changes and how those can be accounted for in the mix design and production procedures of WMA.

A recent previous study by Annette Porter at the University of Arkansas researched the temperature sensitivity of WMA with additives Evotherm, Advera and Sasobit. Maximum temperature reductions were established for each additive and it was concluded that all WMA using these additives showed less sensitivity to temperature change than HMA. It was also found that higher binder grades tended to be more sensitive to temperature changes when considering WMA. More specifically, Evotherm, Advera and Sasobit were most effective as compaction aids when used with polymer modified binders and showed better compaction with higher binder grades. Using polymer modified performance graded (PG) 70-22 and PG76-22 binders, greater temperature decreases were achieved than when using a PG64-22 binder. Porter concluded that mixes containing PG64-22 binder were the least sensitive to temperature changes even with warm mix additives. (Porter 2011)

Foamed asphalt, in particular that produced by a mechanical process, offers unique benefits over other WMA technologies in that it does not require expensive additives or a change in basic mixing procedures from HMA. The only change for production plants is an up-front installation of machinery to foam the asphalt binder. Foamed asphalt is added directly to heated aggregate in the same way that a non-foamed hot binder would be. Foaming asphalt binder can be simply described as the addition small amounts of water and compressed air to the binder. 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 the original volume (Wirtgen Group 2009). The foamed asphalt is believed to have a lower viscosity than regular binder thus increasing the workability. This process is illustrated in the following figure.

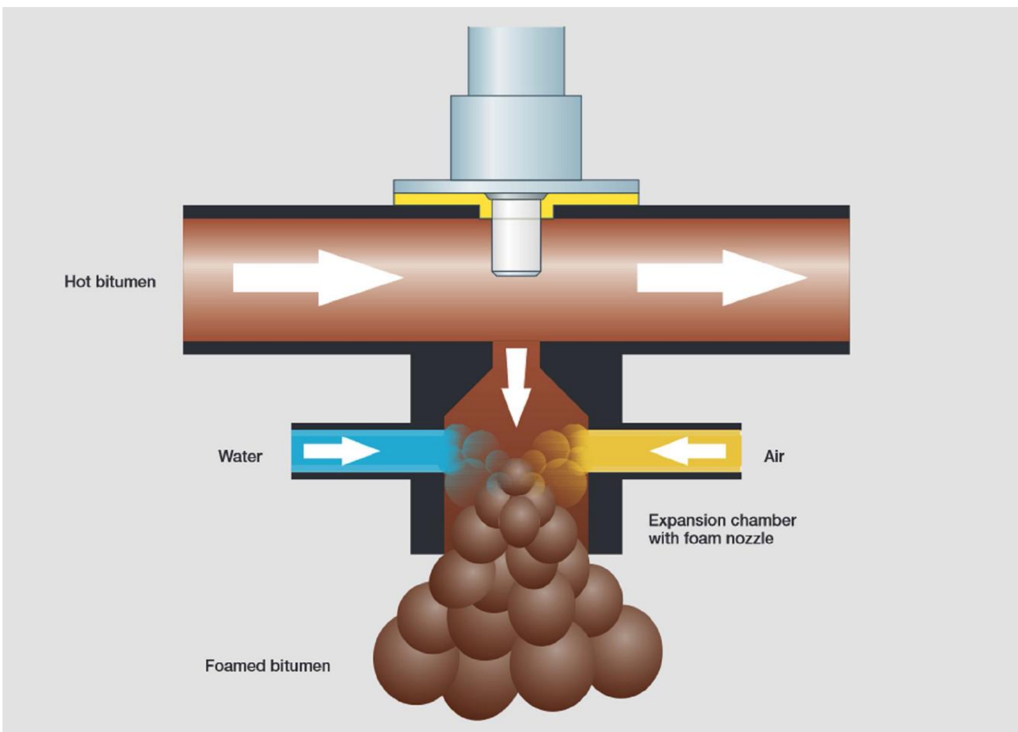

Figure 1: Asphalt Foaming Process (Wirtgen Group 2009)

This study used two different foaming devices in an attempt to accurately mimic plant foaming procedure. The first was a laboratory-scale foamed bitumen plant WLB 10S made by Wirtgen Group. The second was "The Foamer" made by Pavement Technology Inc. (PTI). Both devices operate under a very similar principle with a slight modification. The Wirtgen injects air and water into the asphalt at high pressures while the PTI Foamer uses gravity and lower pressure to inject the water and air. Both foaming machines produce a very similar product but it is not known if one more accurately imitates that of field production. The foamers used in this laboratory study are pictured below.

Figure 2: Wirtgen WLB 10S Foaming Device

Figure 3: Pavement Technology Inc. (PTI) – "The Foamer"

<u>Objectives</u>:

Foamed WMA is beginning to be used extensively across the United States, but not everything is understood about how these mixes actually perform. This study focused specifically on assessing the temperature sensitivity of foamed asphalt mixtures, and the effects on workability. The goal was that, by analyzing the volumetric properties of WMA at different temperatures, either a minimum temperature or an optimum temperature for foamed WMA could be established. This temperature will allow the industry to better understand what temperature reductions can be reasonably achieved for foamed WMA and also what temperatures will produce the greatest economic benefits. Having a better understanding of this is crucial if the benefits of WMA, such as increased haul time, less environmental impact and economic benefits, are to be maximized.

A secondary objective was to determine whether a laboratory scale foaming device could accurately replicate the plant foaming process. In Arkansas, there is currently no approved laboratory foaming device to produce laboratory samples to test WMA mix designs. Determining if an available foaming device is the best option to recreate field samples in the laboratory will allow engineers to properly design WMA mixtures in the future and will make it possible for state agencies to properly assess and approve mix designs. If researchers cannot reproduce this increasingly popular type of asphalt mixture in a lab it will be impossible to know the true performance characteristics until they become evident on public roadways.

Description of Laboratory Work

Mix Designs:

Samples were prepared using mix designs from two prominent plants in Arkansas. Both mix designs used limestone as the primary aggregate source and will therefore be referred to as Limestone-1 and Limestone-2.

Limestone-1 designs were produced in the laboratory using binder grades PG64-22, PG70-22, and PG76-22, which were all obtained from a producer in Arkansas. All Limestone-1 mixes prepared in this study are identified as having 12.5mm nominal maximum size aggregate. Aggregates were primarily limestone with a sandstone component. No recycled asphalt pavement (RAP) was used; therefore optimum binder content was not altered in any way. Other important properties are summarized in Table 1, acceptable field tolerances are shown in parentheses following optimum design values.

Table 1: Limestone-1 Mix Design Properties

Binder Grade	PG64-22	PG70-22	PG76-22
Binder Content (%)	6.0 (5.7-6.3)	5.6 (5.3-5.9)	5.8 (5.5-6.1)
Air Voids (%)	4.5 (3.0-5.0)	4.5 (3.0-5.0)	4.0 (3.0-5.0)
VMA (%)	14.3 (13.5-16.0)	14.6 (13.5-16.0)	14.9 (13.5-16.0)
VFA (%)	68.4	69.2	73.0
% Aggregate Passing #200	4.9	5.0	4.6

Limestone-2 was produced and tested in the laboratory as well as in the field. This mix also contained a 12.5mm maximum nominal size aggregate and contained PG76-22 binder. The binder for Limestone-2 was obtained from a producer in Oklahoma. It was primarily limestone as well and included 15% recycled asphalt pavement (RAP). The total binder content was 5.4%. However, because of the inclusion of RAP, a reduced virgin binder content of 4.7% was actually required. In the following description of the Limestone-2 mix design, the binder content of 5.4% includes the binder present in the RAP added to the mixture as well as the virgin binder content.

Table 2 summarizes the design properties of the Limestone-2 PG76-22 mix. Acceptable field tolerances for several properties are shown in parentheses following optimum design values.

Table 2: Limestone-2 Mix Design Properties

Binder Grade	PG76-22
Binder Content (%)	5.4 (5.1-5.7)
Air Voids (%)	4.0 (3.0-5.0)
VMA (%)	15.1(13.5-16.0)
VFA (%)	73.4
% Aggregate Passing #200	5.8

<u>General Procedure:</u>

Regarding the actual mixing procedure for foamed asphalt, warm mix requires very little modification from hot mix. Aggregate was heated to the desired mixing temperature and mixed with foamed asphalt binder for approximately 90 seconds until all aggregate was adequately coated. Samples were then aged for two hours at their respective compaction temperatures, and were stirred each hour. Samples were prepared with the purpose of either performing a bulk specific gravity test (G_{mb}) or a maximum theoretical specific gravity test (G_{mm}), and these test results were used in volumetric calculations. Bulk samples were compacted in a Pine Gyratory Compactor and specific gravity tests were then run in accordance with AASHTO T-166 (Saturated Surface-Dry Specimens). Maximum theoretical specific gravity tests (also referred to as a Rice sample) were run in accordance with AASHTO T-209. Using the results of these tests, several properties were obtained with the goal of accurately describing each mixture's sensitivity to temperature changes. These properties included air voids present at the design gyration number (N_{des}), degree of compaction or relative density, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA).

In laboratory production of the WMA, two different foaming devices were utilized: the Wirtgen machine and PTI Foamer. Identical mixes were produced using both the Wirtgen and

PTI so that adequate comparisons could be made and so that it might be determined if one device better simulated plant foaming procedures. The foaming devices were set to produce asphalt with 2 percent foam to correspond with standard field procedures.

Limestone-1:

Three different mix designs were used from Limestone-1, corresponding with three binder grades: PG64-22, PG70-22 and PG76-22. Limestone-1 mixes were prepared with the sole purpose of laboratory experimentation and analysis, therefore no field samples were collected and temperatures were selected over a broad range to best analyze temperature sensitivity. Each mix was produced at a total of four different temperatures. For each binder grade, three samples were produced at hot mix asphalt (HMA) temperatures with no foam added. Two samples at approximately 4500 grams for bulk specific gravity (G_{mb}) and one Rice sample at approximately 2000 grams for maximum theoretical specific gravity (G_{mm}) were produced. This procedure was then repeated using foamed asphalt at mixing and compaction temperatures 30, 50 and 60 degrees Fahrenheit below HMA design temperatures. Three samples (two bulks and one Rice) were produced at each temperature for both foaming devices. The bulk samples were compacted using a Pine Gyratory Compactor to their specified design number of gyrations: 75 gyrations for PG64-22, 100 gyrations for PG70-22, and 125 gyrations for PG76-22.

Height data was collected during compaction of each specimen so that compaction effort could also be analyzed. AASHTO R35-12: Superpave Volumetric Design for HMA has special provisions for WMA beginning in Section X2. Included in these provisions, Section X2.8.3 specifies how to accurately determine an index of the workability. In addition to the testing plan outlined above, one 4500 gram bulk sample was produced at a temperature 30 degrees Celsius below each warm mix temperature for each binder grade and foaming device. These samples were used in determination of the workability ratio discussed in later sections. This entire testing matrix is summarized in Table 3.

Table 3: Limestone-1 Laboratory Sample Production Plan

Foam	Binder Grade	Temperature		N_{des}	Samples Produced	
		Mixing (°F)	Compacting (°F)		Bulk (G_{mb})	Rice (G_{mm})
HMA / None	PG64-22	315	295	75	2	1
	PG70-22	325	300	100	2	1
	PG76-22	335	315	125	2	1
PTI	PG64-22	285	265	75	2	1
		265	245	75	2	1
		255	235	75	2	1
		231	211	75	1	-
		211	191	75	1	-
		201	181	75	1	-
	PG70-22	295	270	100	2	1
		275	250	100	2	1
		265	240	100	2	1
		241	216	100	1	-
		221	196	100	1	-
		211	186	100	1	-
	PG76-22	305	285	125	2	1
		285	265	125	2	1
		275	255	125	2	1
		251	231	125	-	-
		231	211	125	-	-
		221	201	125	-	-
Wirtgen	PG64-22	285	265	75	2	1
		265	245	75	2	1
		255	235	75	2	1
		231	211	75	1	-
		211	191	75	1	-
		201	181	75	1	-
	PG70-22	295	270	100	2	1
		275	250	100	2	1
		265	240	100	2	1
		241	216	100	1	-
		221	196	100	1	-
		211	186	100	1	-
	PG76-22	305	285	125	2	1
		285	265	125	2	1
		275	255	125	2	1
		251	231	125	1	-
		231	211	125	1	-
		221	201	125	1	-

Before the completion of this study the PG76-22 specified for the Limestone-1 design became no longer available. Current supplies were completely used up before the three lowest temperatures in the PTI could be produced. Data from the volumetric tests were analyzed to determine correlations between varying temperatures and foaming procedures to properties such as air voids, compaction effort and workability. This analysis is discussed in later sections of this report.

Limestone-2:

At the time of testing, only one Limestone-2 warm mix design was being placed extensively in the field, a PG76-22 with polymer modified binder. Field samples were obtained for Limestone-2 and are discussed later in this report. Laboratory samples of this design were produced following a similar testing plan used for the Limestone-1 designs. Limestone-2 laboratory samples were produced with the principal intention of comparison to field mixtures. Laboratory analysis of temperature sensitivity was also completed, but temperatures were selected with purpose of representing field conditions. For the Limestone-2 design, the WMA design field compaction temperature was 265^{o}F and the laboratory test temperatures were selected accordingly. At each temperature, both foaming devices were used to make four 4500 gram bulk samples and two 2000 gram Rice samples.

As was completed with Limestone-1, three additional bulk samples were produced in each foaming device at 30^{o}C below each WMA temperature tested. This was done in accordance with AASHTO R35-12 special provisions for WMA with the intent of analyzing the compaction ratios. The entire Limestone-2 testing matrix is outlined in Table 4.

Table 4: Limestone-2 Laboratory Sample Production Plan

Foam	Binder Grade	Temperature		N_{des}	Samples Produced	
		Mixing (^{o}F)	Compacting (^{o}F)		Bulk (G_{mb})	Rice (G_{mm})
HMA / None	PG76-22	335	290	125	4	2
PTI	PG76-22	330	285	125	4	2
		310	265	125	4	2
		290	245	125	4	2
		276	231	125	1	-
		256	211	125	1	-
		236	191	125	1	-
Wirtgen	PG76-22	330	285	125	4	2
		310	265	125	4	2
		290	245	125	4	2
		276	231	125	1	-
		256	211	125	1	-
		236	191	125	1	-

Data from the volumetric tests of these samples were analyzed in the same way as described for Limestone-1 with the goal of establishing correlations between foaming device and temperature change to air voids, compaction effort and workability. This analysis is also discussed in later sections of this report.

Description of Field Work

One of the stated goals of this project was to compare plant produced field mixes to those created in the laboratory to investigate how closely laboratory scale foaming could imitate field work. Due the realities and difficulties of scheduling with construction companies, only one such study could be accomplished before the completion of this report. Samples were obtained directly from a construction project placing a Limestone-2 mix on Highway 16 in Fayetteville, Arkansas. The Limestone-2 PG76-22 mix design discussed earlier was being used at this site. Representative samples were obtained from the job site and transported to the laboratory for compaction and tests. Once at the lab, the representative sample taken from the job site was further split into the appropriate sample sizes for bulk specific gravity tests, maximum theoretical specific gravity, moisture damage testing and rut testing. For this purposes of this study, only the specific gravities are of interest. Samples were heated to the same temperatures used during lab tests so that accurate comparisons could be drawn. Using volumetric tests, the percent air voids at N_{des} for the field samples was determined at each testing temperature. Four G_{mb} samples were compacted at each testing temperature. The results of these volumetric tests are analyzed in the following sections of this report.

Analysis and Discussion

Limestone-1 Air Voids Analysis:

Table 5 summarizes the results of the volumetric tests from the Limestone-1 laboratory samples.

Table 5: Limestone-1 Volumetric Results

Foam	Binder Grade	Temperature		Avg. G_{mb}	Avg. G_{mm}	Avg. VMA (%)	Avg. VFA (%)
		Mixing (°F)	Compacting (°F)				
HMA / None	PG64-22	315	295	2.314	2.402	12.4	70.3
	PG70-22	325	300	2.304	2.403	12.8	67.9
	PG76-22	335	315	2.334	2.404	12.1	75.9
PTI	PG64-22	285	265	2.283	2.395	13.6	65.6
		265	245	2.282	2.384	13.6	68.5
		255	235	2.291	2.389	13.3	69.1
		231	211	2.310	2.395	12.6	71.7
		211	191	2.299	2.384	13.0	72.4
		201	181	2.283	2.389	13.6	67.5
	PG70-22	295	270	2.324	2.403	12.1	72.6
		275	250	2.335	2.398	11.6	77.3
		265	240	2.323	2.407	12.2	73.1
		241	216	2.336	2.403	11.6	75.7
		221	196	2.312	2.398	12.5	71.2
		211	186	2.299	2.407	13.0	65.4
	PG76-22	305	285	2.304	2.410	13.2	66.9
		285	265	2.329	2.407	12.3	73.7
		275	255	2.327	2.409	12.4	72.4
		251	231	-	-	-	-
		231	211	-	-	-	-
		221	201	-	-	-	-

Table 5 (cont.): Limestone-1 Volumetric Results

Foam	Binder Grade	Temperature		Avg. G_{mb}	Avg. G_{mm}	Avg. VMA (%)	Avg. VFA (%)
		Mixing (°F)	Compacting (°F)				
Wirtgen	PG64-22	285	265	2.295	2.390	13.1	69.6
		265	245	2.291	2.381	13.3	71.4
		255	235	2.291	2.383	13.3	70.8
		231	211	2.291	2.390	13.3	68.6
		211	191	2.276	2.381	13.9	68.0
		201	181	2.299	2.383	13.0	72.7
	PG70-22	295	270	2.328	2.406	11.9	71.5
		275	250	2.328	2.042	11.9	74.3
		265	240	2.319	2.409	12.2	69.5
		241	216	2.318	2.409	12.3	69.1
		221	196	2.308	2.402	12.6	69.1
		211	186	2.292	2.409	13.3	63.3
	PG76-22	305	285	2.332	2.398	12.2	77.4
		285	265	2.338	2.397	11.9	79.5
		275	255	2.317	2.402	12.7	72.3
		251	231	2.331	2.398	12.2	77.2
		231	211	2.313	2.397	12.9	72.9
		221	201	2.331	2.402	12.2	75.7

Percent air voids in each bulk sample after N_{des} gyrations was calculated in accordance with AASHTO T-269 using the bulk specific gravity and maximum specific gravity. The following three graphs display the findings of these calculations for the Limestone-1 mix, PG64-22, PG70-22, and PG76-22 respectively. The small round data points represent individual samples and the larger symbols represent the average of those samples for each temperature and foaming device.

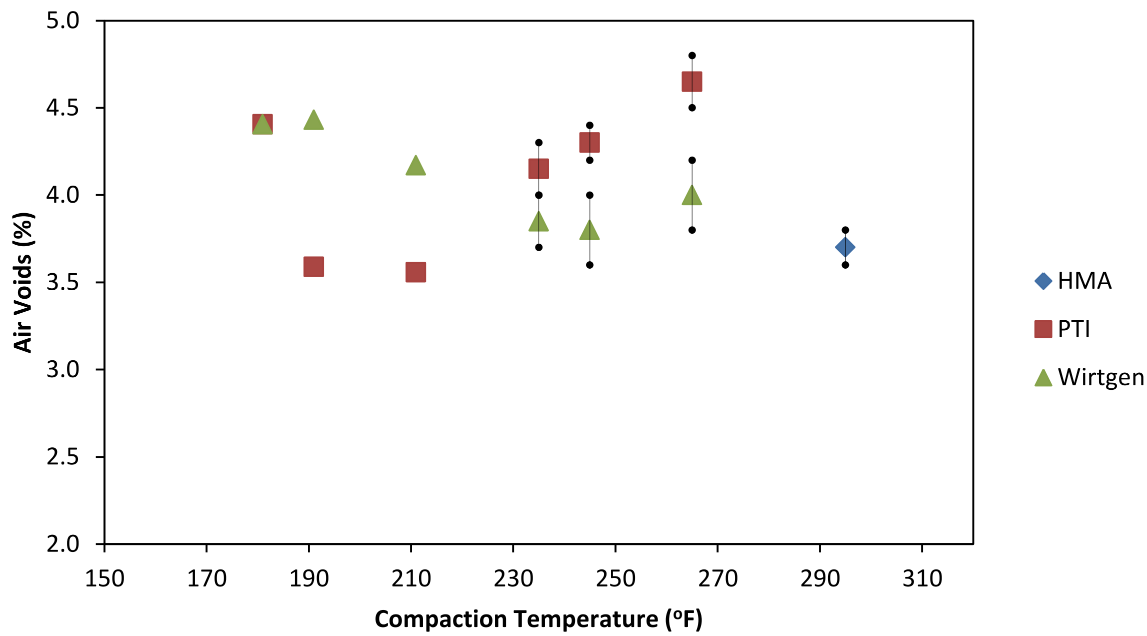

Figure 4: Air Voids at N_{des} for Limestone-1 PG64-22

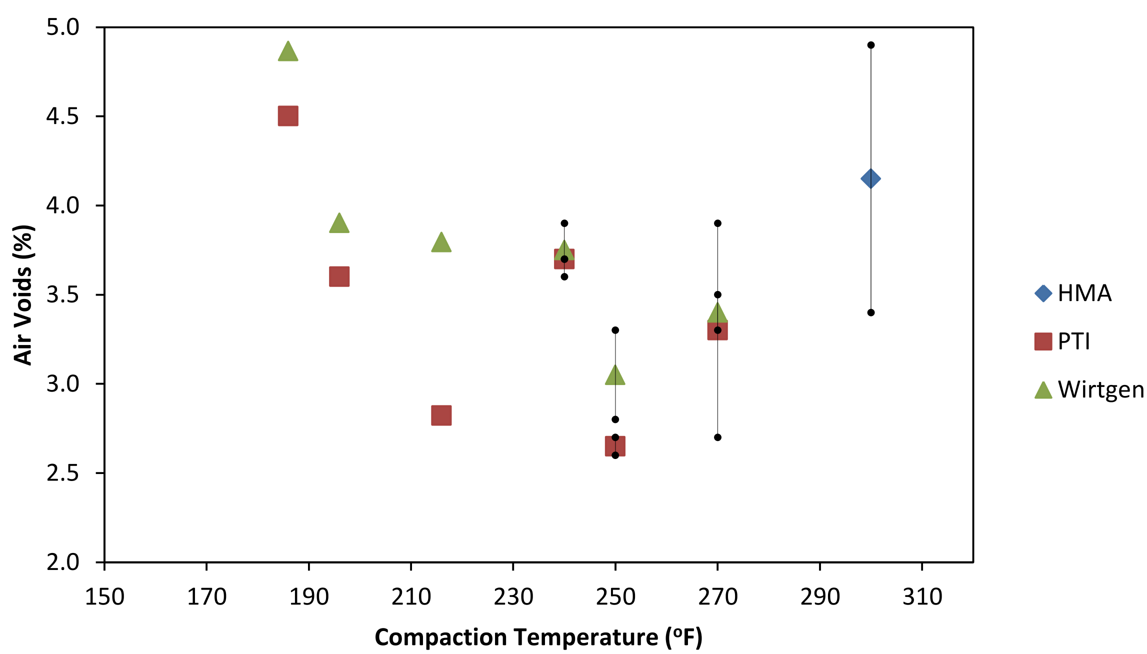

Figure 5: Air Voids at N_{des} for Limestone-1 PG70-22

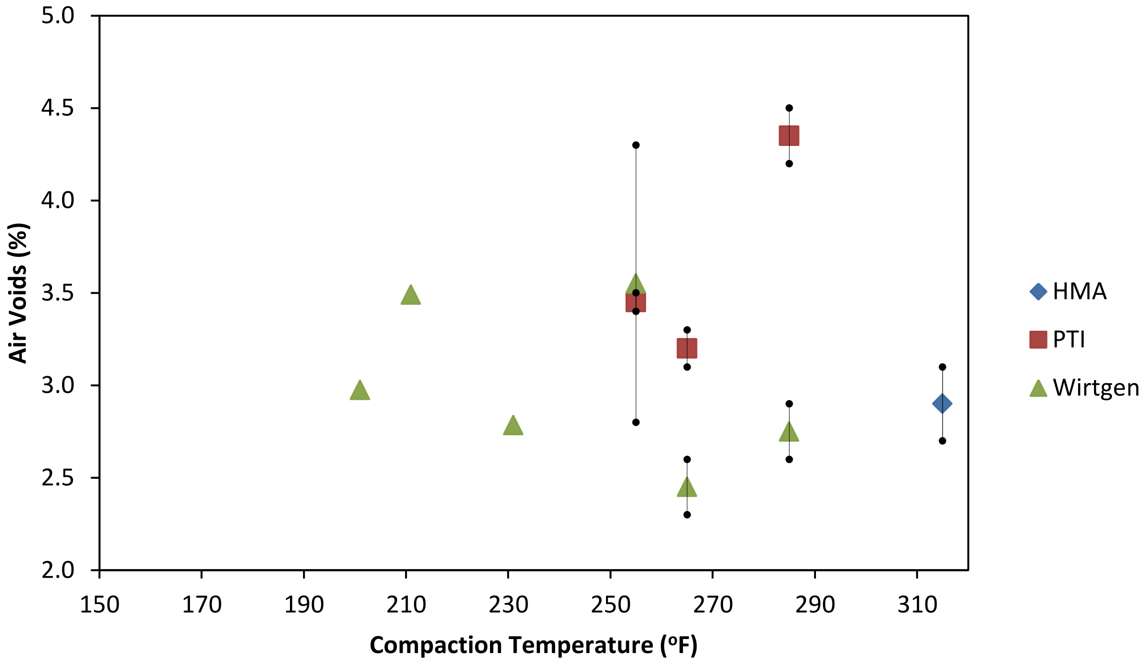

Figure 6: Air Voids at N_{des} for Limestone-1 PG76-22

Logic would suggest that as temperature is decreased, compaction would become more difficult, therefore results would indicate a higher percent of air voids. The initial thought behind studying temperature sensitivity was that a minimum temperature would be established. This minimum temperature would be the point at which compactability deteriorated so far from the original HMA design that it could no longer be reasonably assumed the mix was maintaining the same volumetric and/or performance properties. The data collected during this portion does not necessarily support this theory. Instead, a comparison between compaction temperature and air voids suggested there may actually be an optimum production temperature for foamed WMA. Generally, as compaction temperature decreased, the air voids of the foamed mixes decreased and then increased, suggesting an optimum temperature. For the Limestone-1 mixes tested (excluding the PG64-22), a 50°F decrease in production and compaction temperature resulted in the lowest air voids at N_{des} and therefore generated the greatest compactability and workability.

Mixes prepared with PG70-22 and PG76-22 binder showed a consistent sensitivity to temperature changes. Both binders generally displayed the relationship of decreasing then increasing air voids as temperature was decreased. The PG70-22 and PG76-22 binders used for the Limestone-1 design were both polymer modified binders. As concluded in previous research studies, these results suggest that WMA technologies are in fact more effective when used with polymer modified binders and WMA that utilizes higher binder grades is more sensitive to temperature.

The PG64-22 mix showed significantly less sensitivity to temperature change than the polymer modified mixtures. First, the PG64-22 was the only mix in which HMA showed a lower air void content than WMA produced. In fact, the first sample that produced lower air voids than the original HMA was compacted at a temperature 84^{o}F lower than the design temperature and was produced using the PTI foamer. This sample was initially created only with the purpose of analyzing the workability of the WMA designs, as discussed in later sections. The Wirtgen results showed a continued increase in air voids as temperatures were decreased more than 50^{o}F, which was more consistent with findings for other binder grades. This may be an early indication of which foaming device produces more consistent results to that of field mix, or the fact that it does not follow the consistent pattern of the other two Limestone-1 designs may indicate that PG64-22 binder is simply less sensitive to decreases in temperature. As cited earlier, previous research completed by Annette Porter (2011) also concluded that PG64-22 binder was less sensitive to temperature change than higher grade, polymer modified binder when using warm mix additives. The results of this study suggest this to also be true of foamed WMA.

To further understand how temperature affects this mixture, an Analysis of Variance (ANOVA) was completed. A one-way ANOVA test was completed comparing air voids and compaction temperature to determine whether or not temperature had a significant effect on air voids. A 95% confidence interval was used which meant an alpha of 0.05 was used to determine significance. If the ANOVA test yielded a P-value of less than alpha, temperature change was taken to have a significant impact on air voids. If the P-value was greater than alpha, temperature was taken to be not significant. Table 6 summarizes the results of the one-way ANOVA tests for Limestone-1.

Table 6: One-Way ANOVA P-values for Limestone-1 Laboratory Mixes

Binder	Foam	P-Value	Significant?
PG64-22	PTI	0.15994	NO
	Wirtgen	0.75003	NO
PG70-22	PTI	0.24566	NO
	Wirtgen	0.14770	NO
PG76-22	PTI	0.00975	YES
	Wirtgen	0.33712	NO

Only the PG76-22 mix prepared using the PTI foamer showed temperature actually being significant. While only significant with the PTI, this still supports previous research that higher grade, polymer modified binders are more likely to be sensitive to temperature changes. None of the other Limestone-1 samples were showed even marginal significance. This reinforces the conclusion that temperature and compactability have little correlation when considering the PG64-22 binder. For the majority of the PG70-22 and PG76-22 samples however, even though a trend was observed earlier, statistically it was not considered a significant trend. What this means is that even though there may be an optimum compaction temperature, being higher or lower than this temperature will not consistently result in significantly decreased air voids.

Even though statistical analysis generally showed temperature decreases to not lead to a significant trend with compactability, this is an important concept for asphalt producers to be aware of. Because one of the main benefits of implementing WMA is the energy savings associated with it, establishing a temperature at which compaction requires the least amount of energy would allow asphalt producers to maximize savings. While decreasing the temperature below 50°F below HMA temperatures would save even more money in energy usage, the extra time and money spent to account for the increase in required compaction would probably outweigh those benefits. This is something that should be researched more in depth to better understand how economic benefits interact. However, the results of this research recommend that for the Limestone-1 mixes tested, savings could be maximized at temperatures approximately 50°F less than HMA temperatures.

Limestone-2 Air Voids Analysis:

Table 7 summarizes the results of volumetric testing for Limestone-2 laboratory samples.

Table 7: Limestone-2 Laboratory Volumetric Results

Foam	Binder Grade	Temperature		Avg. G_{mb}	Avg. G_{mm}	Avg. VMA (%)	Avg. VFA (%)
		Mixing (°F)	Compacting (°F)				
HMA / None	PG76-22	335	290	2.308	2.404	15.5	74.0
PTI	PG76-22	330	285	2.309	2.408	15.4	73.1
		310	265	2.265	2.403	17.0	66.2
		290	245	2.286	2.404	16.2	70.0
		276	231	2.330	2.408	14.6	77.8
		256	211	2.256	2.403	17.4	64.7
		236	191	2.261	2.404	17.2	65.5
Wirtgen	PG76-22	330	285	2.308	2.402	15.4	74.8
		310	265	2.300	2.403	15.7	72.8
		290	245	2.287	2.404	16.2	69.8
		276	231	2.277	2.402	16.6	68.8
		256	211	2.253	2.403	17.5	64.3
		236	191	2.241	2.404	17.9	62.1

The same comparison of percent air voids to compaction temperature was made with the Limestone-2 mixtures. The findings are summarized in the following graph. The small round data points represent individual samples and the larger symbols represent the average of those samples for each temperature and foaming device.

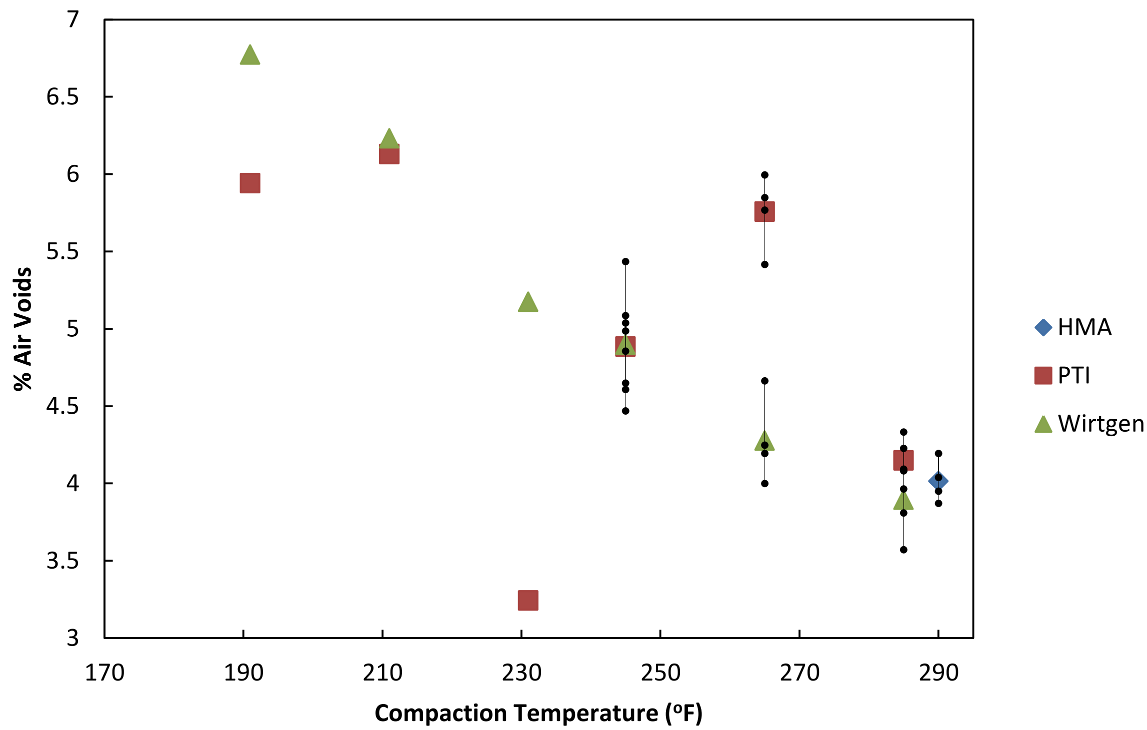

Figure 7: Air Voids at N_{des} for Laboratory Limestone-2 PG76-22

The first thing noticeable from the Limestone-2 results is that they do not seem to exhibit the same "optimum temperature" that was displayed by the Limestone-1 designs. The Wirtgen device displayed a fairly linear relationship, with air voids increasing as temperatures decreased. This pattern is consistent even when considering the mixes prepared at even lower temperatures for the workability index.

The PTI results appeared to be much more randomized and showed no clear trend. This is understandable considering the difficulties experienced with the PTI while attempting to foam the polymer modified PG76-22 binder specified by the Limestone-2 mix design. In order to achieve adequate foaming, (i.e., all water and air properly being injected into the binder) the binder had to be kept at a very high temperature in the machine (330°F minimum) and even then difficulties were experienced producing consistently foamed asphalt binder. This may account for the variability in the data collected from this device. A thermocouple in the machine was later found to be faulty also possibly contributing to difficulties in maintaining the proper binder temperature. It should be noted that if the PTI data points at 265°F and 231°F were considered outliers, then the PTI results exhibit generally the same trend as the Wirtgen. The results of this study suggest that either care is taken to ensure that temperatures remain high enough to achieve proper foaming when foaming polymer modified, high grade binder (such as the PG76-22 used in this study) or that devices that foam at a higher pressure (such as the Wirtgen machine) are used when approving mixtures using polymer modified, high grade binder in the laboratory.

As with the Limestone-1 mixes, an Analysis of Variance (ANOVA) was completed for the Limestone-2 laboratory samples. Again, a 95% confidence was used meaning P-values less than 0.05 represent a significant relationship between temperature and the air voids. The results of this statistical analysis are summarized in Table 8.

Table 8: ANOVA P-Values for Limestone-2 Laboratory Mixes

Binder	Foam	P-Value	Significant?
PG76-22	PTI	0.00010	YES
	Wirtgen	0.00127	YES

Both the PTI and Wirtgen foaming device display a significant trend between and temperature and air voids. Even with inconsistent results from the PTI, this confirms that PG76-22 binder is more sensitive to temperature fluctuations than lower grade binder. These results suggest that the binder source used for Limestone-2 mixtures is especially sensitive as only one foamer displayed a significant relationship using Limestone-1 and the corresponding binder source. This is another important factor, binder source appears to have an impact on temperature sensitivity. It can be reasonably assumed from this study and others that higher grade binders are consistently more sensitive to temperature but even that sensitivity can be variable based on where a producer obtains their binder.

To further investigate if binder source impacted temperature sensitivity, Limestone-2 mixtures were prepared using the Arkansas binder source originally specified for Limestone-1. Comparing the air voids between Limestone-2 mixtures with the different binder sources will better illustrate the effects of binder source. This comparison is illustrated in Figure 8.

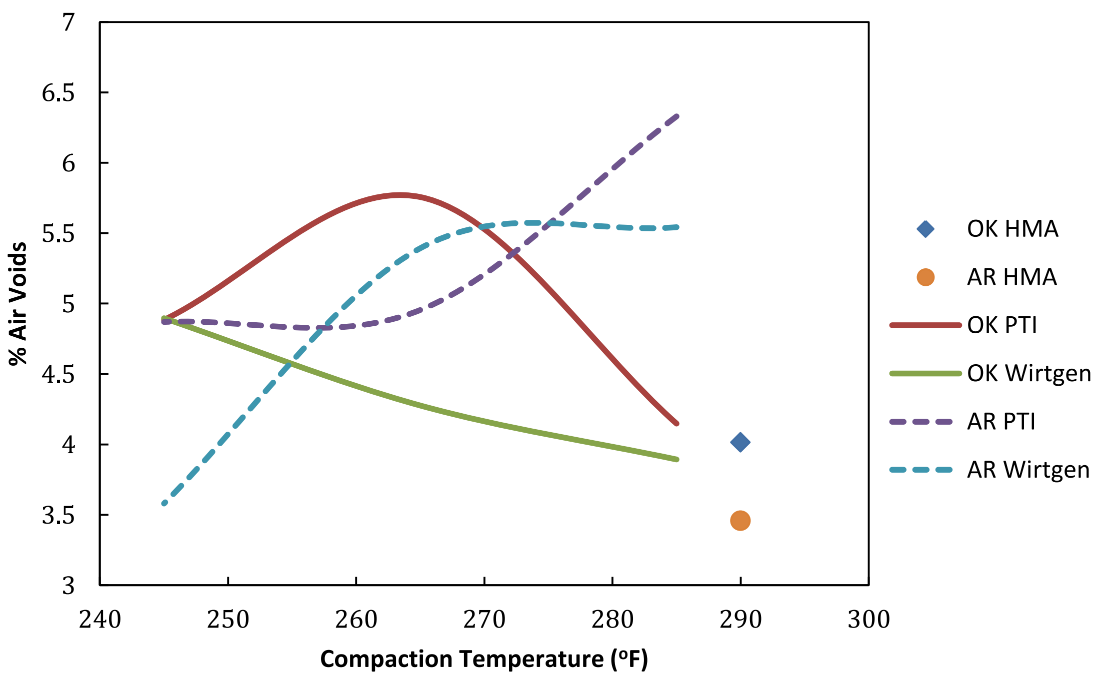

Figure 8: Limestone-2 Binder Source Comparison

Figure 8 confirms that binder source is a major factor when considering temperature sensitivity of WMA. When using the Oklahoma binder originally specified for Limestone-2, both foamers displayed a general increase in air voids as temperature decreased. When using the

Arkansas binder however, both foamers displayed generally decreasing air voids with decreased temperature over the tested temperature range.

Another potential factor that may have contributed to the increased temperature sensitivity of the Limestone-2 mix was the inclusion of recycled asphalt pavement (RAP). To investigate if this was a possible factor in temperature sensitivity, samples were prepared using the Limestone-2 aggregate mix design but mixed with the PG76-22 from the Arkansas binder source used for Limestone-1. The results from these samples were then compared with the Limestone-1 mix designs using Arkansas PG76-22 binder. Because both mix designs are primarily limestone and have very similar gradations, the only major difference is the inclusion of RAP and binder source. By using the same binder source, RAP became the only variable changed. The results of the ANOVA statistical analysis of the effect of temperature are summarized in the following table.

Table 9: ANOVA P-Value Comparison for Samples Including RAP

Aggregate	Binder	Foam	P-Value	Significant?
Limestone-1	AR - PG76-22	PTI	0.00975	YES
		Wirtgen	0.33712	NO
Limestone-2	AR - PG76-22	PTI	0.00129	YES
		Wirtgen	1.11E-06	YES

While not conclusive, these results suggest there may be a correlation between the inclusion of RAP and how sensitive a mix is to temperature change. Using the Limestone-2 aggregate design (which includes RAP), both foaming devices display a significant trend between temperature and air voids. Using the Limestone-1 aggregate design (which does not include RAP), only the PTI foamer showed there to be a significant interaction between temperature and air voids.

Investigating the potential effects of RAP was not an original objective of this project, and this analysis alone is not enough to draw definite conclusions, but it is one that should be explored further. A more precise study of aggregate blends containing RAP and those without RAP should be completed to draw firmer conclusions as to whether there is actually a correlation.

Ultimately, it was concluded that the Limestone-2 mix design exhibited the behavior originally expected at the beginning of this study. Viewing the more consistent results produced by the Wirtgen machine, it is apparent that a minimum temperature based on desired air voids should be established for this mix in contrast to the optimum temperature established for the Limestone-1 designs. For the Limestone-2 PG76-22 prepared in the laboratory, a compaction temperature of approximately 275°F (or 15°F less than HMA temperatures) yielded an average of 4.0% air at N_{des}. The approved mix design for Limestone-2 does state an acceptable tolerance for air voids is 3.0%-5.0%. If up to 5.0% air voids is allowable, the results of this study show that it may be acceptable to decrease compaction temperatures to approximately 240°F, or 50°F below HMA temperatures.

This again supported previous conclusions that PG76-22 binder is much more sensitive to temperature variations than other grades. While PG64-22 and PG70-22 mixes showed increased compactability at temperatures up to 50°F below HMA, the PG76-22 fails to meet the design requirements at only a 15°F decrease. Future researchers as well as industry personnel should be aware of the significant impact temperature variations can have on high grade, polymer modified binder. Special attention must be paid to production and compaction temperatures when producing asphalt mixes with these binders.

Field Study:

Table 10 summarizes the results of volumetric testing for the Limestone-2 field samples.

Table 10: Limestone-2 Field Volumetric Results

Temperature (°F)	Avg. G_{mb}	Avg. G_{mm}	Avg. VMA (%)	Avg VFA (%)
285	2.301	2.438	15.7	64.3
265	2.294	2.438	16.0	63.2
245	2.297	2.438	15.8	63.7

In the same manner as discussed for the laboratory mixes, air voids and temperature decrease were compared for field samples to characterize compaction effort. In the following figure the results of these tests are placed alongside lab results (displayed previously) for comparison purposes. The individual sample results are shown along with averages for the field samples. Only average values have been included for laboratory samples for ease of interpretation.

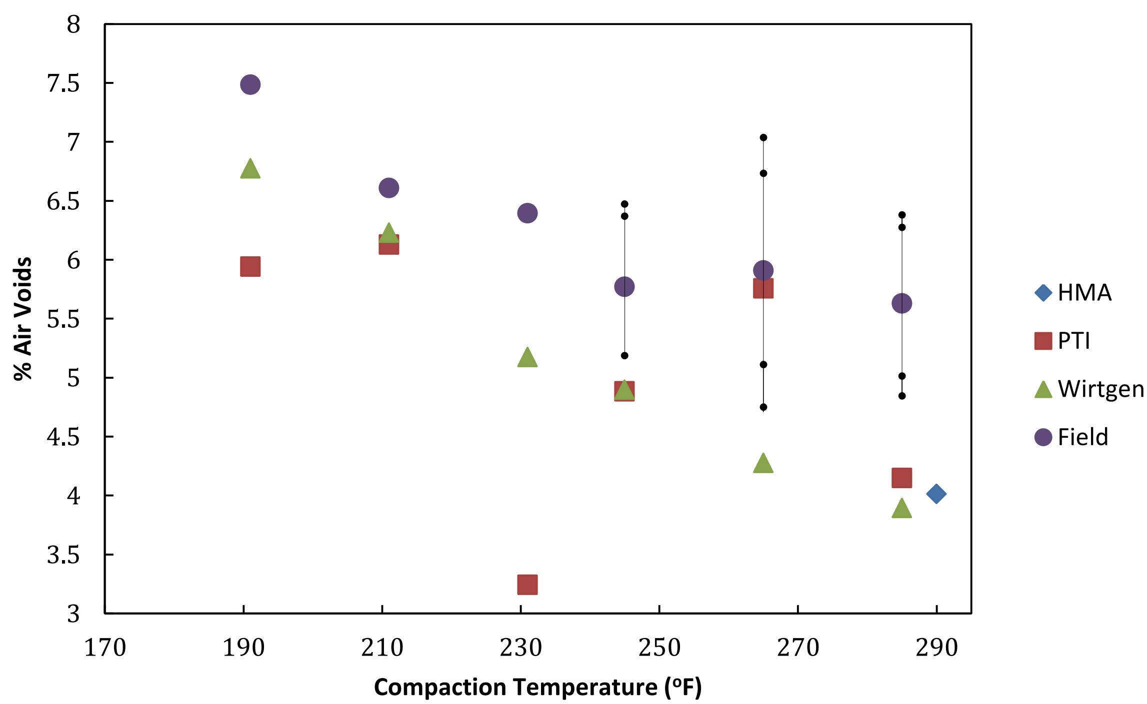

Figure 9: Limestone-2 Field vs. Laboratory Results

A statistical analysis was performed on the field data as well. The ANOVA P-value results showed no significant trend between temperature and air voids. Considering that when prepared in the laboratory, Limestone-2 mixes did show a significant relationship, this is an important topic. This may indicate that current laboratory procedures are not accurately imitating what is being placed in the field. This also means that the field mix is not as sensitive to temperature as mixes being currently produced in the laboratory, which would allow asphalt producers more flexibility in production and compaction temperatures.

Also apparent from these results was that the field mix tends to exhibit a higher percentage of air voids than those mixes prepared in the lab. In fact, none of the field mixes compacted in the laboratory actually achieved the design requirement of 4.0% air voids. The field mix does however exhibit the same trend of increasing air voids with decreasing temperature as laboratory samples prepared using the Wirtgen foaming device. From this data, it appears the Wirtgen may reproduce field conditions more accurately than the PTI foamer. Further research should be conducted in this area though especially considering he previously discussed difficulties and possible outliers with the PTI. More extensive testing may indicate that one foaming device consistently produces mixtures more like those in the field.

It also should be considered that potentially the process of creating foamed asphalt samples in the lab may need modifications to accurately reproduce those being placed in the field. A two-way ANOVA test was completed to compare laboratory samples to those obtained in the field and a P-value of 0.0001 was determined. This means that there was a significant statistical difference between samples prepared in the laboratory and in the field, further supporting the idea that current laboratory procedures may not be in line with field procedures. Evaluating more properties, such as rutting potential and susceptibility to moisture damage, could also lead researchers to conclude whether one of the devices used in this study offers a better representation and if WMA preparation procedures as a whole need to be re-evaluated.

Workability Ratio Analysis:

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.

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

$\%G_{mmN}$ = 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. Determining 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 degrees Celsius below the WMA temperature allowed for AASHTO R35-12 Equation X2.7 to be used to determine the workability ratio.

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

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 becomes sensitive to temperature decrease. The results of this portion of the study are as follows in Table 11. It should be noted that the PG76-22 binder specified for use in Limestone-1 PG76-22 mix design became no longer available before the completion of this research study. Thus, it was not possible to determine workability of this mixture using the PTI Foamer as current supplies were exhausted before completion.

Table 11: Compaction Ratios

Mix ID	Foam	Decrease from WMA Temp (F)	Average N92 Values		Ratio
			N92(T)	N92(T-30)	
Limestone-1 PG64-22	PTI	-30	37.5	28	0.75
		-50	35	28	0.80
		-60	33	32	0.97
	Wirtgen	-30	32	30	0.94
		-50	30.5	33	1.08
		-60	30.5	28	0.92
Limestone-1 PG70-22	PTI	-30	35.5	29	0.82
		-50	30	35	1.17
		-60	35	40	1.14
	Wirtgen	-30	35.5	36	1.01
		-50	32.5	36	1.11
		-60	37.5	45	1.20
Limestone-1 PG76-22	PTI	-30	50	-	-
		-50	40.5	-	-
		-60	40.5	-	-
	Wirtgen	-30	37	33	0.89
		-50	32.5	37	1.14
		-60	42	28	0.67
Limestone-2 PG76-22	PTI	-5	43.25	33	0.76
		-25	62.75	68	1.08
		-45	49.33	64	1.30
	Wirtgen	-5	40.5	52	1.28
		-25	44.25	71	1.60
		-45	50	82	1.64
	Field	-5	68.25	96	1.41
		-25	75	103	1.37
		-45	70.5	131	1.86

This analysis confirms earlier conclusions that the Limestone-1 PG64-22 mix design is the least temperature sensitive mixture tested. The compaction ratio is actually less than 1.0 for the majority of samples from this mix implying that less compaction was required to compact this foamed WMA even at significantly lower temperatures.

The possibility that using foamed asphalt in WMA could increase workability, even at decreased temperatures, had been suggested by earlier studies in this topic and is confirmed by this study although this is not true for all asphalt mix designs. While no mixes prepared using Limestone-1 designs exceeded the ratio of 1.25 specified by AASHTO, several samples of the Limestone-2 PG76-22 did. In fact, the only WMA prepared using the Limestone-2 mix design that was considered workable by this measure were the samples produced in the PTI Foamer at 30 and 50 degrees Fahrenheit below HMA. As discussed previously, the PTI produced highly variable results, specifically a very high air void percentage at 25 degrees below HMA possibly masking the effects of difficult compaction at these temperatures.

No difficulties were experienced in getting binder to fully coat aggregate or in placing mixtures into compaction molds during production of the Limestone-2 mixtures. The Wirtgen results (which were more consistent for this mix) suggest that none of the temperatures tested in this study should be considered workable. It should be noted however that at the 5 degrees below HMA was very close to the limit of 1.25. The field results are in line with this conclusion that even at a very small drop in temperature, the Limestone-2 mix is very sensitive to temperature and may experience difficulties in achieving adequate compaction. Although a significant loss in workability was not noticed, this data supports the idea that the PG76-22 used in the Limestone-2 design was much more sensitive to temperature than the other binders tested.

Conclusions and Recommendations

The following broad conclusions were determined by this study:

- Higher binder grades, especially those which are polymer modified, are more sensitive to temperature changes when used in foamed WMA
- Binder source (not just grade) may also have an impact on temperature sensitivity
- The inclusion of recycled asphalt pavement (RAP) may increase a mixture's temperature sensitivity
- An optimum temperature can be established for some WMA to maximize benefits

The following specific conclusions were also determined by this study:

- For the Limestone-1 WMA design, compaction temperature should be decreased approximately 50^{o}F from HMA temperatures to achieve maximum compactability
- For the Limestone-2 WMA design, compaction temperature should only be decreased between 15-50^{o}F so that adequate compaction can still be achieved

The results of the secondary objective to determine if one laboratory scale foaming device more accurately reproduced field condition mixtures were generally inconclusive. The questions raised from this objective, as well as others, that require further research are as follows:

- Does one laboratory scale foaming device more accurately replicate field conditions?
- Should other aspects of laboratory procedure for producing foamed WMA be adjusted to better represent current field practices?
- Does the inclusion of RAP actually increase a mixture's temperature sensitivity?

The results of this study ultimately recognize that there are many factors affecting the temperature sensitivity of an asphalt mixture. Some of these factors are aggregate source, inclusion of RAP, binder source, binder grade and foaming procedure. While it may be difficult to pinpoint some of these effects by only completing volumetric testing, a more in depth exploration including properties such as rutting potential and susceptibility to moisture damage will to serve to greatly expand the knowledge of how foamed WMA performs at different temperatures.

What is clear is that, at least for some WMA, an optimum temperature can be established for specific mix designs. The asphalt industry should be keenly aware of this if they seek to gain the full potential of producing foamed asphalt. Energy savings are maximized at this temperature in both production as well as placement. Environmental impacts are decreased the most at this temperature. With an understanding of how a mixture cools, hauling distances can also be maximized at this optimum temperature. While understanding the factors that contribute to temperature sensitivity is important, especially in mix design, they all ultimately lead to establishing this optimum temperature.

Research must continue in this area to see if other performance properties are maximized at this optimum temperature. Compactability is an important property but not the only consideration when determining optimum design properties. Producers and researchers must work to establish adequate design temperatures if they wish to maximize the benefits of foamed WMA.

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