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Laboratory Evaluation of Foamed Warm Mix Asphalt

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Abstract: A laboratory study was designed and executed to evaluate the performance of Warm Mix Asphalt prepared using foamed asphalt binders (WMA-FA) and compare it to traditional Hot Mix Asphalt (HMA). Two aggregates (crushed limestone and natural gravel) and two asphalt binders (neat PG 64-22 and polymer modified PG 70-22M) were used in this study. The Indirect Tensile Strength (ITS), Dynamic Modulus (*E**), Modified Lottman (AASHTO T 283), and Asphalt Pavement Analyzer (APA) tests were utilized to evaluate the laboratory performance of the considered mixtures. The test results showed lower ITS values for the WMA-FA mixtures than for the HMA mixtures. No significant difference in dynamic modulus was found between the WMA-FA and HMA mixtures. The WMA-FA mixtures were slightly more susceptible to moisture-induced damage than the HMA mixtures. However, both mixtures met the Ohio Department of Transportation (ODOT) minimum Tensile Strength Ratio (TSR) requirement of 0.7 for medium traffic. The WMA-FA mixtures were more prone to rutting than the HMA mixtures. However, the results suggested that using an appropriate type of aggregate and asphalt binder can address any adverse effects from using the foaming technology.

***Key words**: Dynamic modulus; Foamed asphalt; Hot mix asphalt; Moisture susceptibility; Rutting; Warm mix asphalt.*

Introduction

The rising energy costs, global warming, and more stringent environmental regulations have resulted in increased interest in using a new type of asphalt mixtures called Warm Mix Asphalt (WMA). WMA is a generic term for an asphalt mixture produced at temperatures lower than typically used for Hot Mix Asphalt (HMA) mixtures [1-2]. Key benefits of WMA include energy savings by lowering the amount of fuel required to heat asphalt mixtures during production and placement, reduction of emissions, extending the paving season, reduction of mixture aging, and possibility of increasing Reclaimed Asphalt Pavements (RAP) contents without the need to raise mixing temperature.

Various WMA technologies have been proposed in the past few years [3-5]. Those technologies can be classified into two main types. The first type uses some form of organic or chemical additives to produce the WMA, while the other type is produced by foaming the asphalt binder. The latter is achieved by adding a small amount of water to the binder, either via a foaming nozzle or a hydrophilic material such as Aspha-min. The added water then turns to steam and expands. This results in a reduction of viscosity due to the expansion of the liquid asphalt binder [5]. Foamed WMA produced by water injection (WMA-FA) are gaining popularity among asphalt mix producers. These are sometimes referred to as foamed asphalt or "free water" systems. The main advantage of these systems is that they allow the production of WMA with a standard grade asphalt binder through a one-time mechanical plant modification minimizing the impact of increased material costs identified with other WMA technologies.

Despite the advantages of WMA-FA mixtures, several concerns have been raised regarding the performance of this material because of the reduced temperature level used during production and its impact on aggregate drying and asphalt binder aging [5]. Main concerns include increased propensity to moisture-induced damage since water is used during production and aggregates are heated to lower temperatures and therefore may not thoroughly dry before being mixed with the asphalt binder; and increased susceptibility to permanent deformation (or rutting) since the asphalt binder may not harden as much at lower production temperatures and may easily densify even with proper compaction in the field.

Literature Review

During the past few years several research studies have been conducted to evaluate the performance of WMA-FA mixtures [6-9]. In a recent study conducted by the National Center for Asphalt Technology (NCAT), the laboratory performance of WMA-FA produced in a plant using the Gencor Green Machine Ultrafoam GX was evaluated and compared to that of an HMA mixture with the same aggregate and binder materials [6]. The results of this study showed that while the laboratory performance of the WMA-FA mixtures was lower than the HMA mixtures for many of the tests, the WMA-FA performance exceeded minimum laboratory performance thresholds in most cases. The rutting results of the Hamburg Wheel Tracking and the Asphalt Pavement Analyzer (APA) tests were acceptable for the WMA-FA and HMA mixtures. In addition, the indirect tensile strength (ITS) for the WMA-FA was high and improved with aging. However, its tensile strength ratio (TSR) did not meet the Superpave 0.8 criterion.

Wielinski *et al* [7] reported the results of a study in which Granite Construction, Inc. built two WMA paving projects using its Indio California facility. Both projects were paved with WMA produced using the Astec Double Barrel Green System. Control sections

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consisting of typical HMA were included in both projects to compare the WMA-FA and HMA mix properties and performance. The results of this study demonstrated that the WMA-FA mixtures could be produced and placed at lower temperatures, while yielding mix properties and field compaction similar to those of traditional HMA. The initial field performance of the WMA-FA and HMA sections was similar. The laboratory test results showed lower initial stiffness for the WMA-FA than the HMA, as indicated by the lower Hveem stability, Marshall flow and stability, and higher APA rut depths. In addition, both the HMA and WMA-FA mixtures had low TSR results, with the WMA-FA results being slightly lower than the HMA.

Hodo *et al*. [8] evaluated the rutting potential and moisture susceptibility of plant-produced WMA-FA mixtures containing high amounts of RAP (up to 50 percent), as part of a field demonstration project in Chattanooga, Tennessee. The results of this study revealed marginally acceptable performance with respect to moisture susceptibility. The authors suggested adding anti-stripping agents to improve the resistance to moisture-induced damage, if needed. Based on the Hamburg Wheel Tracking and the Asphalt Pavement Analyzer test results, it was reported that rutting is not an issue.

Based on the previous discussion, several research studies have been conducted to evaluate the performance of WMA-FA mixtures. However, all these studies utilized field-produced WMA-FA mixtures without any consideration to laboratory-produced materials. Therefore, there is a need to develop a procedure by which WMA-FA mixtures can be produced in the laboratory. Developing such procedure will allow preparing laboratory specimens to evaluate the performance of WMA-FA and thereby comparing it to traditional HMA.

Research Objectives

The primary objectives for this study are:

- Suggest a procedure by which WMA-FA can be produced in the laboratory.
- Evaluate the performance of WMA-FA mixtures for moisture-induced damage and permanent deformation.
- Compare the performance of WMA-FA mixtures to traditional HMA mixtures.

Material Description

Two types of aggregates and two asphalt binders were used in this study. The aggregate types were crushed limestone and natural gravel. The asphalt binders were a neat PG 64-22 asphalt binder and a polymer modified asphalt binder meeting the specifications for PG 70-22M.

Mix Design

The aggregate gradation met the Ohio Department of Transportation (ODOT) Construction and Material Specifications (C&MS) Item 441 Type 1 surface mix subjected to medium traffic. Current ODOT WMA-FA mix design procedures involve determining the optimum asphalt binder content for HMA mixtures and using that asphalt binder content in the preparation of the WMA-FA mixtures. ODOT specifies using the Marshall mix design method when constructing highways that are subjected to traffic levels ranging from low to medium. Therefore, the Marshall mix design method was used in the selection of the aggregate gradation and the determination of the optimum asphalt binder content for both HMA and WMA-FA mixtures.

Four different mix design combinations were completed using the two types of aggregates and two types of asphalt binders. These combinations were selected to facilitate determining the effects of the mix type, aggregate type, and asphalt binder type on the mix performance. The mix design procedure resulted in selecting the two aggregate gradations shown in Fig. 1a and 1b for crushed limestone and natural gravel, respectively. It can be seen from this figure that the limestone aggregate gradation was significantly finer than that of the natural gravel.

Table 1 shows a summary of the mix design results. As shown in this table, higher optimum asphalt binder contents were obtained for mixtures containing crushed limestone than those containing natural gravel. As expected, the main challenge in designing the natural gravel mixes was to meet the Voids in Mineral Aggregates (VMA) requirement, whereas in the case of crushed limestone, the main challenge was to minimize the Voids in Mineral Aggregates (VMA) to obtain the lowest possible optimum asphalt binder content.

Laboratory Production of WMA-FA

As discussed earlier, WMA-FA mixtures are produced in the field using various foaming systems, such as the Astec Double Barrel Green system, Terex WMA system, and Gencor Green Machine. These devices operate by injecting small molecular-sized cold water particles into the heated asphalt. Upon contact, the cold water will evaporate forming steam which in turn forces the asphalt binder to expand and increase in volume. Therefore, the use of lower mixing and compaction temperatures can be facilitated since the viscosity of the asphalt binder is reduced.

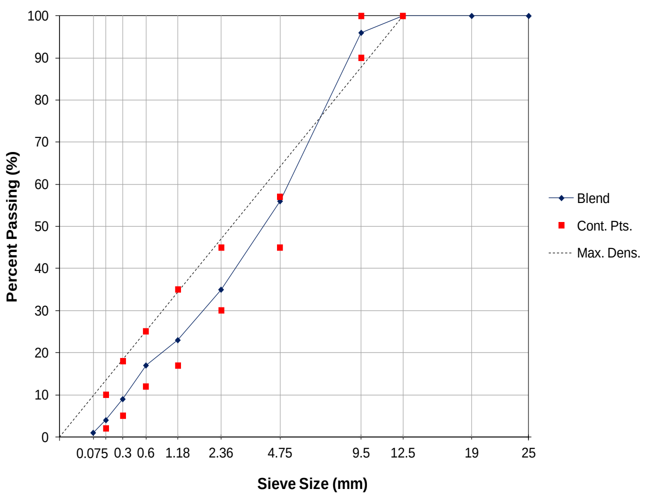
The WMA-FA mixtures were produced at 15^{o}C (30^{o}F) lower mixing and compaction temperatures than the traditional HMA mixtures. Furthermore, a foaming water content of 1.8% was used in the production of the WMA-FA mixtures. This procedure is consistent with current ODOT specifications for WMA-FA mixtures that require using a maximum foaming water content of 1.8% and a compaction temperature that is 15^{o}C (30^{o}F) lower than that of the HMA. ODOT, however, does not control the mixing temperature of the WMA-FA. It is up to the contractor to determine the appropriate mixing temperature for this material.

In this study, a laboratory scale asphalt binder foaming device was used to foam the asphalt binder (Fig. 2). In addition to foamed warm mix asphalt, this device can be used to produce half warm and cold asphalt mixes. This device utilizes a similar process in producing foamed asphalt binders to that used by the previously-mentioned field foaming devices. It consists of an asphalt binder tank, a water tank, an air tank, an asphalt pump, heating components, a foaming nozzle, air and water pressure regulators, and a control panel. To operate the device, the water tank is filled with water and the air pressure and water tanks are pressurized to the desired air and water pressures required to foam

Table 1. Mix Design Results.

Criteria	Required	Natural Gravel		Crushed Limestone	
		PG 64-22	PG 70-22M	PG 64-22	PG 70-22M
Stability (lb)	Min 1200	1673	2300	3200	4217
Flow (0.01 in.)	8-16	10.5	10.6	13	13.5
VMA (%)	Min 16 [1]	15.5	15.5	16.7	16.6
Air Voids (%)	3.5	3.5	3.5	3.5	3.5
AC% Range	5.8-10	6	6	6.4	6.5
F-T Ratio [2]	-2 to 2	+2	2	-2	-2
F/A Ratio [3]	Max 1.2	0.17	0.17	0.47	0.46

[1] ODOT C&MS specifies a minimum VMA of 16 after rounding to the nearest whole number.
[2] F-T Ratio is defined as [(% Passing #30 - % Passing #50) – (% Passing #16 - % Passing #30)].
[3] F/A Ratio is defined as % Passing #200 divided by optimum asphalt binder content.



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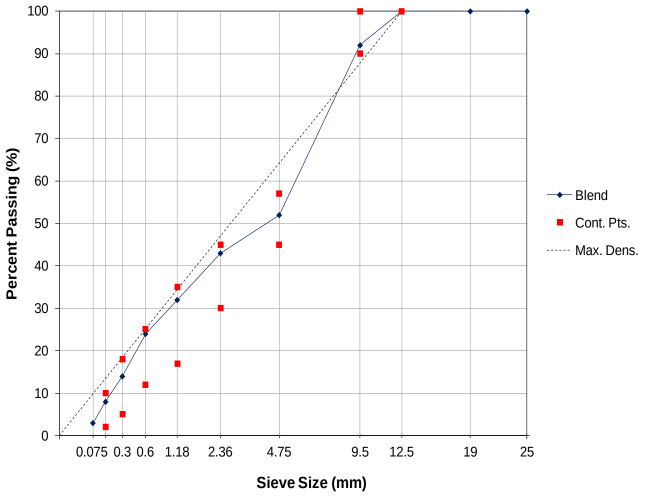


(b)

Fig. 1. Aggregate Gradation: a. Gravel, b. Limestone.

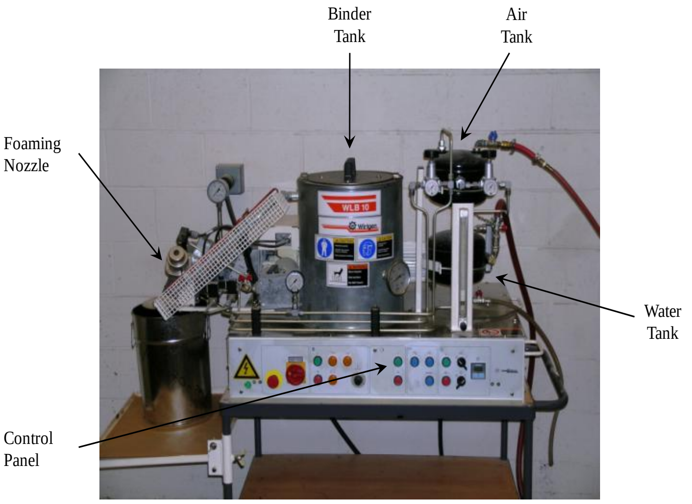


Fig. 2. Laboratory Asphalt Foaming Device.

the asphalt binder by adjusting the air and water pressure regulators (4 bars air pressure and 5 bars water pressure were used in this study). The asphalt binder tank is then heated and filled with the pre-heated asphalt binder. After heating all other components, such as the asphalt pump and the foaming nozzle, the asphalt binder is circulated through the system and the amount of water required to foam the asphalt binder is selected by adjusting the water flow regulator. The amount of foamed asphalt discharged from the foaming nozzle is controlled using a timer. In this timer, every one second results in approximately 100 grams of foamed asphalt binder to be discharged from the nozzle. Therefore, the timer is adjusted depending on the desired amount of asphalt binder to be used in the mix.

In the asphalt tank, the asphalt binder is heated to the mixing temperature provided by the asphalt binder supplier (152°C to 158°C (306°F to 317°F) for PG 64-22 and 152°C to 163°C (306°F to 325°F) for PG 70-22M) to ensure that the asphalt binder is easily circulated through the foaming device. Within the foaming nozzle, the heated asphalt binder is mixed with small molecules of cold pressurized water. Upon mixing, the cold water will vaporize forming steam, which in turn foams and expands the asphalt binder and eventually reduces its viscosity. The amount of water used to foam the asphalt binder was 1.8 percent of the total weight of the asphalt binder. This quantity represents the maximum water content permitted by ODOT in the production of WMA-FA mixtures.

Once the foaming parameters (i.e. air and water pressures, asphalt foaming temperature, and foaming water content) have been selected and the foaming device has been calibrated, the foamed asphalt binder is discharged from the foaming nozzle into a mixing bowl that contains the aggregates, which has been preheated in accordance with ODOT specifications for WMA mixtures (i.e., 15°C (30°F) less than the HMA). The mixing bowl is then transferred to a mechanical mixer for mixing. A mixing period of 3 minutes, similar to that used when preparing HMA mixtures, has shown to be sufficient when preparing WMA-FA mixtures. It is noted that the aggregates used in this study were completely dry prior to mixing with the asphalt binder.

In general, the laboratory procedure for preparing the WMA-FA mixtures was found to be satisfactory. It was noticed that the expansion ratio of PG 64-22 was slightly higher than the expansion ratio of PG 70-22M. Thus, suggesting that PG 64-22 is easier to foam. In addition, it was observed through visual inspection that both limestone and gravel aggregates were fully coated regardless of the type of the asphalt binder.

Testing Program

Various laboratory tests were performed to examine the mechanical properties of the WMA-FA and HMA mixtures. The Indirect Tensile Strength (ITS) test was conducted to examine the strength of the asphalt mixture at intermediate temperatures. The dynamic modulus (E^*) test was used to measure the stiffness of the asphalt mixture over a wide range of temperatures and loading frequencies. The modified Lottman test (AASHTO T 283) was used to evaluate the susceptibility of the asphalt mixture to moisture damage. Finally, the Asphalt Pavement Analyzer (APA) test was used to assess the high temperature permanent deformation resistance of the considered mixtures. Triplicate samples were used for each test. A brief description of each of these tests is provided below.

Indirect Tensile Strength (ITS) Test

This test was conducted at 25°C (77°F). The Marshall Compaction Hammer was used to prepare 100 mm (4 inch) by 50 mm (2.5 inch) cylindrical samples at an air void content of 7±0.5%. The samples were loaded to failure at a deformation rate of 50 mm/min (2 inch/min). The indirect tensile strength (ITS) was calculated from the peak load and the dimensions of the tested specimen.

Dynamic Modulus Test

The dynamic modulus test was conducted on unconfined cylindrical samples in accordance with AASHTO TP 62-03. The stress-strain relationship under a continuous sinusoidal loading for linear viscoelastic materials is defined by a complex number called the "complex modulus" (E^*). The absolute value of the complex modulus, $|E^*|$, is defined as the dynamic modulus. Mathematically, the dynamic modulus is defined as the dynamic stress level divided by the recoverable strain level. The $|E^*|$ tests were conducted at four different temperatures (4.4, 21.1, 37.8, and 54.4°C; 40, 70, 100, and 130°F). Testing began with the lowest testing temperature and proceeded to the highest one. At each testing temperature, six loading frequencies were applied (0.1, 0.5, 1, 5, 10, and 25 Hz), starting with the highest to the lowest frequency. A rest period of 2 minutes was used between successive frequencies. The cylindrical samples that were used in the dynamic modulus test were fabricated by coring and sawing 100 mm (4 inch) diameter by 150 mm (6 inch) high test samples from the middle of 150 mm (6 inch) diameter by 175 mm (7 inch) high Superpave gyratory compacted cylindrical samples. It is noted that the fabricated samples had an air void content of 7±0.5%.

Modified Lottman (AASHTO T 283) Test

This method evaluates the asphalt mixture sensitivity to moisture damage which is necessary to assure its durability. The modified Lottman test compares the indirect tensile strength of a dry sample and a conditioned sample that is exposed to saturation and freeze-thaw cycles. Based on the indirect tensile strength test results, a tensile strength ratio (TSR) is computed. The TSR ratio is defined as the ratio of the original tensile strength that is retained after the moisture and freeze thaw conditioning. For laboratory samples, state highway agencies typically specify a minimum TSR of 0.70 or 0.80.

Asphalt Pavement Analyzer (APA) Test

The Asphalt Pavement Analyzer (APA) is the new generation of the Georgia Loaded Wheel Tester. It simulates actual road conditions by rolling a concave-shaped metal wheel at a speed of approximately 60 cm/sec (23.5 in/sec) over a rubber hose pressurized at 689.5 kPa (100 psi) to 827.4 kPa (120 psi) to generate the effect of high tire pressure. The hose stays in contact with the sample's surface while the metal wheel rolls back and forth along the length of the hose for 8,000 cycles. The APA can test three beam samples or six cylindrical samples simultaneously. Superpave Gyratory compacted cylindrical samples 150 mm (6 inch) by 75 mm (3 inch) were prepared at an air void content of 6±1% and used in the APA tests. Testing was conducted at a temperature of 48.9°C (120°F).

Mix Workability and Compactability

It was evident through handling that the WMA-FA mixtures were more workable than the HMA mixtures even though they were produced at lower temperatures. The compactability of the WMA-FA mixtures was examined using the results obtained from the Superpave Gyratory Compactor (SGC) and the Marshall Compaction Hammer. In the case of the HMA, a compaction temperature ranging from 141.1°C to 145.6°C (286°F to 294°F) was used for PG 64-22 and a compaction temperature ranging from 141.1°C to 152.2°C (286°F to 306°F) was used for PG 70-22M. The compaction temperature of the WMA-FA mixtures was 15°C (30°F) lower than that of the HMA. Table 2 presents the number of gyrations in the SGC and the number of blows per side in the Marshall Compaction Hammer that was used in the sample preparation for the considered performance tests. As can be seen in this table, significantly lower compaction efforts were needed to achieve the target air void levels in the case of the WMA-FA

Table 2. Required Compaction Effort to Achieve Target Air Voids.

Mix Type	Aggregate Type	Binder Type	No. of Blows[1]	No. of Gyrations[2]	Rice Specific Gravity
HMA	Gravel	PG 64-22	18	19	2.405
		PG 70-22M	20	12	2.407
	Limestone	PG 64-22	18	11	2.472
		PG 70-22M	18	8	2.466
WMA-FA	Gravel	PG 64-22	13	11	2.396
		PG 70-22M	15	9	2.401
	Limestone	PG 64-22	10	4	2.461
		PG 70-22M	9	4	2.459

[1] Number of blows per face required to achieve 7±1% air void content in the AASHTO T 283 test specimens.
[2] Number of gyrations required to achieve 6±1% air void content in the APA test specimens.

Table 3. Asphalt Binder Absorption in HMA and WMA-FA Mixtures.

Mix Type	Aggregate Type	Binder Type	Asphalt Binder Absorption (%)[1]
HMA	Gravel	PG 64-22	0.67
		PG 70-22M	0.71
	Limestone	PG 64-22	0.73
		PG 70-22M	0.69
WMA-FA	Gravel	PG 64-22	0.50
		PG 70-22M	0.61
	Limestone	PG 64-22	0.53
		PG 70-22M	0.57

[1] Asphalt binder absorption by dry weight of aggregates.

mixtures as compared to the HMA mixtures. On average, a 30% reduction in the number of gyrations or blows was noticed for mixtures containing gravel. Meanwhile, a 50% reduction in the number of gyrations or blows was observed for mixtures containing limestone. It is believed that the presence of bubbles entrapped within the foamed asphalt binder, even after mixing with the aggregates, was the main contributor to the improvement in workability and compactability of the WMA-FA mixtures.

Table 2 also shows the Rice specific gravity values for both WMA-FA and HMA mixtures. As can be seen in this table, the Rice specific gravity values for the WMA-FA mixtures were slightly lower than those for the HMA mixtures. This slight reduction in Rice specific gravity supports the belief that there are some remaining entrapped air bubbles within the foamed asphalt binder even after mixing with the aggregates. It is noted though that some of the air bubbles present within the WMA-FA may escape during compaction, which might increase the maximum theoretical specific gravity. Hence, using the Rice specific gravity obtained after mixing might lead to inaccurately lowering the compaction effort needed to achieve a target air voids level. Another factor that might have contributed to the reduction in the Rice specific gravity and the improved workability and compactability of the WMA-FA is the reduced amount of asphalt binder absorbed by the aggregates in the case of the WMA-FA mixtures. The asphalt binder absorption by weight of aggregate, P_{ba}, in both WMA-FA and HMA mixtures was calculated from the bulk and effective specific gravities of the aggregates (Table 3). It was found that the percentage of asphalt binder absorbed by the aggregates in WMA-FA mixtures was less than that in HMA mixtures. Although no coating problems have been observed, the reduction in the amount of asphalt binder absorbed might result in less bonding between the aggregates and the asphalt binder. As a consequence, WMA-FA mixtures might be more prone to moisture induced damage when compared to traditional HMA mixtures.

Results and Discussion

The following subsections present the results of the various tests conducted. In addition, they provide the results of the Analysis of Variance (ANOVA) that was conducted using the Statistical Analysis Software (SAS) to examine the effect of mix type, aggregate type, and binder type on the experimental test results.

ITS Test Results

Fig. 3 presents the average indirect tensile strength values for the considered mixtures at 25°C (77°F). Higher ITS values are desirable as they correspond to a strong and durable mixture. As can be seen in this figure, the WMA-FA mixtures exhibited lower ITS values than the HMA mixtures, except for the WMA-FA and HMA gravel mixtures prepared using PG 70-22M, which had similar ITS values. This reduction in ITS values for WMA-FA mixtures is mainly attributed to the softening of the asphalt binder due to foaming. It can also be seen in the same figure that the ITS values for the limestone specimens were higher than those for the gravel specimens. This is expected due to the greater interlock within the limestone aggregate structure.

The ANOVA analysis was conducted to evaluate the effect of the mix type (HMA or WMA-FA), aggregate type, and binder type on the ITS values, as shown in Table 4. As can be noticed in this table, the effect of the binder and mix types and their interaction was significant at 95% confidence level ($Pr < 0.05$). Table 4 also shows that the binder type was the most significant factor affecting the ITS values, as indicated by the F-value.

Dynamic Modulus Test Results

Fig. 4 presents the dynamic modulus master curves at a reference temperature of 21.1°C (70°F) for both WMA-FA and HMA mixtures prepared using gravel and limestone. The master curves were constructed by fitting a sigmoidal function to the shifted dynamic moduli. As can be seen from this figure, the dynamic modulus of the WMA-FA mixtures were very close to those obtained of the HMA mixtures. This figure also shows that the dynamic modulus was

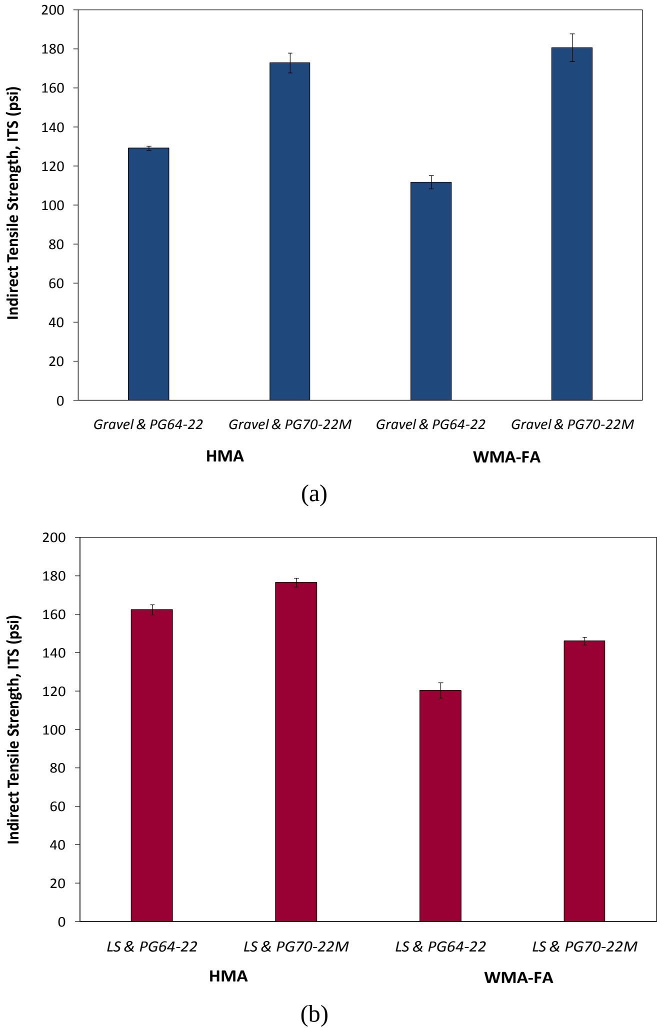


Fig. 3. ITS Test Results: a. Gravel, b. Limestone.

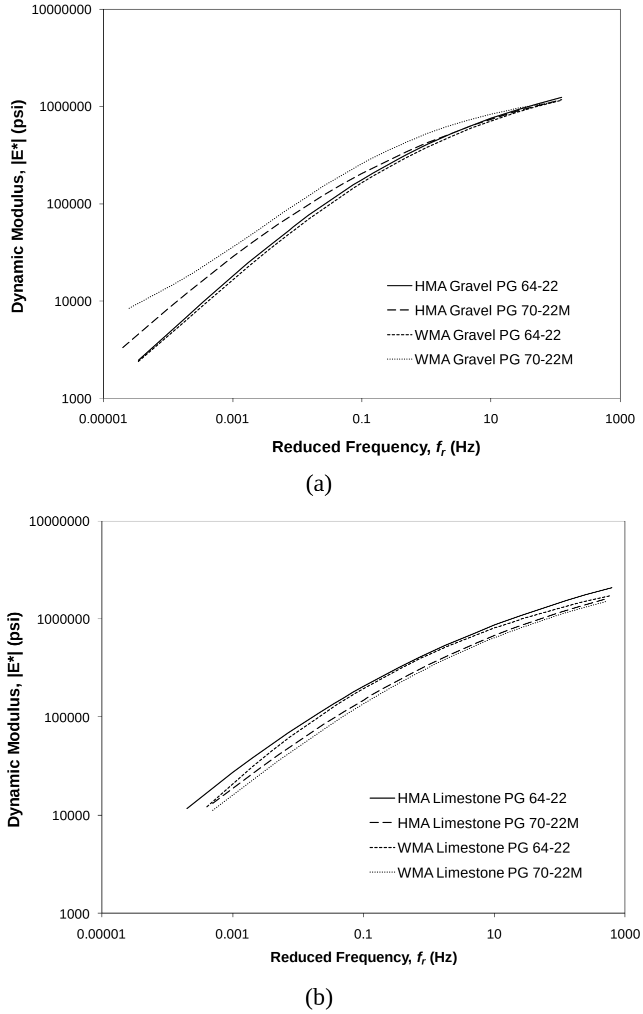


Fig. 4. Dynamic Modulus Master Curves: a. Gravel, b. Limestone.

Table 4. Results of ANOVA for ITS Tests.

Effect	F-Value	Probability (Pr)
Mix	85.86	<.0001
Aggregate	1.50	0.2382
Binder	294.68	<.0001
Mix * Aggregate	50.07	<.0001
Mix * Binder	17.32	0.0007
Aggregate * Binder	67.11	<.0001
Mix * Aggregate * Binder	2.35	0.1448

mainly affected by the aggregate type and to a less extent by the type of asphalt binder. For instance, limestone mixtures exhibited higher $|E^*|$ values than gravel mixtures. As for the effect of the asphalt binder, slightly higher $|E^*|$ values were obtained for PG 70-22M than for PG 64-22 in the gravel mixtures, while slightly higher $|E^*|$ values were obtained for PG 64-22 than for PG 70-22M in the limestone mixtures.

The ANOVA analysis was conducted to evaluate the effect of mix type, aggregate type, and binder type on the $|E^*|$ values obtained at a temperature of 21.1^{o}C (70°F) and a frequency of 10 Hz. The statistical analysis results are summarized in Table 5. It is noted that the effect of the aggregate type, the binder type and their interaction was significant. As indicated by the F-value, the aggregate type seems to have the most significant influence on the $|E^*|$ values at 10 Hz. The results in Table 5 also show that the $|E^*|$ values of the WMA-FA and HMA were statistically the same. Similar results were obtained at other frequencies. Therefore, they were not included in this paper.

Moisture Susceptibility Test Results

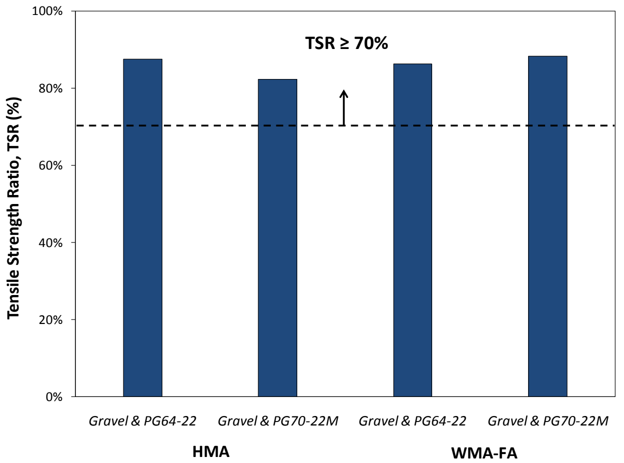
Fig. 5 presents the tensile strength ratio (TSR) values obtained using AASHTO T 283 for both WMA-FA and HMA mixtures. The reader is referred to reference no. [10] for detailed volumetric data as well as dry and wet strength values for individual test specimens. This figure shows that the TSR values for the WMA-FA mixtures were close to those obtained for the HMA mixtures. It also shows that the TSR values for limestone were lower than those for gravel mixtures, which can be attributed to the finer aggregate gradation and the higher asphalt content in the limestone mixtures. It is noted that both WMA-FA and HMA mixtures met the minimum TSR requirement of 0.7 specified in ODOT C&MS for medium traffic. Therefore, although the use of WMA-FA technology lowers the TSR ratio, if designed properly WMA-FA mixtures are still capable of meeting the minimum TSR requirement.

Table 5. Results of ANOVA for Dynamic Modulus Tests.

Effect	F-Value	Probability (Pr)
Mix	1.19	0.2909
Aggregate	49.65	<.0001
Binder	5.54	0.0317
Mix * Aggregate	0.78	0.3910
Mix * Binder	0.16	0.6932
Aggregate * Binder	7.73	0.0134
Mix * Aggregate * Binder	0.33	0.5763

Table 6. Results of ANOVA for Moisture Susceptibility Tests.

Effect	F-Value	Probability (Pr)
Mix	0.31	0.5849
Aggregate	49.81	<.0001
Binder	0.78	0.3915
Mix * Aggregate	4.92	0.0413
Mix * Binder	0.27	0.6074
Aggregate * Binder	0.01	0.9300
Mix * Aggregate * Binder	3.51	0.0794



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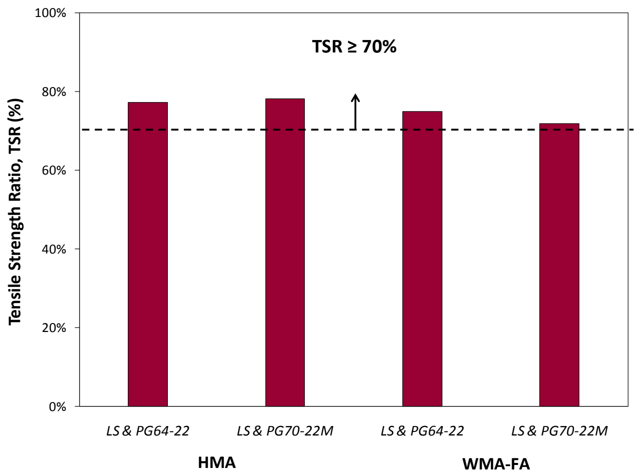


(b)

Fig. 5. Moisture Susceptibility Test Results: a. Gravel, b. Limestone.

Table 6 presents the ANOVA analysis results of the TSR data. It can be noticed that the aggregate type had a significant effect on the TSR value of the considered mixtures. In addition, the effect of the interaction between the aggregate type and the mix type was statistically significant. This suggests that although foaming did not, in general, affect the TSR value, its effect on the TSR value changed when using gravel rather than limestone. This indicates that the performance of WMA-FA mixtures with regard to moisture induced damage is affected by the selection of the aggregate type.

Rutting Susceptibility Test Results

Fig. 6 presents the APA rut depths for both WMA-FA and HMA mixtures. In this figure, it can be seen that WMA-FA mixtures were more susceptible to rutting than HMA mixtures. This may be attributed to the softening of the asphalt binders due to foaming, lower asphalt binder absorption, and reduced binder aging due to the use of lower production temperatures in the case of the WMA-FA mixtures. Fig. 6 also shows that WMA-FA mixtures containing gravel were more susceptible to rutting than those containing crushed limestone. This is mainly due to the greater interlock within the crushed limestone aggregate structure than that within the natural gravel. Moreover, Fig. 6 shows that mixtures containing PG 64-22 were more susceptible to rutting than those containing PG 70-22M, which is expected since the latter is a polymer modified asphalt binder with a higher PG grade.

Table 7 presents the results of the ANOVA analysis that was conducted to assess the effect of the different factors on the rutting depth obtained in the APA test. It can be noticed that the mix type, aggregate type, and binder type significantly affected the rutting depth. However, the effect of the aggregate and binder types is more significant than the mix type, as indicated by the F-value. This result suggests that using appropriate aggregate and binder types can help in overcoming any adverse effects that WMA-FA have on the mixture performance.

Summary and Conclusions

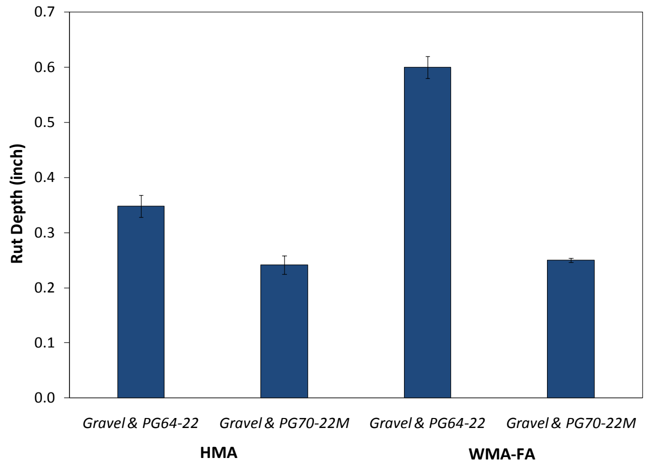
This paper presented a procedure to produce WMA-FA mixtures in the laboratory. The mixtures produced using this procedure were evaluated in comparison to traditional HMA mixtures using the Indirect Tensile Strength, the Dynamic Modulus, the Modified Lottman, and the APA tests.

Based on the experimental test results and the subsequent statistical analyses findings, the following conclusions were made:

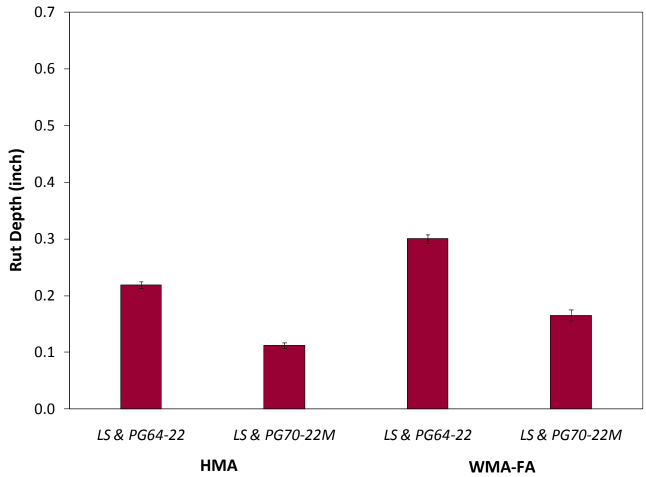
- Both neat and polymer modified asphalt binders (PG 64-22 and PG 70-22M, respectively) were successfully foamed using the laboratory asphalt foaming device. The neat asphalt binder had a higher expansion ratio than the polymer modified asphalt binder, which suggests that the neat asphalt binder is easier to foam than the polymer modified asphalt binder.
- Aggregates in WMA-FA mixtures were fully coated after mixing in a mechanical mixer for 3 minutes even though the mixing temperature was 15^{o}C (30^{o}F) lower than that for HMA mixtures.
- WMA-FA mixtures had slightly lower Rice specific gravities than HMA mixtures. This might have been caused by two

Table 7. Results of ANOVA for APA Tests.

Effect	F-Value	Probability (Pr)
Mix	187.17	<.0001
Aggregate	495.67	<.0001
Binder	582.88	<.0001
Mix * Aggregate	18.91	0.0005
Mix * Binder	88.21	<.0001
Aggregate * Binder	55.17	<.0001
Mix * Aggregate * Binder	55.54	<.0001



(a)



(b)

Fig. 6. APA Rut Depths: a. Gravel, b. Limestone.

factors. First, the presence of entrapped air bubbles within the foamed asphalt binder even after mixing. Second, a slight reduction in the amount of asphalt binder absorbed by the aggregates in the case of WMA-FA mixtures.

- WMA-FA mixtures were found to be more workable and easily compacted in comparison to HMA mixtures even though the mixing and compaction temperatures were 15°C (30°F) lower than the HMA mixtures.
- Lower ITS values were obtained for the WMA-FA mixtures than for the HMA mixtures. This is probably due to the softening of the asphalt binder as a result of foaming.
- The difference between the |*E**| values of WMA-FA and HMA mixtures was statistically insignificant.
- WMA-FA mixtures were slightly more susceptible to moisture induced damage than HMA mixtures. However, both mixtures met ODOT minimum TSR criterion of 0.7 for medium traffic.
- WMA-FA mixtures exhibited higher rut depths in the APA test than the HMA mixtures. This may be attributed to the softening of the asphalt binders due to foaming, lower asphalt binder absorption, and reduced binder aging due to the use of lower production temperatures in the case of the WMA-FA mixtures.
- WMA-FA mixtures were more prone to rutting than HMA mixtures. However, the results suggested that using an appropriate type of aggregate and asphalt binder can address any adverse effects from using the foaming technology.
- Therefore, it is recommended to modify the current WMA-FA mix design procedure to include an indirect tensile strength test and/or a permanent deformation test to ensure satisfactory field performance.

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