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Abstract: Reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) have been increasingly used in asphalt mixtures. The use of RAP and RAS in asphalt mixtures not only reduces the consumption of virgin materials, conserves energy, and protects the environment but also improves the rutting resistance of asphalt pavements. However, as more recycled materials are used in asphalt mixtures, there is increasing concern over their potential negative effects on the mix cracking resistance. To improve the cracking resistance of asphalt mixtures with high RAP/RAS contents, one of the approaches considered is using recycling agents to potentially restore performance properties of the aged binder. This project was conducted to evaluate the effect of a recycling agent (RA), known as Hydrogreen, on the long-term field performance of high RAP and RAS mixes. The field study consisted of three test sections, each constructed by placing a dense-graded surface lift at a depth of 4.5 cm (1.75 in.) on SR 7 near Harrisonville, Missouri, in August 2013. The three mixes placed in the three test sections included: (1) a control mix containing 30% RAP using an SBS-modified PG 70-22 binder with no RA; (2) a 40% RAP mix using the same PG 70-22 binder with RA; and (3) a 25% RAP and 5% RAS mix using a neat PG 64-22 with RA. This paper presents data collected during the construction of the test sections, laboratory performance testing results, and early field performance. The research results showed that the recycling agent could be used in the 40% RAP and 25% RAP and 5% RAS mixes to achieve similar construction quality, laboratory performance, and early field performance to the 30% RAP control mix. As these sections are still in service, it is recommended that they continue to be monitored in order to evaluate their long-term performance. **DOI: 10.1061/(ASCE)MT.1943-5533.0001697.**

Author keywords: Reclaimed asphalt pavement; Recycled asphalt shingles; Warm mix asphalt; Rejuvenator; Recycling agent.

Introduction

As material costs—with the asphalt binder being the most expensive component—comprise about 70% of the total production cost (Copeland 2011), using reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in asphalt mixtures to replace more valuable virgin binders and aggregates can result in significant cost savings. Use of RAP and RAS in asphalt mixtures also provides other environmental benefits, such as conserving energy required to obtain the virgin materials, preserving nonrenewable natural resources, and saving landfill space.

Due to the economic and environmental benefits, there is increasing interest in using more RAP and RAS in asphalt mixtures. Based on the most recent survey conducted by the National Asphalt Pavement Association (NAPA) (Hansen and Copeland 2014), the average percentages of RAP and RAS used in asphalt mixtures by total weight are up to 30 and 5%, respectively. With these amounts of RAP and RAS, the asphalt mixtures are considered to have high recycled contents as the ratios of recycled binder in RAP and RAS to total binder in these mixes are likely greater than 0.25 (West et al. 2013). As more recycled materials are used, state agencies are increasingly concerned over the durability of asphalt mixtures containing high recycled contents, as these mixes have been found to be prone to more cracking based on laboratory test results.

To address this concern, several national research efforts have been conducted. Analyses (West et al. 2011; Carvalho et al. 2010; Bennert and Maher 2013) were conducted on field performance data from pavement sections in the Specific Pavement Studies 5 (SPS-5) of the Long-Term Pavement Performance (LTPP) program to determine the effect of RAP on long-term field performance. The SPS-5 pavement sections consisted of 5- and 12.7-cm (2- and 5-in.) overlays. overlays constructed from both virgin and 30% RAP mixtures on milled and nonmilled surfaces in a variety of climates. Overall, the long-term field performance of asphalt mixtures containing up to 30% RAP was similar to that of asphalt mixtures with virgin materials (West et al. 2011; Carvalho et al. 2010). A detailed analysis of cracking progression in the LTPP SPS-5 virgin and 30%

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RAP sections in New Jersey showed that cracks appeared at approximately the same time but progressed faster in the RAP sections.

In addition to examining the LTPP SPS-5 database, another continuing research effort focuses on evaluating the use of emerging technologies to potentially improve the performance of high recycled content mixes. This effort consists of laboratory studies in combination with constructing new pavement sections to evaluate these technologies in various climatic and field conditions that are difficult to simulate using laboratory testing alone (West et al. 2009, 2013; Johnson and Olson 2009; Zhou et al. 2011, 2015; Hajj et al. 2013).

As part of the national effort to improve the long-term field performance of high recycled content mixes, the National Center for Asphalt Technology (NCAT) was tasked under Work Elements V1a and V1b of the Asphalt Research Consortium (ARC) program to coordinate the construction of new pavement validation sites built with high recycled content mixtures utilizing emerging technologies. This paper summarizes research activities and discusses findings from one of the validation sites that was constructed by APAC Missouri, Inc. in August of 2013 on SR 7 approximately 24 km (15 mi) southeast of Harrisonville, Missouri.

Objectives and Scope

The overall objective of this validation site was to examine the long-term field performance of high RAP and RAS mixes with a recycling agent (RA), known as Hydrogreen supplied by Green Asphalt Technologies (Pass Christian, Mississippi). The validation site consisted of three test sections, each constructed by placing a dense-graded surface lift at a depth of 4.5 cm (1.75 in.) The following three test mixes were placed in these sections over 3 days of production:

- The control mix contained 30% RAP with an SBS-modified PG 70-22.
- The second mix contained 40% RAP using an SBS-modified PG 70-22 blended with RA.
- The third mix contained 25% RAP and 5% RAS using a neat PG 64-22 blended with RA.

In the following sections, some background information is first discussed, followed by information relating to mix design, laboratory performance of the test mixtures, and early field performance of the test sections. Finally, a summary of key findings from this study is provided.

Background

The aged asphalt binders in RAP and RAS are often stiffer than the corresponding virgin binders; thus, the asphalt mixtures with RAP and RAS are generally stiffer than their comparable virgin mixes. Depending on the contents of RAP and RAS used in the mixes, they can help improve resistance to rutting and moisture damage but can potentially reduce cracking resistance (Cooper et al. 2014, 2015; Kandhal et al. 1995; Hong et al. 2010; Zhou et al. 2011, 2014; West et al. 2011; Tran et al. 2012; Willis 2012; Zhao et al. 2012, 2013, 2015). Therefore, one of the concerns regarding the use of RAP and RAS in asphalt mixtures is the potential for premature cracking of recycled mixes due to the effect of the stiff RAP/RAS binder, especially when higher recycled contents are used.

Recycling agents have been used in asphalt mixtures produced with high recycled contents to mitigate the potential negative effect of the recycled binder on cracking resistance. Several past and ongoing studies have investigated the effect of various RAs on the performance of asphalt mixtures with high RAP and/or RAS contents. Key findings from these studies can be summarized as follows:

- RAs can soften the aged asphalt binders and reduce the stiffness of RAP/RAS mixtures (O'Sullivan 2011; Tran et al. 2012; Mallick et al. 2010; Hajj et al. 2013; Im and Zhou 2014).
- RAs may reduce the resistance to permanent deformation of RAP/RAS mixes (Tran et al. 2012; Zhou et al. 2015).
- RAs can improve the moisture susceptibility of recycled mixtures (Tran et al. 2012; Hajj et al. 2013; Im and Zhou 2014).
- RAs may improve the resistance to cracking of RAP/RAS mixes (Tran et al. 2012; Mallick et al. 2010; Hajj et al. 2013; Im and Zhou 2014; Zhou et al. 2015).
- RAs can also improve the mix resistance to aging (Mogawer et al. 2015).

For this field evaluation site, Hydrogreen (supplied by Green Asphalt Technologies) was used as a recycling agent to improve the field performance of 40% RAP and 25% RAP/5% RAS mixtures. The RA was blended with the corresponding virgin binder used in each mix and was part of the virgin binder in the mix design. This means the mix designs with or without RA are the same, except that in the mix design with RA, the equivalent amount of virgin binder is removed and replaced with the RA determined at the recommended dosage. The following sections of this paper discuss research activities and findings from the field validation study.

Material and Mix Design

For the validation site near Harrisonville, Missouri, three test sections were constructed using the following three 12.5-mm nominal maximum aggregate size (NMAS) mixtures placed in the surface lift at a depth of 4.5 cm (1.75 in.):

- The control mix contained 30% RAP and an SBS-modified PG 70-22 (PG 64-22 Grade H) base binder with no RA (referred to as 30% RAP mix).
- The second mix contained 40% RAP and an SBS-modified PG 70-22 (PG 64-22 Grade H) base binder blended with 0.75% RA by weight of RAP (referred to as 40% RAP mix).
- The third mix contained 25% RAP and 5% RAS and a neat PG 64-22 base binder blended with 1.33% RA by weight of RAS (referred to as 25% RAP/5% RAS mix).

The three mix designs were approved by the Missouri Department of Transportation (MoDOT) before construction. Each fine-graded 12.5-mm NMAS Superpave mix was designed with a compactive effort of 80 gyrations. The RAP was not crushed prior to adding to the plant, but an in-line RAP crusher was used to crush the oversized material to -1.27 cm (−1/2 in.) The RAS used for the 25% RAP/5% RAS mix was postconsumer RAS, which was ground off-site to -1 cm (−3/8 in.) in Stanley, Kansas, and then delivered to the plant. The RAP and RAS were added in separate cold-feed bins. The aggregate used for the design and production was limestone and mine chat.

The same virgin materials were used for all three mixes. The proportions of the virgin material were changed, but the volumetrics and gradations of the overall designs were similar. An SBS-modified PG 70-22 (PG 64-22 Grade H) liquid asphalt binder supplied by Conoco Phillips in Kansas City, Missouri, was used as the virgin binder for the 30% RAP and 40% RAP mixes. A virgin PG 64-22 binder from the same supplier was used for the 25% RAP/5% RAS mix. The liquid antistrip Morelife T280 [Ingevity (MeadWestvco), North Charleston, South Carolina] was added at a rate of 0.8% by weight of virgin binder for all three mixes. The rejuvenator was preblended with the virgin binder at the

Table 1. Design Gradation, Asphalt Content, and Volumetrics for Mix Design

Sieve size mm (in.)	30% RAP	40% RAP	25% RAP/5% RAS	Control points
19.0 (3/4″)	100	100	100	100
12.5 (1/2″)	94	96	95	90–100
9.5 (3/8″)	88	90	89	90 max
4.75 (#4)	66	72	66	—
2.36 (#8)	44	50	43	28–58
1.18 (#16)	31	36	31	—
0.6 (#30)	20	24	21	—
0.3 (#50)	13	16	15	—
0.15 (#100)	8	9	10	—
0.075 (#200)	6.2	7.1	7.5	2–10
Total AC (%)	5.2	5.2	5.3	—
Virgin AC added[a]	4.3 (0.83)	3.6 (0.69)[b]	3.4 (0.64)[b]	—
AC from RAP[a]	0.9 (0.17)	1.6 (0.31)	0.9 (0.17)	—
AC from RAS[a]	0	0	1.0 (0.19)	—
Air voids (%)	4.0	4.0	4.0	—
G_{mb} @ N_{des}	2.319	2.335	2.325	—
G_{mm}	2.416	2.433	2.422	—
VMA (%)	15.1	14.8	15.2	>14.0
VFA (%)	73.0	72.8	73.5	65–75
Vbe (%)	11.1	10.8	11.2	—
G_{sb}	2.590	2.599	2.595	—
G_{se}	2.607	2.628	2.619	—
P_{ba}(%)	0.26	0.44	0.36	—
P_{be} (%)	4.95	4.78	4.95	—
D/A ratio	1.3	1.5	1.5	0.8–1.6

[a]Binder content and (ratio of virgin AC, RAP AC, or RAS AC to total AC).
[b]Virgin binder was preblended with the rejuvenator.

recommended dosage before mixing with aggregates. The base binder used in the 30% RAP mix contained no RA. The approved job mix formulas (JMFs) and control points are shown in Table 1.

Production and Construction

The plant used for this field evaluation was located in Harrisonville, Missouri, approximately 23 mi north of the paving site. This Terex CMI counter-flow drum plant incorporated a Maxam AquaBlack foaming system to use as a compaction aid for this project. This plant had two silos, each with a 200-t capacity. Recycled No. 4 fuel was used to power this plant. The foaming allows for maximum coating of the aggregate as well as improved compactability at lower temperatures. The water was injected at a rate of 2% by weight of base binder for all three mixes.

A Caterpillar AP-1055E paver was used to pave these mixes. The asphalt mixtures were delivered using a variety of truck types including long dump beds, triaxle dump beds, and quad-axle dump beds. All trucks were covered, and a cycle of 15 trucks was used for each mix. A Weiler E2850 material transfer vehicle (MTV) was used to transfer the mixes to the paver. The temperature of the mix was measured every 5–20 min in the auger and behind the paver with a handheld temperature gun. Table 2 shows the temperatures of the mix in the behind the screed. The three mixes were paved at similar temperatures with the 40% RAP mix having a higher standard deviation than the others. However, it is unclear whether the variation was attributable to the higher RAP content.

All three mixes were compacted using the same three rollers. The breakdown roller was a Caterpillar C864 steel wheel roller. The rolling pattern for all three mixes was two passes on the joint, two passes on the edge of shoulder, and then forward in the center and back on the joint. A pass here is defined as both wheels of the machine rolling over a specific point on the mat. The intermediate roller was an Ingersoll Rand PT-240R rubber-tire roller. The rolling pattern for the intermediate roller was also the same for all mixes. The rolling pattern was two passes on each side in static mode. The finishing roller used on this project was a Caterpillar CB 54 steel-wheel roller. This roller was operated in the static mode for two passes on each side.

Table 2. Temperatures of Mix behind the Screed

Temperature (°F)	30% RAP	40% RAP	25% RAP/5% RAS
Average	267.5	262.1	268.8
SD	7.3	12.2	5.5
Maximum	285.0	286.5	280.5
Minimum	256.0	221.5	260.0

Table 3. In-Place Density from Cores

Test	Statistic	30% RAP	40% RAP	25% RAP/5% RAS
In-place density (%)	Average	92.9	92.3	94.0
	SD	1.08	2.23	0.71

After construction, six 150-mm (6-in.) cores were obtained from each mix section. These cores were taken back to the lab, and the density of the surface layer was determined for the cores from each mix after trimming from the underlying layers. Average core density results are shown in Table 3. It was observed that the average in-place density for the three mixes was similar and higher than the in-place density requirement of 92% G_{mm}. Therefore, these mixes had similar compactability under the same compaction effort.

Laboratory Performance Testing

Binder Grading

Table 4 shows the performance grades (PG) of six binders. The three tank binders were sampled at the plant during production. The tank binder used to produce the 30% RAP mix was not blended with RA, but the tank binders used for the 40% RAP and 25% RAP/5% RAS mixes were blended with 0.75 and 1.33% RA by weight of RAP and RAS materials, respectively. The dosage of RA was higher in the 25% RAP/5% RAS mix because of the stiffer post-consumer RAS binder used in this mix. The recovered binders shown in Table 4 were extracted from plant mixes in accordance with Method A of AASHTO T164 (AASHTO 2014) and then recovered in accordance with ASTM D5404/D5404M (ASTM 2012). After extraction and recovery, the recovered binder from each mix was graded according to AASHTO M320 and AASHTO R29 (AASHTO 2010b, 2011b) to determine continuous and PG grades.

Table 4. Asphalt Testing Results

Material	Test	30% RAP mix	40% RAP mix	25% RAP/5% RAS mix
Tank binder	True grade	71.7–23.7	64.5–27.6	58.2–31.3
	PG grade	70–22	64–22	58–28
	Rotational viscosity @ 135°C, PaS	0.615	0.400	0.275
Recovered binder	True grade	82.2–27.7	86.9–25.1	88.6–26.9
	PG grade	82–22	82–22	88–22

As required by MoDOT for this field trial, the performance grades of the binders extracted from the 40% RAP and 25% RAP/5% RAS mixes must be equal or better than that of the binder extracted from the control 30% RAP mix. To meet this requirement, the base binders used to produce the 40% RAP and 25% RAP / 5% RAS mixes were blended with 0.75% and 1.33% RA by weight of RAP and RAS and graded as PG 64-22 and PG 58-28, respectively. As shown in Table 4, with the recommended dosages, the binders recovered from the corresponding plant mixes met the MoDOT requirement—to be graded as PG 82-22 or better. It was also observed that the binder with RA for 25% RAP/5% RAS mixes showed the lowest rotational viscosity at 135°C, followed by that for 40% RAP mix and by that for 30% RAP.

Mixture Performance Testing

To evaluate the effect of the RA on performance of mixtures with high RAP and RAS, the following laboratory tests were conducted in this study: (1) Hamburg wheel-track (Hamburg) testing to determine both the rutting and stripping susceptibility; (2) tensile strength ratio (TSR) test to evaluate moisture susceptibility; (3) dynamic modulus (E^*) test to compare the linear viscoelastic characteristics; (4) overlay test (OT) to determine the resistance to cracking at intermediate temperatures; and (5) indirect tensile testing (IDT) to investigate the resistance to cracking at low temperatures.

As for the aforementioned volumetric samples, specimens for performance tests were also plant-mixed/lab-compacted (PMLC) on-site in the mobile lab. During the specimen preparation, mix was split out at trial masses for each specimen type and compacted to the required height once the compaction temperature [130°C (265°F)] was reached. These trial specimens were then bulked according to AASHTO T166 to determine G_{mb} and air voids. These data were then used to determine the required mass for each specimen type to reach the required air void level for the performance tests. In addition, field cores were also extracted to test for IDT low temperature cracking.

The following subsections briefly describe each laboratory testing procedure and discuss testing results to characterize the performance of the mixes evaluated in this field study.

Hamburg Wheel-Tracking Test

Hamburg wheel-track testing was performed to determine both the rutting and stripping susceptibility of the mixtures sampled in this project. Testing was performed in accordance with AASHTO T324-11 (AASHTO 2011a). Three replicates were tested per mix. The specimens were originally compacted using an SGC to a diameter of 150 mm and a height of 95 mm. These specimens were then trimmed so that two specimens, with a height between 38 and 50 mm, were cut from the top and bottom of each gyratory-compacted specimen. The air voids of these cut specimens were $7.0 \pm 1.0\%$.

The specimens were tested under a 71.1 ± 0.5 kg (158 ± 1 lb) wheel load for 10,000 cycles (20,000 passes) while submerged in a water bath maintained at a temperature of 50°C. While being tested, rut depths were measured by an linear variable differential transformer (LVDT), which recorded the relative vertical position of the load wheel after each load cycle. After testing, these data were used to determine the point at which stripping occurred in the mixture under loading as well as the relative rutting susceptibility of those mixtures.

Comparing the stripping inflection points and total rutting of the different mixtures gives a measure of the relative moisture and deformation susceptibility of the mixtures. A stripping inflection point of greater than 10,000 passes has been considered to be an indicator of a moisture-resistant mixture. The Texas Department of Transportation (TxDOT) uses the criteria in Table 5 to evaluate the rutting resistance of their asphalt mixtures.

Table 5. Texas Department of Transportation Requirements for Hamburg Testing

High-temperature binder grade	Minimum passes to 12.7 mm (0.5 in.) rut depth
PG 64 or lower	10,000
PG 70	15,000
PG 76 or higher	20,000

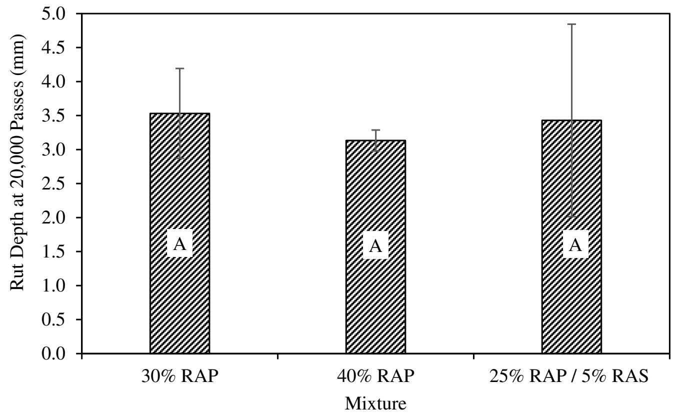

Fig. 1. Hamburg test results

Fig. 1 shows the average rut depth of triplicate specimens for the three mixes at 20,000 wheel passes. All three mixtures passed TxDOT's criteria of 12.5 mm at 20,000 wheel passes. The 40% RAP and 30% RAP mixes exhibited the lowest and highest rut depths, respectively.

A one-way ANOVA statistical test with Tukey-Kramer statistical groupings was conducted on the rutting results at a significance level (α) of 0.05. The results of the statistical test suggested that the rutting resistance of these mixes was not significantly different.

Besides the rutting depth, the striping inflection point (SIP) obtained from the Hamburg test was also used to evaluate the moisture susceptibility of these mixes. No stripping was observed for these mixes in the Hamburg test, indicating that the resistance to moisture damage of these mixes was acceptable.

Tensile Strength Ratio Test

Tensile strength ratio moisture susceptibility testing was performed for this project in accordance with AASHTO T283 (AASHTO 2012b). This methodology uses 95-mm samples compacted in an superpave gyratory compactor (SGC). The target air void level for these samples was $7.0 \pm 0.5\%$.

A set of three specimens was vacuum saturated so that 70–80% of the internal voids were saturated with water. The samples were then placed in a freezer for a minimum of 16 h prior to being placed in a warm water bath (60°C) for 24 h. This process constitutes one freeze-thaw cycle. These conditioned specimens, along with a group of three unconditioned specimens that had not been saturated, were then tested for indirect tensile strength (ITS) using a Marshall press apparatus. In this test, all samples are placed in a 25°C water bath for 2 h to equilibrate their temperature. The ratio of the indirect tensile strengths of the conditioned and unconditioned samples is recorded as the tensile-strength ratio.

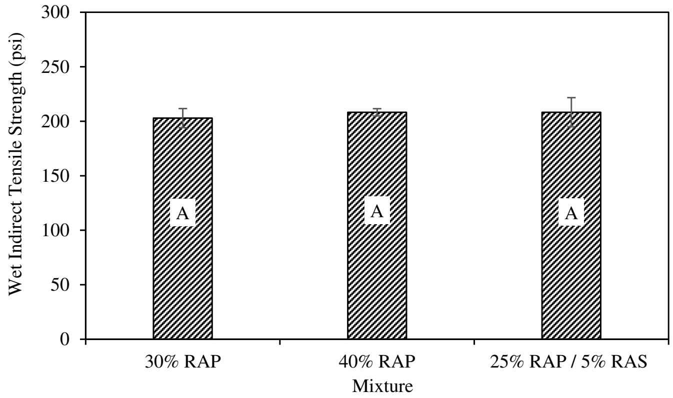

Fig. 2. Comparison of wet indirect tensile strength results

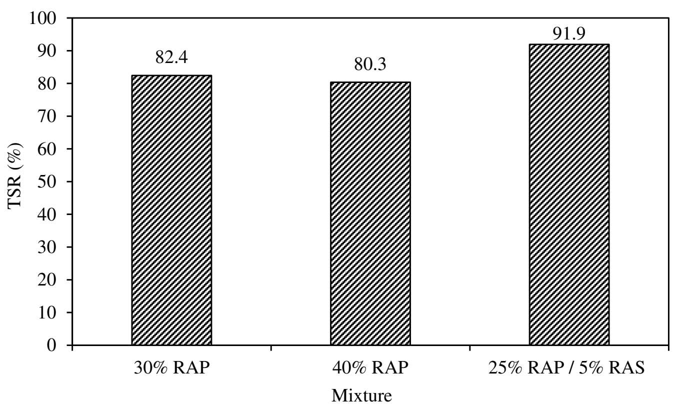

Fig. 3. Comparison of TSR results

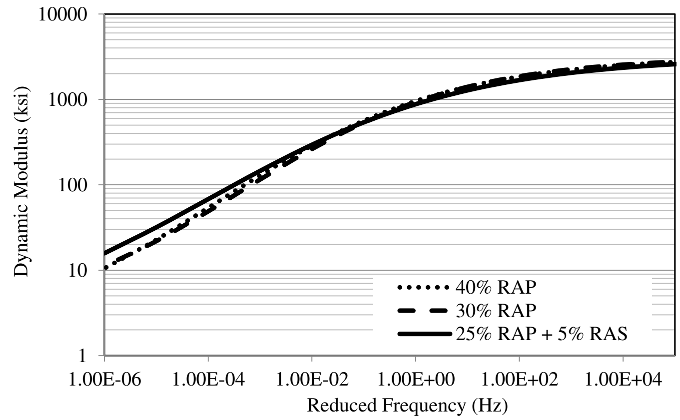

Fig. 4. Comparison of *E* test results

In accordance with AASHTO R35 (AASHTO 2012a), the minimum TSR criteria is 0.8 for moisture-resistant mixes, indicating less than a 20% reduction in splitting tensile strength given conditions conducive to moisture-induced damage.

Fig. 2 compares the average wet indirect tensile strengths of triplicate specimens. A one-way ANOVA ($\alpha = 0.05$) with Tukey-Kramer statistical groupings showed that the difference between the wet IDT strengths of the three mixes was not statistically significant. The TSR values for all the mixtures tested in this study (Fig. 3) were equal or greater than the commonly accepted failure threshold of 0.8. Overall, the use of RA and foaming technology in producing these high recycled content mixtures did not negatively affect their resistance to moisture damage.

Dynamic Modulus Test

The samples for this testing were prepared in accordance with AASHTO PP60-09 (AASHTO 2009). The samples were compacted to a height of 175 mm and a diameter of 150 mm, then cut and cored to a height of 150 mm and a diameter of 100 mm. The target air void level for these specimens was $7.0 \pm 0.5\%$ after trimming. Three samples were prepared for testing from each mix. Dynamic modulus testing was performed in accordance with AASHTO TP79-12 (AASHTO 2012c) in an IPC global asphalt mixture performance tester (AMPT). This testing was performed unconfined and test data were screened for data quality in accordance with the limits set in AASHTO TP 79-12 (AASHTO 2012c). The temperatures and frequencies used for testing these mixes are those recommended by AASHTO PP61-10 (AASHTO 2010a). The collected data were used to generate a master curve for each mix. The master curve uses the principle of time-temperature superposition to shift data at multiple temperatures and frequencies to a reference temperature so that the stiffness data can be viewed without temperature as a variable. This method of analysis allows for visual relative comparisons to be made between multiple mixes.

Fig. 4 compares the E^* master curves at the reference temperature of 20°C for the three mixes. The E^* master curves for the 30% RAP and 40% RAP mixes overlapped each other, indicating the softening effect of RA on stiffness of the 40% RAP mixture. The 25% RAP/5% RAS mixture exhibited slightly lower E^* at higher reduced frequencies (lower temperatures) but slightly higher E^* at lower reduced frequencies (higher temperatures) than the other mixes.

Overlay Test

The Texas overlay test is designed to simulate accelerated reflective cracking in asphalt concrete overlays. The TxDOT 248-F specification is the current testing methodology used for conducting the overlay test. In this study, the overlay test was conducted using a fixture and software within the IPC Global AMPT. For this test, SGC specimens were compacted to a target height of 125 mm. Upon achieving the desired height, two specimens per pill were trimmed to the following dimensions: 150 mm (6 in.) long, by 75 mm (3 in.) wide by 38 mm (1.5 in.) tall. Target air voids for the cut specimens was $7.0 \pm 1.0\%$. The specimens were glued to two aluminum plates using a two-part epoxy. A minimum of three replicates was desired for each mixture in the testing plan.

In this procedure, the samples are tested at 25°C in the controlled displacement mode. Loading occurs when a movable steel plate attached to the asphalt specimen slides away from the other plate. Loading occurs at a rate of one cycle every 10 s with a sawtooth waveform, and the maximum displacement per cycle is 0.63 mm (0.025 in.). The maximum load the specimen resists in controlled displacement mode is recorded for each cycle. The test continues until sample failure, which is defined as a 93% reduction in load magnitude from the first cycle (Tex 248-F).

The number of cycles to failure was determined for each mix. A mix with a higher number of cycles to failure may have better resistance to reflective cracking. Table 6 summarizes the test results, and Fig. 5 compares the average number of cycles to failure determined through the overlay testing. The 30% RAP mix had a higher average number of cycles to failure than the other mixes,

Table 6. Summary of Overlay Test Results

Mix identifier	Average air voids (%)	Number of tests	93% load reduction–cycles to failure		
			Average	SD	CV (%)
30% RAP	6.9	3	38	29.4	76.6
40% RAP	6.9	4	17	6.2	37.2
25% RAP/5% RAS	7.1	4	16	11.2	69.1

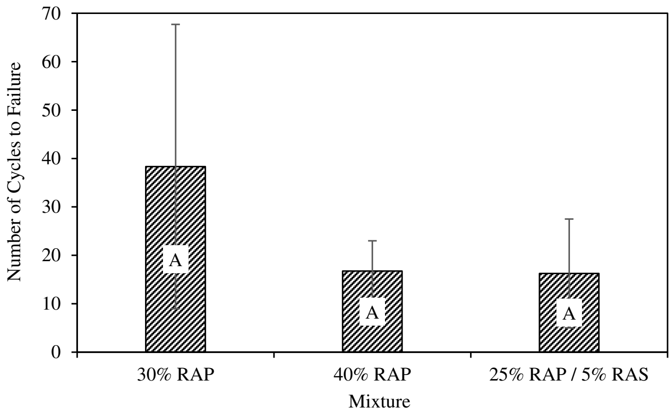

Fig. 5. Comparison of overlay tester results

which showed similar average cycles to failure. However, based on a statistical comparison [one-way ANOVA ($\alpha = 0.05$) with Tukey-Kramer statistical groupings], the difference in the number of cycles to failure between the three mixtures was not significant when considering the OT variability, making it difficult to distinguish the effect of the RA based on the OT results.

Low Temperature Indirect Tensile Test

The low-temperature cracking susceptibility of the mixes used in this study was evaluated using the AASHTO T322-07 (AASHTO 2007) procedure. The testing was conducted using an indirect tensile testing system with an MTS load frame and an environmental chamber capable of maintaining the required temperatures. Creep compliances at 0, –10, and –20°C and a tensile strength at –10°C were measured in accordance with AASHTO T322-07 (AASHTO 2007). These temperatures are specified as a function of the low-temperature PG grade of the binder in AASHTO T322-07 (AASHTO 2007). The indirect tensile test was conducted on both the PMLC specimens and cores extracted from the field test sections. PMLC specimens were compacted to 125 mm tall and

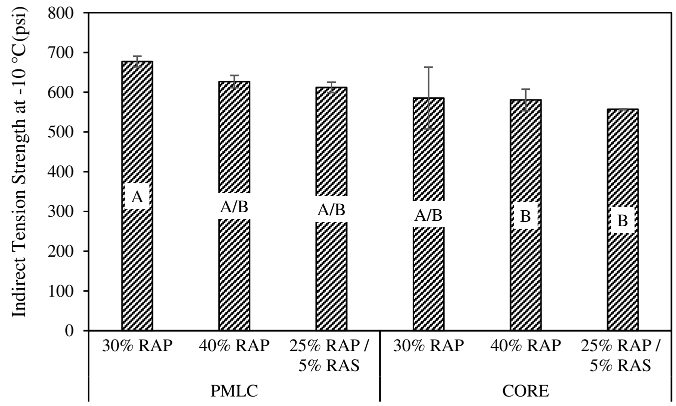

Fig. 6. Indirect tension strength at −10°C

150 mm in diameter prior to being trimmed. Four cut specimens were prepared for each mixture. Specimens used for the creep and strength tests were 150 mm in diameter and trimmed to a thickness of 38–50 mm. Trimmed specimens were prepared to 7.0 ± 0.5% air voids.

Table 7 summarizes the low-temperature cracking results. Fig. 6 shows the indirect tension strength at −10°C. As shown Fig. 6, the 30% RAP mix had the highest IDT strength at –10°C, followed by the 40% RAP and 25% RAP/5% RAS mixes for both the PMLC specimens and field cores. A one-way ANOVA ($\alpha = 0.05$) with Tukey-Kramer statistical groupings was performed to verify the statistical differences in indirect tension strength at −10°C for the three mixes. The statistical results are presented in Fig. 6 with A and B representing groupings with statistically different IDT strength results. The PMLC set of specimens for the 30% RAP mix had statistically higher IDT strength results than the other sets of specimens, which had statistically similar IDT strength results.

Early Field Performance

A field performance evaluation of the validation site near Harrisonville, Missouri, was conducted on June 20, 2014 after approximately 10 months of traffic was applied to its three test sections. The following subsections summarize the field performance results.

Rutting

The rut depths were measured at the beginning of each 200-ft section with a straight edge and a wedge. After 10 months, all three test sections had performed well in terms of rutting. None of the

Table 7. Summary of Low Temperature Cracking Results

Mix identifier	Average air voids (%)	Number of tests	IDT values at −10°C			Critical low temperature (°C)
			Average (psi)	SD	CV (%)	
30% RAP PMLC	7.0	3	677	13.6	2.0	−17
40% RAP PMLC	6.8	3	627	15.7	2.5	−14
25% RAP/5% RAS PMLC	6.9	3	612	13.2	2.2	−18
30% RAP core	7.1	3	585	77.8	13.3	−13
40% RAP core	6.6	3	581	27.2	4.7	−16
25% RAP/5% RAS core	6.6	3	557	1.5	0.3	−13

Note: CV = coefficient of variation; SD = standard deviation.

Table 8. Total Cracking Observed in Harrisonville, MO after 10 Months

Mix section	Severity	Transverse cracking: Number of cracks	Transverse cracking: Total length [m (ft)]
30% RAP	Low	3	9.1 (30)
	Moderate	0	0.0
	High	0	0.0
40% RAP	Low	3	11.0 (36)
	Moderate	0	0.0
	High	0	0.0
25% RAP/5% RAS	Low	6	22.0 (72)
	Moderate	0	0.0
	High	0	0.0

three data sections from any mix exhibited any measurable rutting after 10 months.

Cracking

The entirety of each 200-ft section was carefully inspected for visual signs of cracking and rated based on the LTPP Distress Identification Manual (Miller and Bellinger 2003). All of the three test sections exhibited some low-severity (<6 mm wide) transverse cracking. Table 8 shows the total cracking observed for each test section. As shown in Table 8, the 30% RAP mix had a total of 30 ft of cracking, and the 40% RAP mix had a total of 36 ft of cracking, compared to a total of 72 ft of cracking for the 25% RAP and 5% RAS mix. The majority of transverse cracking was deemed to be reflective cracking, since the cracks propagated across both lanes and the shoulder.

Conclusions and Recommendations

To mitigate the potential negative effect of the RAP/RAS binder on the durability of asphalt mixtures with high recycled contents, a national research effort has been spent on evaluating the use of emerging technologies to improve the durability of these mixes. As part of this effort, this field study was conducted to evaluate the long-term field performance of high RAP and RAS mixes with a recycling agent (RA) known as Hydrogreen, supplied by Green Asphalt Technologies. The field study consisted of three test sections on SR 7 (approximately 24 km (15 mi.) southeast of Harrisonville, Missouri), each constructed by placing a dense-graded surface lift at a depth of 4.5 cm (1.75 in.) in August 2013. The three mixes placed in the three test sections included

- 30% RAP mix (control) produced with an SBS-modified PG 70-22 binder with no RA.
- 40% RAP mix produced with the same PG 70-22 binder blended with 0.75% RA by weight of RAP.
- 25% RAP and 5% RAS mix produced with a neat PG 64-22 binder blended with 1.33% RA by weight of RAP and RAS.

This paper describes the construction activities, presents the laboratory test results of asphalt mixtures sampled during production, and discusses the early field performance of the test sections. Based on the results presented in this paper, the following key findings are offered:

- While the three mixes were designed with different proportions of virgin and recycled materials, their gradations and volumetric properties were very similar. The dosages of RA were determined for the 40% RAP and 25% RAP/5% RAS mixes to achieve the same level of field performance as the control mix. The RA was then blended with and replaced the equivalent amounts of the corresponding virgin binders used in the 40% RAP and 25% RAP/5% RAS mixes. The binder contents of these two mixes were similar with and without RA. MoDOT approved all of the mix designs before construction.
- The three mixes were compacted using the same rolling patterns with breakdown, intermediate, and finishing rollers. The three test sections met the MoDOT in-place density requirement of 92% measured by field cores.
- With the recommended dosages of RA, the binders recovered from the corresponding plant mixes met the MoDOT requirement—the performance grades of the binders extracted from the 40% RAP and 25% RAP/5% RAS mixes were PG 82-22 and PG 88-22, respectively, which were equal to or better than that extracted from the control 30% RAP mix (PG 82-22).
- The use of RA in the 40% RAP and 25% RAP/5% RAS mixes yielded statistically similar resistance to intermediate-temperatue and low-temperature cracking to that of the 30% RAP mix in the laboratory without negatively affecting the mix resistance to rutting and moisture damage. The mix resistance to rutting and moisture damage was determined based on the Hamburg wheel-track and tensile strength ratio tests, while the mix resistance to intermediate-temperature cracking and low-temperature cracking was evaluated based on the overlay test and the low-temperature indirect tensile test, respectively.
- Based on the dynamic modulus test results, the stiffness of the 40% RAP mix was very close to that of the 30% RAP mix, suggesting that the RA lowered the stiffness of the 40% RAP mixture. The 25% RAP/5% RAS mixture was stiffer at high temperatures and slightly softer at low temperatures than the other mixes, but these differences were not statistically significant.
- Based on the field survey of the three test sections at 10 months after construction, none exhibited any measurable rutting. However, low-severity reflective cracking was observed in all sections, with the 25% RAP/5% RAS mix section having more cracks than the other two sections.

In summary, a recycling agent can be used in asphalt mixtures with higher recycled contents to achieve similar in-place density and laboratory and early field performance as those with lower recycled contents. As these sections are still in service, it is recommended that they continue to be monitored in order to evaluate their long-term performance.

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