Effect of Binder Modification on the Performance of an Ultra-Thin Overlay Pavement Preservation Strategy

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The objective of this study was to determine whether asphalt rubber (AR) binders will provide similar or better performance compared with a polymer modified asphalt (PMA) binder when used in a high-performance, ultra-thin lift overlay pavement preservation strategy. Current specifications for these types of overlays normally require the use of a PMA binder, because it has the ability to make these overlays more elastic under traffic loading and is less sensitive to temperature fluctuations. However, several state agencies are looking into the feasibility of incorporating sustainable and environmentally friendly technologies, such as AR binders and warm mix asphalt (WMA) technologies, into their asphalt mixtures, including those used for high-performance, ultra-thin lift overlays. This study examined the effect of binder modification type (AR or PMA) and the influence of the use of WMA in high-performance, ultra-thin lift overlays. In general, the mixtures that were tested provided comparable rutting, moisture damage, and low-temperature cracking performance in the high-performance, ultra-thin lift overlay. However, the use of the AR binders indicated reduced performance compared with the PMA binder in mixture fatigue cracking via the beam fatigue test, and mixture reflective cracking in the overlay tester. The results from the beam fatigue test were not always supported by the fatigue life predictions from the simplified viscoelastic continuum damage model. The only detriment to mixture performance for mixtures incorporating WMA was a reduction in fatigue cracking performance when used with AR binders.

The FHWA has enacted the Every Day Counts initiative, which focuses on rapidly deploying proven innovations in an effort to benefit road users. One of the goals of the initiative is to improve the environmental sustainability of roads. State agencies have acted on this goal by incorporating sustainable and environmentally friendly technologies, such as ground tire rubber (GTR) and warm mix asphalt (WMA), into the engineered asphalt mixtures used for pavement preservation strategies, including high-performance, ultra-thin lift overlays (UTOL). These overlays generally have a thickness of 1 in. or less and are used in applications requiring higher levels of rutting and fatigue cracking resistance.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2550, Transportation Research Board, Washington, D.C., 2016, pp. 1–7.
DOI: 10.3141/2550-01

GTR is a sustainable product produced from scrap rubber that is ground and pulverized into various mesh sizes. GTR can be added to an asphalt binder to be used in hot mix asphalt (HMA). The results of modifying asphalt binders with GTR through a wet process is rubberized asphalt or asphalt rubber (AR) (*1*). Rubberized asphalt is a term applied to rubber modified asphalt with less than 15% GTR by total weight of the liquid asphalt. At percentages greater than 15%, rubber modified asphalt is referred to as AR (*1*). In general, rubber increases the elasticity of HMA and thus has the potential to improve the cracking resistance of asphalt mixtures, including those used for pavement preservation strategies like UTOL.

WMA technologies increase environmental stewardship and have been used extensively throughout the world. These technologies can be classified into three categories: chemical additives, foaming processes, and organic additives. WMA can provide multiple benefits, such as lower emissions at the plant and in the field, better workability and compactability, the ability to pave in colder conditions, and longer haul distances (*2*). Incorporating WMA into asphalt mixtures, including those used for pavement preservation strategies like UTOL, would achieve the goal of increased environmental sustainability outlined in the Every Day Counts initiative if they provide similar or better performance.

Several department of transportation (DOT) agencies, such as Arizona, Maryland, Michigan, New Jersey, New York, and Ohio, have developed specifications for high-performance, thin overlays used in pavement preservation. These mixes are reported to be rut and crack resistant while maintaining excellent skid resistance. However, the specifications normally require the use of polymer modified asphalt (PMA) binder, because it has the ability to make the overlays more elastic under traffic and less sensitive to temperature fluctuations.

OBJECTIVE

The objective of this study was to determine if AR binders used in conjunction with and without WMA will provide similar or better performance compared with a PMA binder used with and without WMA in a high-performance UTOL mixture.

EXPERIMENTAL METHODOLOGY

To compare the influence of binder modification on a high-performance UTOL, first a PMA binder was selected that had shown field success in a pavement preservation strategy. Next, AR binders were developed

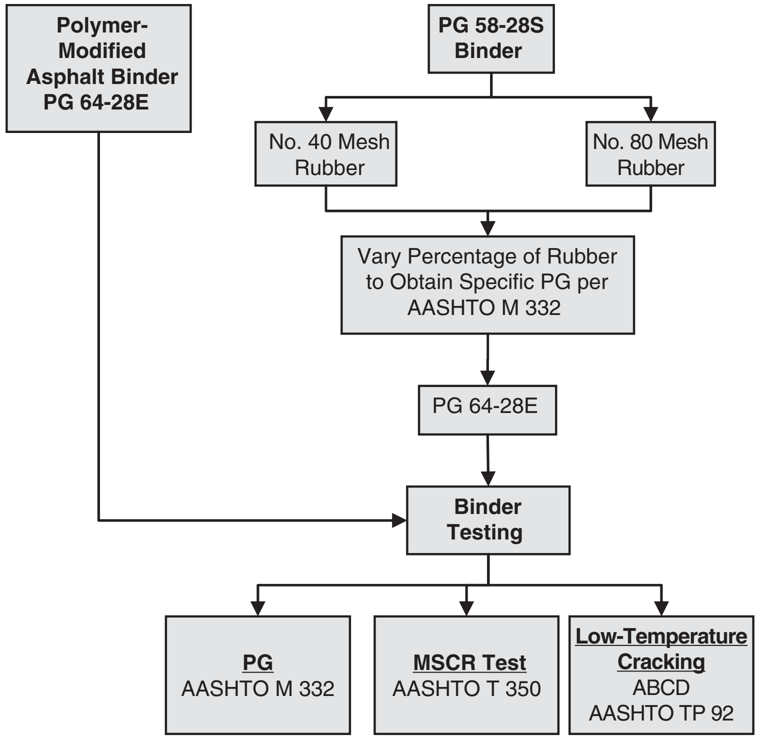

FIGURE 1 Experimental plan for binder (ABCD = asphalt binder cracking device).

by varying the percentage and mesh size of the GTR to determine the combination of percentage and mesh size that provided a similar binder performance grade (PG) as the PMA binder in accordance with AASHTO M 332, Performance-Graded Asphalt Binder Using the Multiple Stress Creep Recovery (MSCR) Test (*3*). This AR binder and the selected PMA binder were then used to design the high-performance UTOL.

EXPERIMENTAL PLAN

To fulfill the objectives of the study, two experimental plans were developed. Figure 1 outlines the experimental plan for evaluation of the PMA binder and development of the AR binder. Figure 2 outlines the experimental plan for performance testing of the high-performance UTOL developed with the PMA and AR binders.

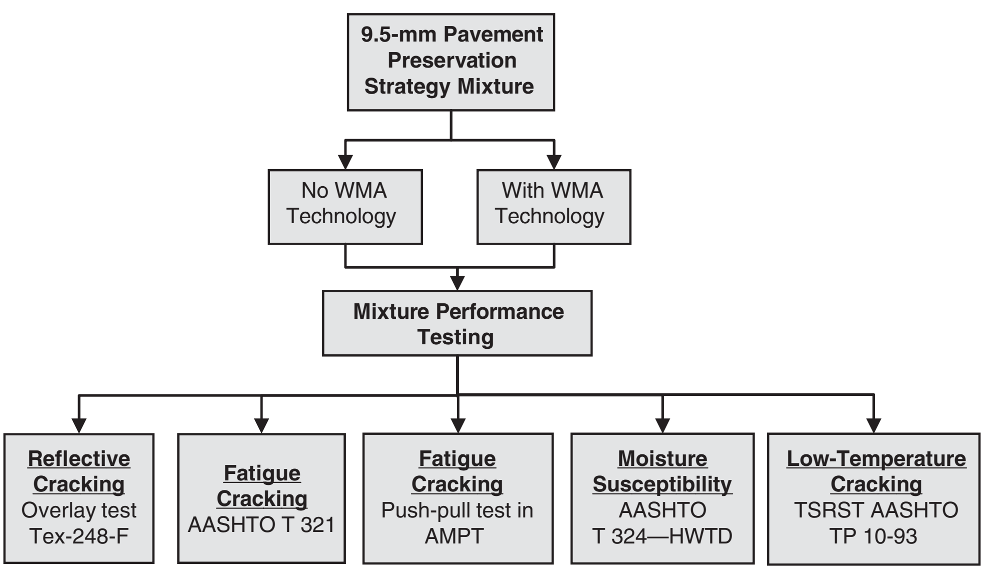

FIGURE 2 Experimental plan for mixture (AMPT = asphalt mixture performance tester; HWTD = Hamburg Wheel Tracking Device; TSRST = thermal stress restrained specimen test).

MATERIALS

A description of each material used in this study is provided in the following subsections.

Virgin Binder to Produce AR

A PG 58-28 base binder from a local supplier in Massachusetts was used for development of the AR binder. This binder type and grade were selected because it has been used to produce AR binders in the New England states.

Ground Tire Rubber

The GTR used throughout this study was obtained from Lehigh Technologies, Inc. Two mesh sizes were obtained, No. 40 and No. 80 mesh. This GTR was used to fabricate the AR binders through a wet process. The GTR dosage was varied for each mesh size to obtain a resultant AR binder with properties comparable to the PMA binder.

AR: Wet Process

The AR binders were prepared in the laboratory with a wet process by blending the PG 58-28 virgin binder with the GTR. A Silverson L4RT-W bench top laboratory high-shear mixer was used to blend the virgin binder and GTR. The virgin binder was heated to 374°F (190°C) with an independent temperature controller. Once at temperature, mixing commenced with the shear mixer at a speed of 5,000 rpm. The GTR was then slowly added to the binder to avoid any sudden drop in temperature, which was monitored throughout the mixing process. Mixing of the virgin binder and GTR continued for 60 min at 374°F (190°C) after all the GTR had been added. This was the same process used in a previous study (*4*), which determined that the mixing temperature and time used were sufficient to ensure that the complex shear modulus of the binder reached an almost constant value. This was considered to be a sign of complete reaction between the rubber particles and the binder.

The AR binders were used for mixture specimen fabrication immediately after the binder was finished being mixed. The mixture mixing temperature was 177°C (351°F) and the compaction temperature was 154°C (309°F) for all the AR binders in this study. These represent typical temperatures used for AR mixtures in the Northeast.

PMA Binder

The PMA binder selected for the study was a PG 64-28E, which has been used by the Rhode Island DOT for its paver placed elastomeric surface treatment (PPEST) preservation mixture. In accordance with AASHTO M 332 (*3*), the PG 64-28E designation confirms the polymer modification of the binder, and the E designation indicates the binder is suitable for an extremely heavy expected traffic level and loading rate. To be consistent with the AR binders, the mixture mixing temperature was 177°C (351°F) and the compaction temperature was 154°C (309°F).

WMA Technology

The WMA technology that was used for this study was chosen from the approved list of the Northeast Asphalt User Producer Group. An organic-based WMA technology known as SonneWarmix was used at a dosage rate of 0.75% by weight of the binder. The reduced mixing and compaction temperatures for the mixture with the WMA with each binder type were 160°C (320°F) and 141°C (286°F), respectively. These temperatures were approximately a 30°F reduction in mixing temperature and a 23°F reduction in compaction temperature compared with the HMA.

TABLE 1 Aggregate Properties

	Result by Aggregate Stockpile		
Sieve Size (%)	9.5 mm	Stone Sand	Stone Dust
19.0 mm	100	100	100
12.5 mm	99.4	100	100
9.5 mm	93.8	100	100
4.75 mm (No. 4)	29.7	99.8	99.4
2.36 mm (No. 8)	5.2	83.7	81.6
1.18 mm (No. 16)	2.8	54.3	56.1
0.600 mm (No. 30)	2.3	33.8	38.4
0.300 mm (No. 50)	2.1	19.0	25.3
0.150 mm (No. 100)	1.8	9.4	16.1
0.075 mm (No. 200)	1.5	4.3	11.2

NOTE: No. = number. Bulk-specific gravity (G_{sb}) results: for 9.5 mm, 2.642; for stone sand, 2.644; for stone dust, 2.600. Absorption results: for 9.5 mm, 0.43; for stone sand, 0.53; for stone dust, 0.77.

Aggregates

The study used aggregates from a crushed stone source in Wrentham, Massachusetts. Three aggregate stockpiles were obtained: 9.5 mm crushed stone, stone sand, and stone dust. Each aggregate stockpile was tested to determine its properties, which are shown in Table 1. Sieve analysis was completed in accordance with AASHTO test methods T 11 Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing, and T 27 Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates (*3*). The bulk specific gravity and absorption of the aggregates shown in Table 1 were determined in accordance with AASHTO test methods T 84 Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate, and T 85 Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate (*3*).

BINDER TESTING AND ANALYSIS

This section outlines the results of the binder testing for the virgin binder, PMA binder, and AR binders.

Performance Grade and MSCR Tests

The virgin binder that was used to develop the AR binders and the PMA binders was tested to determine its performance grade in accordance with AASHTO M 332 (*3*). The MSCR provides an indication of the degree of modification in the binder, which was of interest for this study in comparing the PMA and AR binders. The MSCR test is performed at the environmental high-temperature grade and the nonrecoverable creep compliance ($J_{nr3.2}$) is measured. Based on the nonrecoverable creep compliance value, a designation is assigned to the binder grade correlating to traffic loading. A grade of S is for standard loading (<10 million equivalent single axle loads [ESALs]) with a $J_{nr3.2}$ of 4.5 kPa^{-1} maximum. Designation H is for high loading (10 million to 30 million ESALs) with a $J_{nr3.2}$ of 2.0 kPa^{-1} maximum. Designation V is for very high loading (>30 million ESALs or standing traffic) with a $J_{nr3.2}$ of 1.0 kPa^{-1} maximum. Finally, Designation E is for extremely high loading (>30 million ESALs and standing traffic such as toll plazas or port facilities) with a $J_{nr3.2}$ of 0.5 kPa^{-1} maximum.

The results of this performance grading are shown in Table 2. The loading designation for the virgin binder was PG 58-28S, which indicated that there was no modification. The PMA binder was graded to be PG 64-28E. Thus, by trial and error, AR binders were prepared with each mesh size at varying GTR contents until the grade of the resultant AR binder matched the PMA binder grade of PG 64-28E. For each mesh size, it was determined that 15% GTR was required to attain the PG 64-28E grade as outlined in Table 2. A grade of PG 64-28V was attained for the AR binder with the 10% No. 40 mesh, whereas 13% No. 80 mesh was required. This finding indicates that the degree of modification is influenced by the GTR mesh size.

Low-Temperature Cracking

The low-temperature PGs presented in Table 2 were determined with the bending beam rheometer following AASHTO T 313, Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (*3*). The asphalt binder cracking device (ABCD) was also used to determine the low-temperature cracking resistance of the PMA and AR binders with and without WMA.

The effects of the binder modification on low-temperature cracking are of great interest in New England states because these binders will be used as part of a surface layer pavement preservation strategy that might be highly susceptible to temperature-related cracking. It was also hypothesized that this test might provide more accurate results for binders that are highly modified. Each binder was tested in the ABCD in accordance with AASHTO TP 92-14, Standard Method of Test for Determining the Cracking Temperature of Asphalt Binder Using the Asphalt Binder Cracking Device (*5*). The results of the ABCD testing are shown in Table 3. The ABCD data indicated temperatures that were unrealistically colder than those provided by the bending beam rheometer and the low-temperature cracking tests performed on the mixtures.

TABLE 2 Binder Performance Grading Results

Characteristic	Results by Binder: PG 58-28 Virgin Binder	PMA Binder	AR 15% No. 40 Mesh	AR 15% No. 80 Mesh
Rolling Thin–Film Oven Residue (T 240)				
MSCR test temperature (°C)	58	64	64	64
$J_{nr\,3.2}$	2.602	0.1586	0.4301	0.4907
Loading designation	S	E	E	E
Final AASHTO M 332 performance grade	58-28S	64-28E	64-28E	64-28E

TABLE 3 ABCD Results

Binder	Average ABCD Cracking Temperature (°C)
PMA binder	−37.8
AR binder 15% No. 40 mesh	−37.8
AR binder 15% No. 80 mesh	−44.9
PMA binder + WMA	−36.0
AR binder 15% No. 40 mesh + WMA	−40.9
AR binder 15% No. 80 mesh + WMA	−44.9

MIXTURE DESIGNS

Since the study compared the mixture that used the PMA binder with similar mixtures designed to use the AR binders, AR binders meeting the PG 64-28E grade were used for mixture designs. The rubber binders with both mesh sizes required 15% rubber to meet the PG 64-28E grade.

The rubber binder mixtures were developed with the Rhode Island DOT PPEST specification (*6*). The aggregate blend for the mixture was a 9.5 mm nominal maximum aggregate size and met the PPEST specification requirements as shown in Table 4. With the stockpiles available, the aggregates were sieved to individual sizes for the purposes of batching for mixture fabrication.

Because the PPEST specification required the Marshall method of compaction, Marshall specimens were used for the mixture design process at 50 blows per side. The PPEST specification required 6.0% minimum binder content. The optimum binder content was found to be 6.75% based on the mixture design.

Because most of the performance tests for this study required Superpave® gyratory compactor (SGC) specimens, all the mixture designs that used the PMA or AR binders were verified to ensure that the mixture volumetric properties did not change significantly

TABLE 4 Mixture Design Gradation and PPEST Specification Criteria

Sieve Size	9.5-mm Mixture Gradation	9.5-mm PPEST Gap–Graded Specification
12.5 mm	100	100
9.5 mm	93.0	91–95
4.75 mm (No. 4)	42.5	40–45
2.36 mm (No. 8)	24.0	22–26
1.18 mm (No. 16)	16.0	na
0.600 mm (No. 30)	10.5	9–12
0.300 mm (No. 50)	7.0	6–8
0.150 mm (No. 100)	5.0	na
0.075 mm (No. 200)	4.0	4.0

NOTE: na = not applicable. Binder content for 9.5-mm mixture gradation = 6.75%; for 9.5-mm PPEST gap–graded specification, 6.0% minimum.

based on the compaction method. A compactive effort of 75 gyrations was used in the SGC, which is typical for mixtures in New England. This gyration level corresponded to design ESALs of 0.3 to <3 million with the Superpave design methodology.

MIXTURE PERFORMANCE TESTING

All the specimens were fabricated at the mixing and compaction temperatures noted. All the mixture performance specimens were aged in a loose state for 4 h prior to compaction.

Rutting and Moisture Susceptibility: Hamburg Wheel Tracking Device

The Hamburg Wheel Tracking Device (HWTD) was used to measure the rutting and moisture susceptibilities of the mixtures in accordance with AASHTO T 324, Hamburg Wheel–Track Testing of Compacted Hot-Mix Asphalt (*3*). Previous research has suggested that rutting and moisture susceptibility might be a concern for WMA mixtures (*2*). The test specimens were fabricated to 7.0%±1.0% air voids in the SGC. Testing in the HWTD was conducted at a test temperature of 50°C (122°F). The specimens were tested at a rate of 52 passes/min after a soak time of 30 min at the test temperature. Testing terminated at 20,000 wheel passes or until visible stripping was noted.

In this test, a steel wheel loads the specimen and the corresponding rut depth is recorded. The rut depth versus number of passes of the wheel is plotted to determine the stripping inflection point. The stripping inflection point gives an indication of when the test specimen begins to exhibit stripping (moisture damage). As shown in Tables 5 and 6, the mixtures in this study did not exhibit any significant rutting or moisture damage. Therefore, all the mixtures provided comparable rutting and moisture damage performance.

Fatigue Cracking: Four-Point Flexural Beam Fatigue Test

The four-point flexural beam fatigue test was used to measure the fatigue cracking resistance of the mixtures in accordance with AASHTO T 321, Determining Fatigue Failure of Compacted Asphalt Concrete Subjected to Repeated Flexural Bending (*3*). This is one of the most commonly and historically used laboratory test procedures for evaluating fatigue cracking resistance.

Slabs with dimensions 150 mm wide, 180 mm tall, and 450 mm long were fabricated for each mixture with the IPC Global Pressbox slab compactor. From each slab, beams with dimensions 63 mm wide, 50 mm tall, and 380 mm long were cut such that the sides had smooth faces. The air voids of the final cut specimens were 7.0%±1.0%. The beam specimens were conditioned at the test temperature of 15°C (59°F) for at least 2 h prior to testing. A 15°C (59°F) test temperature was selected, as it represents the intermediate temperature for the Northeast.

This fatigue test was conducted in strain control mode at a load frequency of 10 Hz applied with a sinusoidal waveform. The specimens were tested at a strain level of 1,000 με. This strain level was selected to ensure at least 10,000 cycles would be achieved prior to failure and that the test would not run for an extensive period of time. The number of cycles to failure was determined by fitting an exponential function to the flexural stiffness versus number of cycles, and then evaluating the number of cycles it took to decrease the initial stiffness by 50% measured at the 50th cycle.

The data in Tables 5 and 6 indicate that the HMA mixtures with the PMA binder performed better than the same mixture with the AR binders. The addition of WMA to the mixtures increased fatigue performance with the PMA binder, but decreased performance with the two AR binders. The data also indicate that coarser mesh size for the AR binders yielded better performance than the finer mesh size.

TABLE 5 PMA Mixture Performance Testing Results and PPEST Specification Criteria

Characteristic	Result by Mixture PG 64-28E PMA: HMA	Result by Mixture PG 64-28E PMA: WMA
Rutting and moisture susceptibility HWTD results—AASHTO T 324		
Stripping inflection point	None	None
Rut depth at 10,000 passes (mm)	0.75	3.63
Rut depth at 20,000 passes (mm)	0.97	4.28
Low-temperature cracking TSRST Results—AASHTO TP 10: average TSRST specimen temperature at failure (°C)	–27.0	–28.8
Reflective cracking Texas overlay test results—Tex–248–F: average number of cycles to failure	753	644
Fatigue cracking beam fatigue test results—AASHTO T 321: average number of cycles to 50% initial stiffness, N_f at 1,000 με	59,644	152,219
Fatigue cracking—S-VECD		
Average number of cycles to failure N_f at 250 με	4,090,094	89,690
Average number of cycles to failure N_f at 500 με	4,463	21,096
Average number of cycles to failure N_f at 750 με	83	9,047

NOTE: These are 9.5-mm PPEST gap–graded UTOL mixtures. S-VECD = simplified viscoelastic continuum damage.

TABLE 6 AR Mixture Performance Testing Results and PPEST Specification Criteria

Characteristic	Result by Mixture			
	15% No. 40 Mesh		15% No. 80 Mesh	
	HMA	WMA	HMA	WMA
Rutting and moisture susceptibility HWTD results—AASHTO T 324				
Stripping inflection point	None	None	None	None
Rut depth at 10,000 passes (mm)	1.86	2.39	2.18	3.88
Rut depth at 20,000 passes (mm)	2.36	3.97	2.66	5.22
Low-temperature cracking TSRST results—AASHTO TP 10: average TSRST specimen temperature at failure (°C)	–29.8	–30.3	–28.7	–28.0
Reflective cracking Texas overlay test results—Tex–248–F: average number of cycles to failure	45	60	151	182
Fatigue cracking beam fatigue test results—AASHTO T 321: average number of cycles to 50% initial stiffness, N_f at 1,000 με	44,060	21,485	11,059	6,556
Fatigue cracking—S-VECD				
Average number of cycles to failure N_f at 250 με	107,421	17,616	4,538,185	29,973
Average number of cycles to failure N_f at 500 με	3,432	310	7,770	527
Average number of cycles to failure N_f at 750 με	458	29	187	50

NOTE: These are 9.5-mm PPEST gap–graded UTOL mixtures.

Fatigue Cracking: Simplified Viscoelastic Continuum Damage Model

Continuum damage theory methods have been evolving for asphalt concrete since at least the late 1980s, and their characterization and analysis protocols involve more complex calculus than is used in traditional beam fatigue analysis. The method used in this paper is the simplified viscoelastic continuum damage (SVECD) model, which was developed by Underwood and Kim (*7*). This technique allows the fatigue life of an asphalt mixture at various strain–stress amplitudes under different temperatures to be predicted from its dynamic modulus and cyclic fatigue data. For this study, cyclic fatigue tests were performed at strain levels of 250, 500, and 750 με at 15°C. These conditions were determined following AASHTO TP 107, Determining the Damage Characteristic Curve of Asphalt Concrete from Direct Tension Cyclic Fatigue Tests (*5*).

The data in Tables 5 and 6 show that, unlike the beam fatigue test, the HMA mixtures with the PMA binder performed worse than the HMA mixture with the AR binder with the fine mesh size (No. 80), although the data are similar. The results are mixed for the coarse mesh size (No. 40), where the HMA mixture with the PMA performed significantly better than the HMA mixture with the AR binder at a strain level of 250 με, but not at 500 and 750 με strain levels. The addition of WMA on mixture fatigue performance with the PMA binder also significantly varied with the strain level. As in the beam fatigue test, SVECD analysis indicated that the WMA decreased fatigue performance with the AR binders. Unlike the beam fatigue test, the SVECD analysis indicated that the PMA binder with WMA had reduced performance compared with the HMA mixture. In addition, the SVECD analysis indicated that the finer mesh size (No. 80) for the AR binders performed better than the coarser mesh size (No. 40), which was opposite to the beam fatigue trend.

At strain level 750 με, which was closest to the strain level of 1,000 με used in the beam fatigue test, the results from SVECD did not agree with the results from the beam fatigue test. The HMA mixture with PMA performed worse that the two HMA mixtures with AR, although all performance was low at strain level 750 με.

Reflective Cracking Testing: Overlay Tester

The overlay tester was used to evaluate the reflective cracking resistances of the asphalt mixtures. The device applies tensile loading to the test specimen while recording load, displacement, temperature, and time (*8*). Research studies have outlined the use of this device for evaluating reflective cracking (*9, 10*).

Texas DOT specification Tex–248–F was followed (*8*). Trimmed gyratory specimens for this test had an air void level of 7.0%±1.0%. The specimens were tested with joint opening (displacement) 0.06 cm (0.025 in.), test temperature 15°C (59°F), and failure criteria 93% reduction in the load measured during the first cycle. The results are shown in Tables 5 and 6. Mixtures exhibiting more cycles to failure exhibit more resistance to reflective cracking.

The data in Tables 5 and 6 indicate that the HMA mixtures with the PMA binder had a greater resistance to reflective cracking than the two HMA mixtures with the AR binders. The effects of WMA on the mixtures, regardless of binder, were regarded to be insignificant. Like the SVECD fatigue results, the finer mesh size (No. 80) for the AR binders performed better than the coarser mesh size (No. 40).

Low-Temperature Cracking: Thermal Stress Restrained Specimen Test

The thermal stress restrained specimen test (TSRST) was used to evaluate the low-temperature cracking resistances of the asphalt mixtures. The test was performed in accordance with AASHTO TP 10-93, Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength, with the exception that the SGC specimens were used

(*11*). A minimum of three SGC specimens that were 185 mm (7.3 in.) tall by 150 mm (5.9 in.) in diameter were fabricated for each mixture. The TSRST specimens were then cored and cut to a final height of 160 mm tall (6.3 in.) by 54 mm (2.1 in.) in diameter. The air voids in the final cut specimens were 7.0%±1.0%.

The TSRST results are shown in Tables 5 and 6. All the mixtures that were tested exhibited comparable low-temperature cracking performance.

CONCLUSIONS

The objective of this study was to determine whether AR binders with and without WMA can provide similar or better performance compared with a PMA binder with and without WMA when used in a high-performance UTOL mixture. The following are the conclusions from the study:

- All the mixtures that were tested provided comparable rutting, moisture damage, and low-temperature cracking performance.
- The HMA mixtures with the PMA binder had more resistance to fatigue cracking than the two HMA mixtures with the AR binders, according to the beam fatigue test. The addition of WMA increased the mixture fatigue performance with the PMA binder, but decreased fatigue performance with the two AR binders.
- The results of the fatigue test that used SVECD did not always agree with the results of the beam fatigue test, and often showed a dependency on the applied strain level and AR mesh size. For the use of WMA, the only consistent result was that it decreased performance with the AR binders.
- The HMA mixture with the PMA binder had greater resistance to reflective cracking than the HMA mixtures with the two AR binders. The effects of WMA were regarded to be insignificant.
- The finer mesh size for the AR binders performed better than the coarser mesh size in the fatigue test with SVECD and the reflective cracking test, but had reduced performance with the bending beam fatigue test. The reason for this is unknown and requires further investigation.
- In conclusion, the two AR binders did not perform as well as the PMA binder in the high-performance UTOL mixture in (*a*) fatigue cracking, as measured by the beam fatigue test and (*b*) reflective cracking. However, the results of the beam fatigue test were not always supported by the results of the fatigue test with SVECD, which were variable. The only detriment to performance provided by WMA was that it decreased fatigue cracking performance with the AR binders.
- Future studies should concentrate on improving the fatigue and reflective cracking performance provided by AR binders, along with evaluating the mixture tests used to measure fatigue cracking performance for these types of high-performance UTOL mixtures.

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The Standing Committee on Pavement Preservation peer-reviewed this paper.