PERFORMANCE EVALUATION OF VESTENAMER (TOR) USING DRY AND WET MIXING PROCESSES IN HOT MIX ASPHALT

- Preliminary Results -

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PROPOSED RESEARCH

A research study was conducted to evaluate the addition of VESTENAMER® (TOR) to asphalt rubber (AR-HMA). The addition of the VESTENAMER® (TOR) to the AR-HMA was conducted for both a dry mix process and a wet mix process, as defined by Hicks (2004). The dry process is defined as mixing 4.5% of VESTENAMER® (TOR), by weight of the crumb rubber, and 20% crumb rubber, by weight of the asphalt binder, directly with the aggregate used for the hot mix asphalt. The reaction of the VESTENAMER® (TOR), crumb rubber, and asphalt binder takes place in the presence of the aggregates. The wet process is defined as adding the 4.5% VESTENAMER® (TOR), by weight of the crumb rubber, and 20% crumb rubber, by weight of the asphalt binder, to the asphalt binder prior to mixing. The VESTENAMER® (TOR) and crumb rubber are allowed to react with the asphalt binder for approximately one hour. After the reaction time has taken place, the blended binder mixture (VESTENAMER® + crumb rubber + asphalt binder) is mixed with the aggregate. Both the dry and wet processes are currently used mixing methods at hot mix asphalt plants when using asphalt rubber. The results of the study is to provide guidance as to which mixing method provides a better performing AR-HMA. The results of the study will also be shared with the New Jersey Department of Transportation (NJDOT) in an effort to promote the use of crumb rubber hot mix asphalt in New Jersey.

MATERIALS

In the past, the New Jersey Department of Transportation (NJDOT) has added crumb rubber only to open-graded friction course (OGFC) asphalt mixes. The aggregate structure of the OGFC is like its name, open. It is a very, poorly graded gradation, with the overall goal of having a final air void content greater than 18 %. This provides a large amount of internal space for the crumb rubber. The SMA is another poorly graded mix that utilizes stone-on-stone contact to provide a rut resistant mix. The stone-on-stone design also allows a large amount of internal space for the crumb rubber to reside. However, these two mixes are only used in small quantities at particular highway locations.

The most common asphalt mix type used by the NJDOT is the 12.5mm surface coarse mix. This mix type may be used in almost any location, and is most commonly found as the surface course. It is used for both new construction and rehabilitation projects. Therefore, to provide the greatest potential for using the most crumb rubber possible, the 12.5mm surface course mix was selected.

The final aggregate gradation selected for the mix design is shown in Figure 1. It is a 12.5mm Superpave mix, however, the nature of the gradation is coarse/open. Also shown in the figure are the two crumb rubber mixes currently in service in New Jersey. Both mixes are OGFC and have a much different gradation characteristic than the 12.5mm gradation selected for analysis.

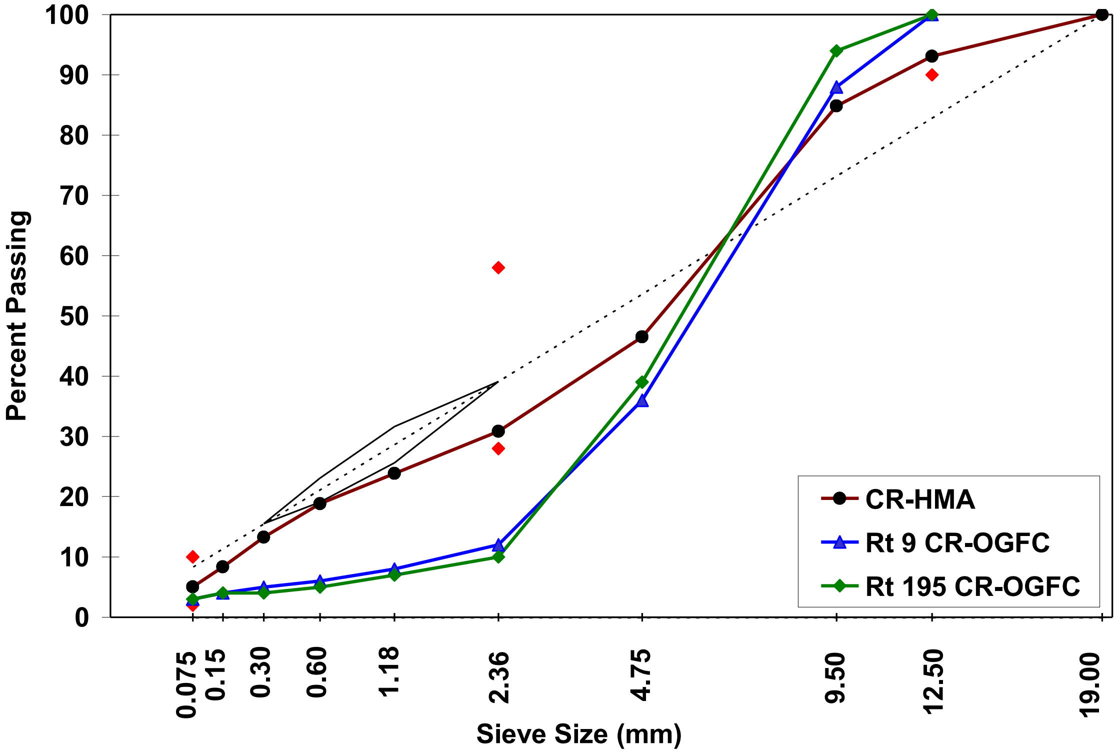

Figure 1 – Aggregate Gradation Used for the 12.5mm Superpave Design (CR-HMA)

MIXTURE DESIGN AND VOLUMETRIC RESULTS

To evaluate the potential benefit of adding the VESTENAMER® (TOR) to a asphalt rubber hot mix asphalt (AR-HMA), it was proposed to test two baseline mixes, as well as the following:

- PG64-22 + 20% Ground Tire Rubber (GTR) – mixed using the wet process, called AR-HMA #1
- PG64-22 + 20% (GTR) + 4.5% VESTENAMER® (TOR) – mixed using the wet process, called AR-HMA #2
- PG64-22 + 20% (GTR) + 4.5% VESTENAMER® (TOR) – mixed using the dry process, called AR-HMA #3

A mix design was conducted to determine the optimum asphalt binder content of the PG64-22 + 20% GTR under the wet and dry mix conditions. All AR-HMA mixtures utilized a #30 mesh crumb. The Superpave mixture design was also conducted on the baseline mixes, which were constructed using the identical aggregate gradation but had asphalt binders with a performance grade of PG64-22 and PG76-22. The final volumetric parameters at optimum asphalt content are shown in Table 1.

The TSR (Tensile Strength Ratio) is a method used to determine the potential for moisture damage. In this procedure, conditioned and unconditioned samples are tested for their respective tensile strength. If the ratio between the conditioned versus unconditioned samples is less than 80%, the asphalt mix is considered to be susceptible to future moisture damage/pre-mature aging and the mixture design/material selection should be re-run.

The results from the Superpave mix design show that the asphalt rubber mixes require a higher amount of asphalt binder than the baseline mixes. This is typical for asphalt rubber mixes. The TSR results indicate that AR-HMA wet process with TOR provided the best moisture resistant mixture. The addition of the TOR to the AR-HMA mixture increased the TSR results by 5.6%. The asphalt mix with the lowest TSR values was the PG64-22 mix.

Table 1 – Final Volumetric Properties of Baseline Samples

			AR-HMA		
Volumetric Property	PG76-22	PG64-22	#1	#2	#3
Asphalt Content (%)	5.1	5.1	6.1	6.1	5.7
VMA (> 14%)	15.7	15.7	17.9	17.9	17.9
VFA (65 to 75%)	74.3	74.3	77.4	77.4	77.7
Dust/Binder (0.6 to 1.2%)	1.1	1.1	0.9	0.9	1.0
TSR (> 80%)	96	87.3	93.1	98.7	95.4

PERFORMANCE TESTS

Two different performance tests will be conducted on the samples; 1) the Superpave Shear Tester (SST) using the Frequency Sweep at Constant Height (FSCH) mode and 2) the SST using the Repeated Shear at Constant Height (RSCH) mode.

Superpave Shear Tester

In 1987, SHRP began a 5 year, $50 million study to address and provide solutions to the performance problems of HMA pavements in the United States (FHWA-SA-95-003, 1995). As part of the study, the Superpave Shear Tester (SST) was developed to become the performance test used in the mix design process. The initial testing required a total of 6 different tests (*AASHTO M-003, Determining the Shear and Stiffness Behavior of Modified and Unmodified Hot Mix Asphalt in the Superpave Shear Test*). The tests included:

1. Uniaxial
2. Hydrostatic
3. Repeated Shear at Constant Stress Ratio (RSCSR)
4. Frequency Sweep at Constant Height (FSCH)
5. Simple Shear at Constant Height (SSCH)
6. Repeated Shear at Constant Height (RSCH)

The first two tests, as well as the Simple Shear, were mainly used for modeling purposes within the Superpave modeling program. However, test complexities associated with industry use resulted in eliminating the first three tests. The test now only utilizes the SSCH, FSCH, and RSCH modes (AASHTO TP7-01).

The SSCH test evaluates the creep properties of the asphalt mix under at varying (low to moderate) temperatures. The FSCH test evaluates the shear stiffness of the asphalt mix at varying (low to high) temperatures. The RSCH test evaluates the asphalt mixes ability to resist permanent deformation (rutting) at high temperatures.

The development and selection of the Superpave Shear Tester (SST) by the SHRP researchers was based on the device having the capability of measuring properties under states of stress that are encountered within the entire rutting zone of the pavement, particularly near the surface. Since there are an infinite number of states of stress that could exist within the pavement, it would be impossible to truly simulate all of them considering the non-linear and viscous behavior of HMA. Realizing this (Sousa et al., 1993) the SHRP researchers concentrated on the most important aspects and simulative conditions of the HMA behavior.

The following summary of factors which significantly affect the behavior of HMA was taken from the SHRP research product entitled, *Accelerated Performance-Related Tests for Asphalt-Aggregate Mixes and Their Use in Mix Design and Analysis Systems, SHRP-A-417.*

1. Specimen Geometry: a) A six inch by 2 inch specimen can easily be obtained from any pavement section by coring, or from any typical compaction method; b) the state of stress is relatively uniform for the loads applied; c) the magnitude of loads needed to be applied can easily be achieved by the use of normal hydraulic equipment.
2. Rotation of Principle Axis: The test set-up permits the controlled rotation of principal axes of strain and stress which represent the conditions that impact rutting.
3. Repetitively Applied Loads: Work by the SHRP researchers has indicated that to accurately capture the rutting phenomena, repetitive loads are required. This type of loading is needed given the viscous nature of the binder (load frequency dependent) and also granular nature of the aggregate (aggregates behave differently under static and dynamic loading).
4. Dilation: As discussed earlier, the dilation plays an important role in the rutting behavior of HMA. The SST constrains the dilation, and by doing so, confining stresses are developed. It is in part due to the development of these confining stresses that a mix derives most of its stability against rutting. The SST allows this by implying a constant height on the specimen while under going a shear stress. In the constant height regime, the development of axial stresses (confining stress in the SST) is fully dependent on the dilatency characteristics of the HMA. A vertical LVDT is positioned on the specimen to measure the dilation. This in turn props the axial actuator to either create a compressive or tensile force on the

> sample, depending on the volume change characteristic of the specimen. In this configuration, the HMA will either resist permanent deformation by relying on the high binder stiffness to minimize shear strains or the aggregate structure stability developed by the axial stresses from the dilation. In the constant height test, these two mechanisms are free to fully develop their relative contribution to the resistance of permanent deformation.

Figure 2 is an illustration of the SST device with an asphalt sample ready for testing.

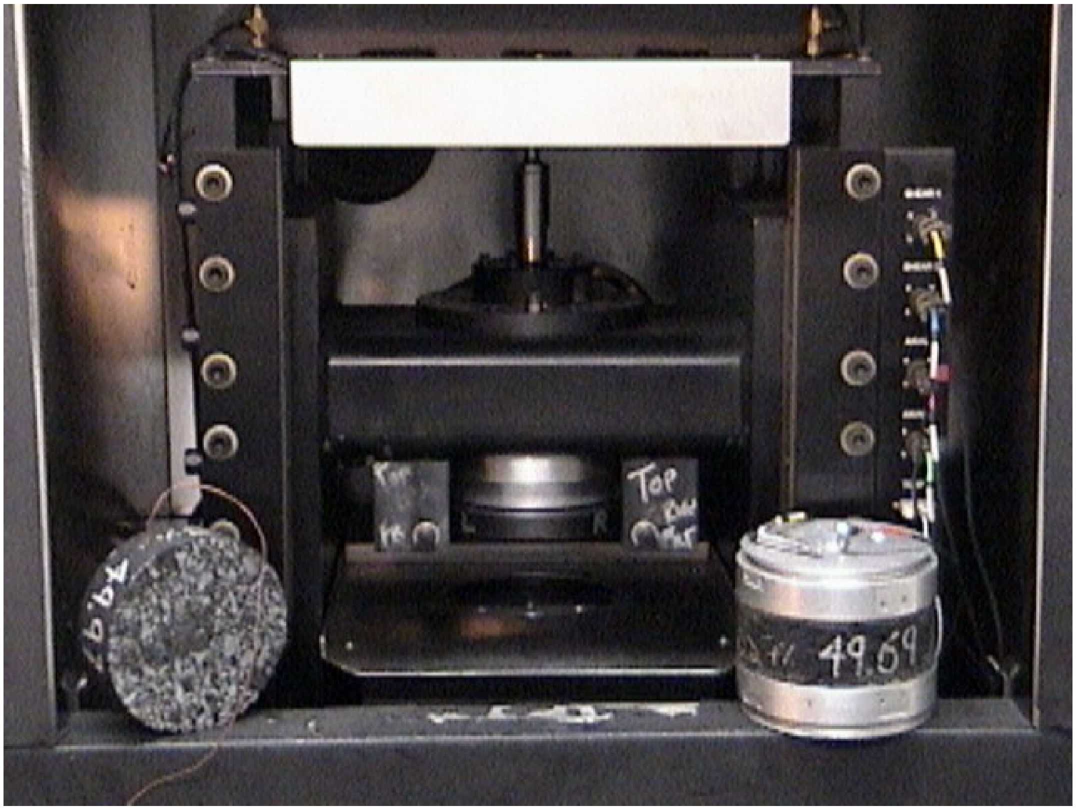

Figure 2 – Superpave Shear Tester (SST) at the Rutgers Asphalt/Pavement Laboratory

<u>Frequency Sweep at Constant Height (FSCH)</u>

Background of FSCH

The FSCH test procedure was conducted at 4, 20, 40, and 64ºC. At each test temperature, a strain-controlled sinusoidal wave-form is applied at a loading rate of 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz. The sample is loaded to achieve a shear strain of 100 micro-strain. From this, the dynamic shear modulus and the phase angle are determined.

Mathematically, the dynamic shear modulus is defined as the maximum (peak) dynamic shear stress (τ_o) divided by the peak recoverable shear strain (γ_o), as shown as equation (1).

$$G^* = \frac{\tau_O}{\gamma_O} \qquad (1)$$

Under this loading regime, the sinusoidal shear stress at any given time, t, can be defined as:

$$\tau_t = \tau_O \sin(\omega t) \qquad (2)$$

where,

τ_O = peak dynamic shear stress amplitude;
ω = angular frequency in radian per second; and
t = time (second)

The resultant dynamic shear strain at any time is given by:

$$\gamma_t = \gamma_O \sin(\omega t - \phi) \qquad (3)$$

where,

γ_O = recoverable strain (in/in)
ϕ = phase lag or angle (degrees)

The phase angle is simply the angle at which the γ_O lags τ_O and is an indicator of the viscous or elastic properties of the material being evaluated. For pure elastic material, $\phi = 0^o$. This condition would occur at very low temperatures for asphalt materials. For pure viscous materials, $\phi = 90^o$. This condition would occur at very high temperatures for asphalt materials.

Both the dynamic shear modulus (G*) and the phase angle (ϕ) can be used to evaluate the performance of the HMA material at different test temperatures. For example, when comparing the performance at low temperatures, an engineer would prefer an HMA material to obtain a lower G* and a higher ϕ. This would be an indication of lower stiffness. Lower stiffness at low temperatures would aid in minimizing fatigue cracking. Meanwhile, when comparing materials at high temperatures, an engineer would prefer that the HMA material obtain a higher G* and a lower ϕ. This would indicate a stiffer material. A stiffer HMA at high temperatures would aid in resisting permanent deformation.

After the sample has been tested over a range of temperatures, a master stiffness curve can be developed. The master stiffness curve of HMA allows for the comparison of visco-elastic materials when testing has been conducted using different loading frequencies and temperatures. The master curve can be constructed using the time-temperature superposition principle. This principle suggests that the temperature and loading frequency of visco-elastic materials are interchangeable.

The data from the FSCH tests can be “shifted” relative to the time of the frequency, so that the various curves can be aligned to form a single “master curve” (Pellinen, 2001).

Repeated Shear at Constant Height (RSCH)

Background of RSCH Test

The RSCH test involves applying a repeated haversine shear stress of 10 psi a sample that has the dimensions of 150 mm in diameter and 50 mm in height. The applied load has a duration of 0.1 seconds, with an unload time of 0.6 seconds. An axial load is applied to the sample during the test to ensure a constant height is obtained at all times. The test procedure followed for this test was AASHTO TP7-01, Test Procedure C. The HMA sample is tested at a test temperature that corresponds to local pavement temperatures.

For this study, samples were tested at the high temperature performance grade used for New Jersey (64°C). The shear stress is applied to the sample for 5,000 loading cycles, or until the sample reaches 5% permanent shear strain. Work conducted by a number of researchers (Harvey et al., 1994; Monismith et al., 2000; Witzcak et al., 2002) has indicated the RSCH to be an excellent tool in determining rut susceptible HMA mixes. For this study, the test was expanded to 6,000 cycles. The parameter used for evaluation from the test is the % permanent shear strain that has occurred at 5,000 loading cycles.

PERFORMANCE TEST RESULTS

All samples were compacted, cut and trimmed to a final air void content of 4% (+/- 0.5%).

Superpave Shear Tester

Two modes of testing were conducted in the Superpave Shear Tester; 1) Frequency Sweep at Constant Height (FSCH) and 2) Repeated Shear at Constant Height (RSCH). Both the small-strain stiffness testing (FSCH) and the permanent deformation testing (RSCH) were conducted on the identical samples. The samples were first tested under the FSCH at test temperatures of 20, 40, and 52°C. The RSCH test was conducted at a test temperature of 64°C.

Prior to testing, the samples were allowed to equalize at the required test temperature. A “dummy” sample with a thermister embedded into its center was used to determine when the samples had equalized in temperature. Typically, once the “dummy” sample had reached test temperature, another 30 minutes was allowed to expire before testing resumed.

Frequency Sweep at Constant Height (FSCH) – Test Results

Three distinct parameters, as well as the overall master stiffness curve, were used to compare and rank the different mixes. The main three parameters were 1) the shear modulus (G*) at 52ºC at a loading frequency of 5 Hz, 2) the rutting parameter at 52ºC, which is defined as G*/sin ϕ (where G* is the shear modulus and ϕ is the phase angle) at a loading frequency of 5 Hz, and 3) the shear modulus (G*) at 40ºC and at a loading frequency of 10 Hz.

Recent work under NCHRP project 9-29 "Simple Performance Tester for Superpave Mix Design" has indicated that both G* and G*/sin ϕ, when measured at 52ºC and a loading frequency of 5 Hz, provide a good correlation to rutting in the field (Witczak et al, 2002). HMA samples that obtained higher values of G* and/or G*/sin ϕ were less prone to rutting than samples that obtained lower values.

Utilizing the same test procedure, the Indiana Department of Transportation (INDOT) has found that measuring the shear modulus (G*) at 40ºC and a loading frequency of 10 Hz can indicate the overall stability of the compacted HMA (McDaniel et al, 2003). Work previously conducted by the Asphalt Institute and the Heritage Research Group during the initial implementation of Superpave indicated that HMA mixtures placed in the field that obtained a G* greater than 36,200 psi showed minimal rutting after six years of service life (Anderson et al., 2000).

The master stiffness curves developed from the FSCH test results are shown in Figure 5. In evaluating the stiffness performance of the master stiffness curve, it is important to remember the following.

- Since the data is shifted to one respective test temperature, the loading frequency essentially "represents" the test temperature. The lower the loading frequency, the higher the test temperature.
- HMA materials with a higher stiffness at high temperatures will be able to resist permanent deformation better than HMA materials with a lower stiffness. HMA materials with a lower stiffness at lower temperatures will be able to resist low temperature cracking better than HMA materials with a higher stiffness.

In the case of the testing in this study, the lowest test temperature utilized in the SST was 20ºC. Therefore, an assessment of the low temperature performance is not possible.

All of the AR-HMA samples had a shear stiffness at high temperatures either equal to or greater than the polymer-modified PG76-22 samples. However, the AR-HMA with TOR obtained the largest values, indicating that this material had the best rut resistant properties at high temperatures. The PG64-22, which was the baseline asphalt binder used to produce the asphalt rubber, obtained the lowest shear stiffness values.

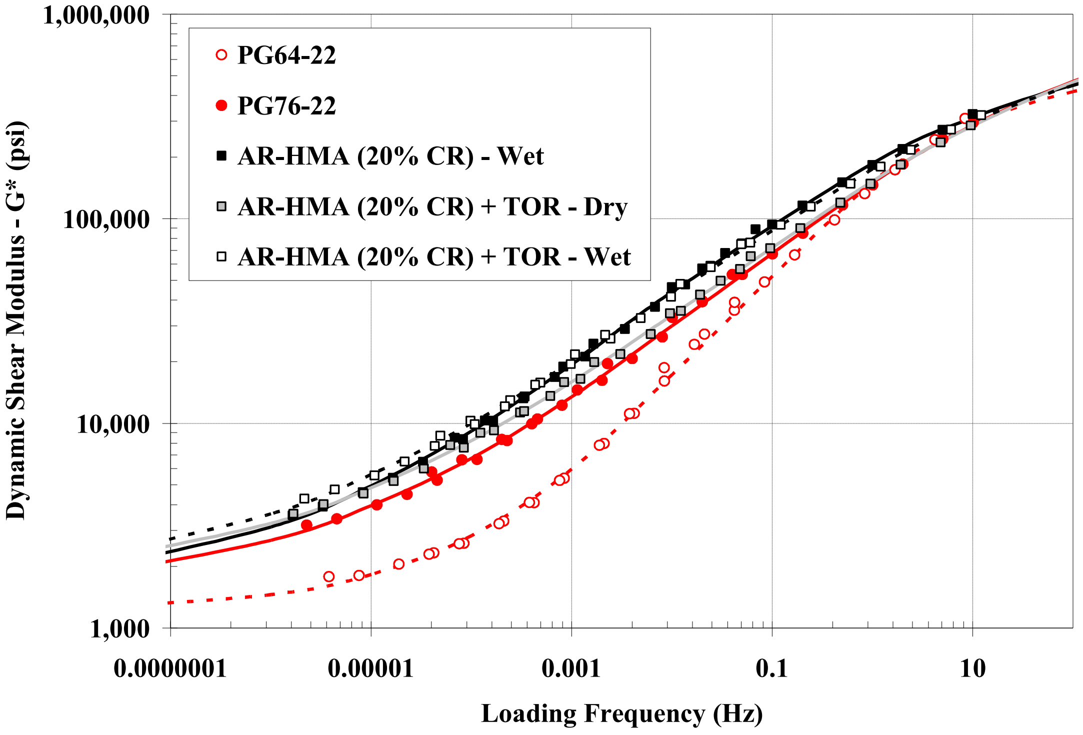

Figure 5 – Master Shear Stiffness Curve for Data from the SST FSCH Test

Table 2 and Figure 6 include the calculated performance parameters from the FSCH as defined earlier. When comparing the test parameters that were established during the NCHRP 9-27 project, the AR-HMA with TOR using the wet process obtained the highest values, indicating that this material would develop the lowest amount of rutting in the field.

All samples met the minimum shear stiffness established by the INDOT (32,800 psi at 40ºC and 10 Hz), and therefore, based on the INDOT's experience, should be stable and sustain minimum permanent deformation. When comparing the absolute values under these test conditions, the AR-HMA using the wet process obtained the largest shear stiffness, with the AR-HMA + TOR using the wet process recording the second largest shear stiffness. Once again, the PG64-22 sample had the lowest shear stiffness at a test temperature of 40ºC and a loading frequency of 10 Hz.

Table 2 – Rutting Performance Parameters Determined from the SST FSCH Test

Mix Type	Air Voids (%)	Binder Content (%)	FSCH - NCHRP 9-27 Project		FSCH - INDOT
			G* (52°C @ 5 Hz) (psi)	G*/sinφ (52°C @ 5 Hz) (psi)	G* (40°C @ 10 Hz) (psi)
PG 64-22	4.1	5.1	6,747	8,204	32,767
	3.6	5.1	8,856	11,373	45,051
	3.8	5.1	---	---	39,067
PG 64-22 Ave.	***3.8***	***5.1***	***7,802***	***9,789***	***38,962***
PG76-22	3.6	5.1	14,078	20,376	49,157
	3.7	5.1	15,007	22,108	57,348
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PG 76-22 Average	***3.6***	***5.1***	***14,543***	***21,242***	***53,253***
AR-HMA (20% CR) - Wet	3.7	6.1	15,526	22,286	92,412
	4.0	6.1	21,878	33,888	95,284
	4.4	6.1	19,335	30,250	78,153
AR-HMA (Wet) Ave. =	***4.0***	***6.1***	***18,913***	***28,808***	***88,616***
AR-HMA (20% CR) + TOR - Dry	4.3	5.7	20,494	33,565	51,620
	3.8	5.7	15,059	16,084	79,408
	3.9	5.7	---	---	---
AR-HMA + TOR (Dry) Ave.	***4.0***	***5.7***	***17,777***	***24,825***	***65,514***
AR-HMA (20% CR) + TOR - Wet	4.2	6.1	19,685	29,968	89,493
	3.9	6.1	25,609	42,105	73,733
	3.6	6.1	19,812	31,360	61,902
AR-HMA + TOR (Wet) Ave.	***3.9***	***6.1***	***21,702***	***34,478***	***75,043***

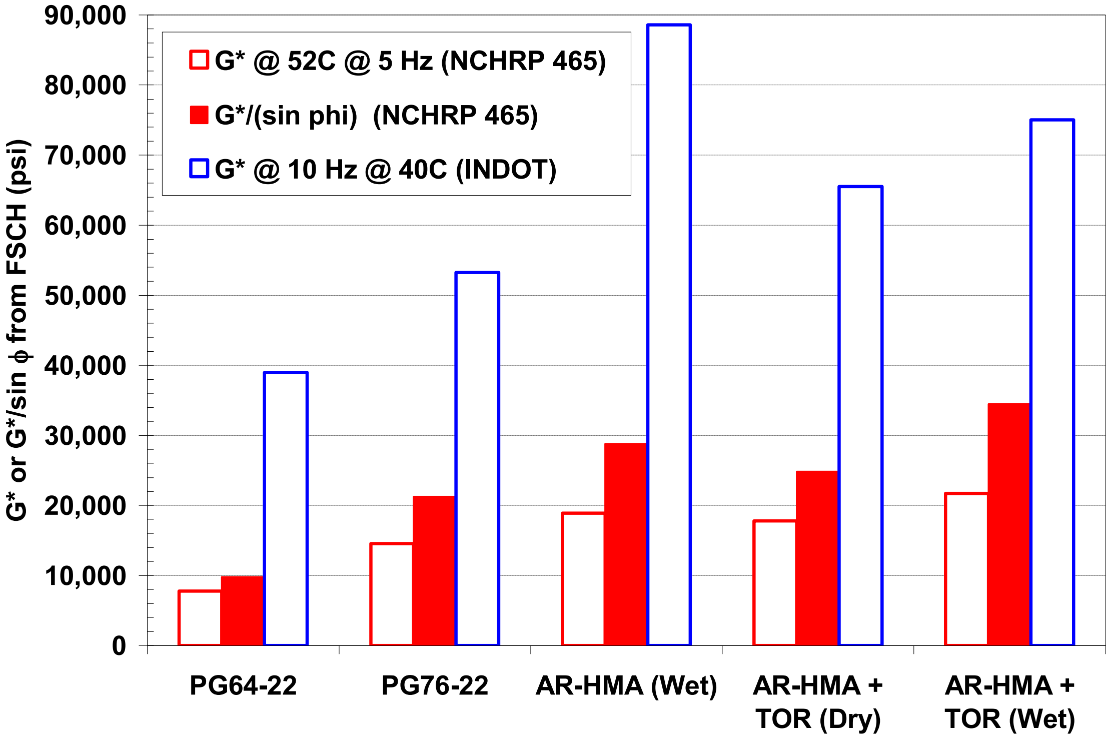

Figure 6 – Rutting Performance Parameters Determined from the SST FSCH Test

Repeated Shear at Constant Height (RSCH) – Test Results

The RSCH test involves applying a repeated haversine shear stress of 10 psi. The applied stress has a duration of 0.1 seconds, with an unload time of 0.6 seconds. An axial load is applied to the sample during the test to ensure a constant height is obtained at all times. The test procedure followed for this test was AASHTO TP7-01, Test Procedure C.

For this study, samples were tested at the high temperature performance grade used for New Jersey (64°C). The shear stress is applied to the sample for 5,000 loading cycles, or until the sample reaches 5% permanent shear strain. Work conducted by a number of researchers (Harvey et al., 1994; Monismith et al., 2000; Witzcak et al., 2002) has indicated the RSCH to be an excellent tool in determining rut susceptible HMA mixes. For this study, the test was expanded to 6,000 cycles. The parameter used for evaluation from the test is the % permanent shear strain that has accumulated at 5,000 loading cycles.

Figure 7 shows the permanent strain versus loading cycles for the five mixes tested. All mixes containing crumb rubber were able to withstand the repeated shear stress loading condition better than the polymer-modified PG76-22 mix, however, the asphalt rubber mix containing TOR obtained the lowest amount of permanent shear strain. Table 3 shows this in tabular form, along with the test results from the FSCH test.

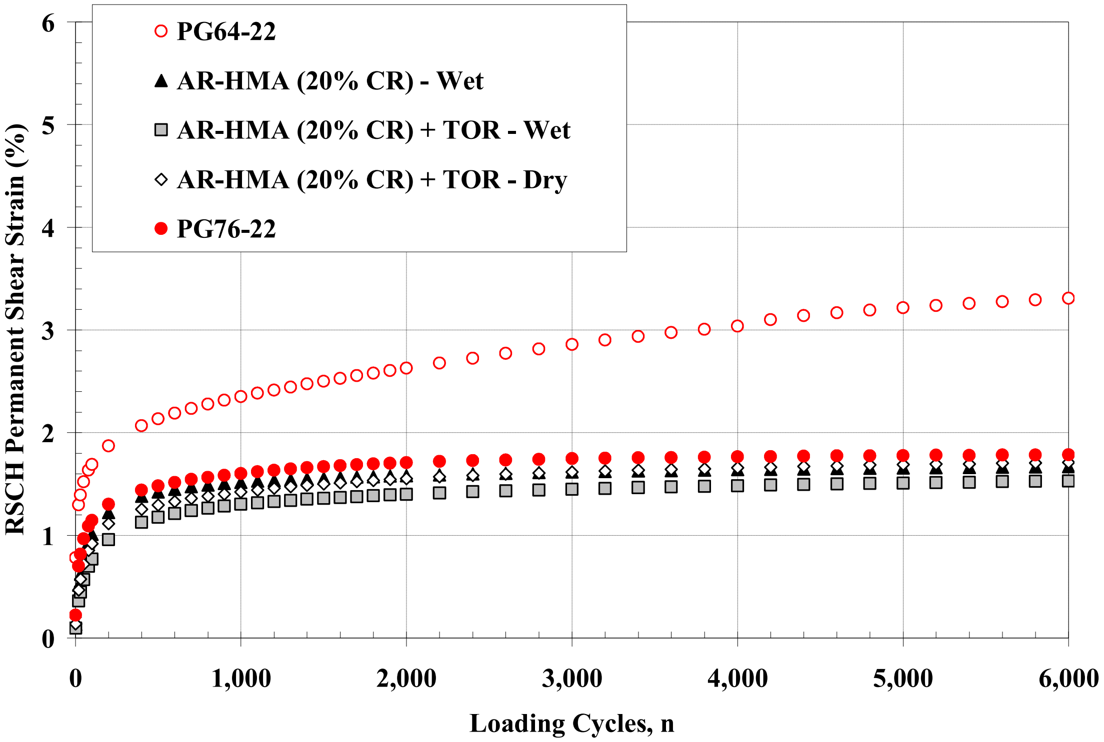

Figure 7 – Permanent Shear Strain versus Loading Cycles Curves

Table 3 – RSCH and FSCH Test Results for All Samples Tested

Mix Type	**Air Voids (%)**	**Binder Content (%)**	**ε_P from RSCH (5,000 cycles) (%)**	**FSCH - NCHRP 9-27 Project**		**FSCH - INDOT**
				G* (52°C @ 5 Hz) (psi)	**G*/sinϕ (52°C @ 5 Hz) (psi)**	**G* (40°C @ 10 Hz) (psi)**
PG 64-22	4.1	5.1	3.43	6,747	8,204	32,767
	3.6	5.1	3.22	8,856	11,373	45,051
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AR-HMA (Wet) Ave. =	***4.0***	***6.1***	***1.66***	***18,913***	***28,808***	***88,616***
AR-HMA (20% CR) + TOR - Dry	4.3	5.7	1.78	20,494	33,565	51,620
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AR-HMA + TOR (Dry) Ave.	***4.0***	***5.7***	***1.69***	***17,777***	***24,825***	***65,514***
AR-HMA (20% CR) + TOR - Wet	4.2	6.1	1.68	19,685	29,968	89,493
	3.9	6.1	1.16	25,609	42,105	73,733
	3.6	6.1	1.68	19,812	31,360	61,902
AR-HMA + TOR (Wet) Ave.	***3.9***	***6.1***	***1.51***	***21,702***	***34,478***	***75,043***

PRELIMINARY CONCLUSIONS

The Superpave mix design was used to construct two baseline HMA mixes and 3 asphalt rubber HMA mixes using the identical aggregate gradation (12.5mm nominal aggregate size). The two baseline mixes contained a PG64-22 and a PG76-22 asphalt binder, respectively. The three asphalt rubber (AR-HMA) mixes used a #30 mesh crumb rubber added by 20% of the total weight of the asphalt binder. Two of the AR-HMA mixes utilized the “wet” process of crumb rubber addition, while only one mix used the “dry” process. The TOR additive was added to one of the “wet” process mixes and the “dry” process mix by 4.5% of the total weight of the crumb rubber.

After the Superpave mix design phase, samples were compacted, cut and trimmed to a final air void content of 4% (+/- 0.5%) and tested in the Superpave Shear Tester (SST). The samples were tested under the Frequency Sweep at Constant Height (FSCH) and Repeated Shear at Constant Height (RSCH) test modes in the SST. The test results of the five different mixes were then compared using performance parameters established by different researchers (Harvey et al., 1994; Monismith et al., 2000; Witzcak et al., 2002; McDaniel et al, 2003) to determine which mixes obtained the best performance (in this case, primarily rutting performance).

Based on the test results determined in this study, the following conclusions can be drawn:

- The addition of crumb rubber to hot mix typically results in a HMA product that results in a higher optimum asphalt content than if the identical aggregate used an asphalt binder without crumb rubber. A number of researchers have shown that by increasing the asphalt content of the HMA will increase the fatigue life. Therefore, it may be concluded that most AR-HMA mixes will have a higher fatigue life than typical asphalt binders. This is illustrated in Figure 8, which is sample data obtained by testing samples with and without asphalt rubber on the flexural fatigue beam device at the Rutgers Asphalt Pavement Laboratory (RAPL). The figure clearly shows the AR-HMA sample having a much greater fatigue life than the polymer-modified and unmodified asphalt binders.
- The Tensile Stress Ratio (TSR) values measured during the Superpave mixture design phase indicate that the addition of TOR to HMA aids in reducing the moisture sensitivity of the HMA. This may be due to the TOR increasing the bond strength between the asphalt binder and aggregate in the HMA. In many cases, samples that fail the TSR test criteria usually show either de-bonding (or stripping) of the asphalt binder from the aggregate or the aggregate simply breaking due to the applied tensile stress.
- The FSCH test results measured in the SST indicated that the AR-HMA + TOR using the wet process performed the best under high test temperatures (52ºC). On average, the AR-HMA + TOR using the wet process achieved shear stiffness 1.4 times that of the polymer-modified PG76-22 at a test temperature of 52ºC. This would indicate that the AR-HMA + TOR mix would be more rut resistant at higher temperatures than the PG76-22 mixture. It should also be noted that the

AR-HMA + TOR mixture has 1.0% more asphalt binder than the PG76-22 HMA mix.

- The RSCH test results measured in the SST at a test temperature of 64oC showed that the AR-HMA + TOR accumulated the lowest amount permanent shear strain at 5,000 loading cycles. The AR-HMA + TOR accumulated approximately 18% less permanent shear strain than the polymer-modified PG76-22 sample.

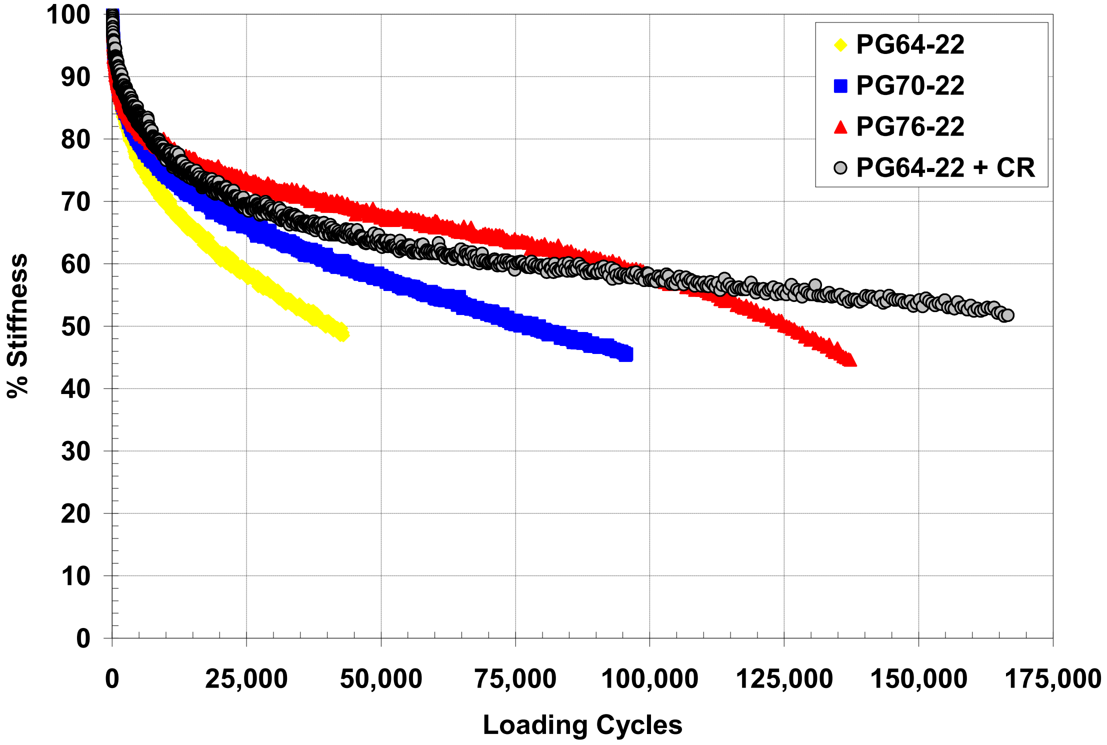

Figure 8 – Flexural Beam Fatigue Test Results Comparing Traditional Asphalt Binders and an Asphalt Rubber Mixture (Tensile Strain = 500 μ-strain)

RELATED REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), *Test Method for Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST), AASHTO TP7-01*, AASHTO Provisional Standards, pp. 146 – 156.

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