Assessing Binder Blending Level in Asphalt Mixtures Containing Recycled Asphalt Shingles

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Abstract: The recycling of asphalt shingles (RAS) in hot mix asphalt (HMA) has been the topic of much research. The asphalt binder of RAS is highly aged, oxidized, and stiffened, and the incorporation of it into HMA may alter the performance characteristics of the asphalt mixture. The first goal of this study was to determine the degree to which RAS binder blends with HMA virgin binder; the second goal was to determine the potential effects of this blending of binders on the long-term performance of RAS-containing HMA. A series of laboratory experiments were conducted, and the performance of RAS-containing HMA, which was fabricated replicating practical field conditions, was compared in two extreme scenarios—zero binder blending and total blending. The results showed that the performance of RAS-containing HMA tended to be closer to the total blending scenario. This suggests that RAS binder blends with HMA virgin binder nearly to the full extent. In addition, increasing RAS content makes HMA brittle and, therefore, more vulnerable to early-age cracking. **DOI: 10.1061/(ASCE)MT.1943-5533.0002835.** *© 2019 American Society of Civil Engineers.*

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Introduction

Asphalt shingles are one of the most widely used roofing materials in North America (Arnold 2016). A typical shingle is manufactured with approximately 20%–35% asphalt binder, 20%–38% fine aggregate, 8%–40% mineral filler, 2%–15% reinforcing mat, and 0.2%–2% adhesives, by weight (McGraw et al. 2007; Zhou et al. 2012). When asphalt shingles reach the end of their service lives, they can be recycled; recycled shingles have been used in many applications, including asphalt pavements. Using recycled asphalt shingles (RAS) in asphalt pavements has been reported to have environmental benefits (Zhou et al. 2012; Zinke and Mahoney 2015). Because shingles contain high levels of asphalt binder, RAS has often been considered a valuable resource in the construction of asphalt pavement. Recycling asphalt shingles has been a developing technology for more than two decades (McGraw et al. 2007).

Before using RAS in asphalt mixtures, it is important to remember that the service life of asphalt shingles may be very long (20–50 years); therefore, the asphalt binder in RAS is severely aged, oxidized, and stiffened by the end of its service life (You et al. 2011). Thus, when aged binder from RAS is combined with the virgin binder of an asphalt mixture, it can significantly alter the physical properties of the asphalt binder in the mixture, which may influence the performance of the mixture. Because the binder content of RAS is relatively high (20%–35% by weight), even adding RAS at low percentages may impact the physical properties of the finished product. Therefore, RAS needs to be used very carefully in order to account for its stiffening effect on hot mix asphalt (HMA) binder and on the total mixture. For example, in previous studies, the percentage of incorporated RAS has been limited to 5.0% by weight of HMA (Zhao et al. 2013; Zinke and Mahoney 2015; Tavassoti-Kheiry et al. 2016).

This study was designed based on concepts presented in another study, in which the effects of incorporating reclaimed asphalt pavement (RAP) into asphalt mixtures on the performance of asphalt mixtures were evaluated (McDaniel et al. 2000). The main goal of this applied research was to determine whether the asphalt binder of RAS blends with the virgin binder of HMA to any extent and, if binder blending occurs, how the blending influences the performance of the mixture. If there is no blending, then RAS can be said to behave simply as a black rock—the aged asphalt binder remains entirely with the RAS material and does not contribute to the overall physical properties of the HMA binder or to the total binder content.

To address the question of blending, mixture specimens were prepared and tested, simulating three blending scenarios: actual practice (AP), black rock (BR), and total blending (TB). The black rock and total blending scenarios represent the two possible binder blending extremes—from the extreme in which all of the RAS binder blends with the virgin binder (TB) to the case in which there is no blending between the RAS binder and the virgin binder (BR).

To prepare specimens for the BR scenario, the aggregate portion of RAS was simulated by adding additional virgin fine aggregate with a gradation equivalent to that of the extracted RAS aggregate. This practice was chosen instead of adding extracted RAS aggregate directly because of the difficulty of separating fibers and filler from the RAS aggregate. At low RAS levels (maximum of 5%),

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it was assumed that the impact on the overall aggregate structure resulting from this substitution would be minimal. In addition, under this scenario the binder was simply virgin asphalt binder, with no RAS binder contribution.

Specimens prepared for the AP scenario were intended to replicate actual field practice conditions in which RAS is added directly to HMA, with some binder blending expected to occur during the mixing. Finally, specimens for the TB scenario were fabricated by extracting and recovering the RAS binder and physically blending it with the virgin binder before mixing the blended binder with the virgin and extracted RAS aggregates.

The concern about the impact of RAS on HMA performance is shared by other researchers, making the subject of this paper highly relevant (Abbas et al. 2013). In order to investigate the effects of incorporating RAS on some of the key performance parameters of asphalt mixtures, a series of laboratory experiments were conducted. In addition, to study the effects of RAS content on mixture performance, two RAS percentages (2.5% and 5.0% by weight) were incorporated into the asphalt mixtures for each of the three blending scenarios.

In this study, the specimens were aged under severe conditions to simulate the long-term cracking performance of RAS-containing HMA—specifically fatigue and fracture. MINITAB 1972 version 17, a statistical analysis program, was used to perform ANOVA and Tukey tests for pairwise comparisons in order to provide a statistically based understanding of the experimental results (at a significance level of alpha = 0.05 or confidence level of 95%).

Materials and Methods

Materials and Mix Design

Two mix designs were prepared for the three blending scenarios: actual practice, black rock, and total blending. The mixtures were designed with 2.5% and 5.0% recycled asphalt shingles by weight of the HMA. The percentages were selected to represent average and high RAS usage rates in asphalt mixtures. The asphalt content of the RAS in this study was 23.5%, and the nominal maximum aggregate size (NMAS) was 2.36 mm. The total binder content of each mix design was 5.4%, and the NMAS of the HMA was 9.5 mm. PG 58-28 was used as the virgin binder and contributed 4.8% and 4.2% by weight of the HMA for the 2.5% and 5.0% RAS mixtures, respectively. Because the RAS contained 23.5% asphalt binder and the total asphalt binder content of each asphalt mixture was 5.4%, 2.5% RAS by weight of the mixture means that the RAS contributed 10% of the total asphalt binder used. Similarly, the asphalt mixtures made with 5.0% RAS by weight had 21% RAS binder used in the total asphalt binder blend. The results of the sieve analysis of the RAS aggregate and the RAS-containing asphalt mixtures are presented in Table 1.

Each RAS mixture design was established using the actual practice conditions, which assume that some blending of the RAS binder and the virgin binder occurs. For this scenario, RAS particles were added directly to the HMA mixture and mixed and integrated into the overall mixture using a hand-held mixer. The black rock scenario was simulated by using no RAS material in the HMA specimens; essentially, the bulk material of the RAS was treated as a virtual aggregate. Therefore, the RAS quantity was represented in the HMA by an equal amount of virgin fine aggregate to account for the aggregate portion of the RAS.

The binder content in the BR scenario was designed to 5.4% for both RAS quantities. However, because no RAS material was used, the binder content was the amount of virgin binder in the mixtures, 4.8% and 4.2% for 2.5% and 5.0% RAS content, respectively. The total blending scenario assumed there was complete blending of the RAS and virgin binders. The TB mixtures were prepared by extracting and recovering the RAS binder and force-blending the recovered binder with the virgin asphalt binder. The RAS-containing HMA mixtures were then prepared by mixing the fully blended binder with the RAS and virgin aggregates. To blend the RAS and virgin binders, the RAS and virgin binders were heated to temperatures at which they were fluid to pour, approximately 190°C and 150°C, respectively. The RAS binder was weighed into a tared container based on its proportional contributions of 11% and 22% by weight to the total binder content. To produce the 2.5% and 5.0% RAS binder contents, 89% and 78% virgin binder, respectively, was poured into the blending container with the RAS binder. The container was placed into a thermal heating well to keep the binder at an appropriate temperature for blending (approximately 150°C). A hand-held mixer using approximate 1,200–1,500 round per minute (RPM) was used to thoroughly blend the binders until an even fluidity was achieved. After sufficient blending, the binder and container were placed back into the oven at mixing temperature. Once the binder reached mixing temperature (after approximately 30 min) and immediately prior to introducing the binder to the aggregate, the RAS and virgin binder blend was stirred for a short period of time to ensure homogeneity.

Table 1. Sieve size analysis of RAS aggregate and RAS-containing asphalt mixtures

Sieve size (mm)	Passing percentage		
	RAS aggregate	RAS-containing asphalt mixtures: 2.5% RAS content	5.0% RAS content
12.5	100	100	100
9.5	100	95	95
4.75	97	73	73
2.36	94	49	49
1.18	78	32	32
0.6	58	21	21
0.3	48	12	12
0.15	38	7	7
0.075	29.3	5.1	5.3

Mixtures containing RAS can stiffen asphalt mixtures; therefore, a softer virgin binder is often used to account for this phenomenon (You et al. 2011; Abbas et al. 2013). In this study, the PG grade of the virgin binder was lowered by one grade from PG 64-22 to PG 58-28. In another study, a similar modification to the virgin binder grade of the asphalt mixture was made to account for the stiffening effects of RAS on the binder (Zinke and Mahoney 2015).

Using these blend percentages (11% and 22%), the recovered RAS binder was physically blended with the appropriate percentage of virgin PG 58-28 asphalt binder (89% and 78%, respectively) to produce the 2.5% and 5.0% RAS blends. The binder blends were then tested to determine their physical properties. The continuous PG grade of the 2.5% and 5.0% RAS blends were determined to be 65-26 (PG 64-22) and 72-23 (PG 70-22), respectively.

Mixture Testing

Two sets of experiments were conducted on the mixtures: flexural beam fatigue in accordance with AASHTO standard T321 (AASHTO 2007); and fracture using the semicircular bend test in accordance with AASHTO TP124 (AASHTO 2016). Both experiments were performed at intermediate temperatures (20°C ± 0.5°C and 25°C ± 0.5°C, respectively).

Fatigue Life of Compacted Asphalt Mixtures

Fatigue is an important failure mode in asphalt pavements and is exacerbated by material brittleness (Maggiore et al. 2014; Shishehbor et al. 2019). In asphalt pavements, microcracks originate at the bottom (or top) of the asphalt layer due to repetitive flexural stresses and strains induced by traffic loads. Microcracks propagate under cyclic loading and eventually lead to severe cracking and pavement failure (Maggiore et al. 2014). In order to evaluate the effects of incorporating RAS into asphalt mixtures on the fatigue performance of asphalt mixtures, four-point bending beam fatigue tests were conducted on the samples in accordance with AASHTO T321. This standard provides a procedure for determining the fatigue life and dissipated energy of asphalt mixtures, which can be used to estimate the fatigue life of asphalt pavement layers under repeated traffic loading. Cycles to failure and dissipated energy are the two important parameters that are measured in this test. Failure is defined as the point at which the product of the specimen stiffness and the loading cycles is a maximum (AASHTO 2007). This test also allows investigators to measure the cumulative energy that is dissipated in a specimen before it fails.

The beam fatigue experiment was conducted on six mixtures—three blending scenarios (BR, AP, and TB) with two RAS contents (2.5% and 5.0% by weight of the mixes) for each scenario. To provide a valid statistical analysis, three specimens were tested for each of the six mixture conditions. Loose mix samples were conditioned for 24 h at 135°C. This represented severe aging conditions relative to the conditioning reported by other researchers (Bonaquist 2011). The results obtained from the severely aged specimens in this study were expected to conservatively mimic the long-term performance of RAS-containing HMA. The fatigue test specimens were compacted into beams with dimensions of $380 \times 95 \times 82$ mm using a segmented rolling wheel compactor. Next, each compacted beam specimen was extruded from the mold, cooled to room temperature, and cut to the test size of 380 $380 \times 62 \times 50$ mm. The beam specimens were tested at 500 microstrains ($\mu\varepsilon$) with a loading frequency of 10 Hz at a temperature of 20°C ± 5°C.

Fracture Potential of Asphalt Mixtures

Semicircular bend (SCB) tests were conducted on the HMA specimens in accordance with the AASHTO TP124 standard. This test determines the fracture resistance parameters of an asphalt mixture at an intermediate temperature. The fracture energy G_f is calculated by dividing the work of fracture by the ligament area. By definition, the work of fracture is equal to the area under the load versus the average load-line displacement curve, and the ligament area is defined as the product of the ligament length and the thickness of the specimen (AASHTO 2016). The calculated fracture energy indicates the mixture's overall capacity to resist cracking-related damage. In addition, using the fracture parameters obtained from this experiment, the flexibility index (FI) of an asphalt mixture can be calculated. The FI is intended to characterize the damage resistance of an asphalt mixture using the slope of the elongation curve (i.e., the ductility of the mixture). Steep slopes represent brittle mixtures, while shallow slopes indicate better adhesion and flexibility. Using the FI parameter makes it possible to evaluate the effects of RAS modification on the brittleness and elongation capabilities of a mixture (Elseifi et al. 2012).

As in the fatigue life experiments, a total of six mixtures were studied; however, for each mixture, four specimens were tested. As with the beam fatigue specimens, loose mix was conditioned for 24 h at 135°C. Again, these severe aging conditions made it possible to conservatively evaluate the fracture performance RAS-modified asphalt mixtures. The SCB specimens were prepared by first compacting cylindrical specimens with a diameter of 150 mm and a height of 150 mm using a Superpave gyratory compactor (SGC). The specimens were then trimmed and cut into 50-mm thick slices. Each 50-mm specimen was then cut along its diameter into two half-moon specimens. A propagation notch was cut, perpendicular to the midpoint of the diameter-cut face. The SCB specimens were tested with a loading rate of 50 mm/min at a temperature of 25°C ± 5°C.

Results and Discussion

Fatigue Life of Compacted Asphalt Mixtures

Data analyzed from beam testing produced three sets of results: cycles to failure, dissipated energy, and initial/final stiffness. The results for cycles to failure as a function of RAS content are presented in Fig. 1. For the BR scenario, the number of cycles to failure N_f for RAS content of 2.5% was approximately 436,000 cycles. Under the BR scenario, no aged binder from the RAS was introduced to the mixture, and only the virgin binder, which lacked age-induced brittleness, was present in the HMA. Therefore, when RAS content was as low as 2.5%, the flexibility of the mixture was relatively high, which resulted in a high number of cycles to failure.

However, when 5.0% RAS was used in the mix, N_f dropped to approximately 52,000 cycles. Under the BR scenario, no RAS binder was blended with the virgin asphalt; this lowered the total asphalt binder content to 4.2%, requiring the virgin binder to cover more surface area of the aggregates, which may have made the mixture more brittle. This indicates that if there is no binder mixing, a mixture requires additional asphalt to be added, defeating the purpose of using RAS. For the 2.5% RAS mix, the flexibility of the binder masked the reduced asphalt binder content (from 5.4% to 4.8%), causing the mixture to perform better than expected. However, for the 5.0% RAS mix, there was a much lower total effective asphalt binder content, making the mixture stiff and brittle. As a result, the number of cycles to failure decreased drastically. This suggests that fatigue life would decrease with higher RAS content, even with softer virgin asphalt binder grades.

For the TB scenario, the virgin binder was physically blended with the recovered RAS binder in the percentages previously described. As expected, this caused the overall blended binder to stiffen. Consequently, N_f was significantly lower for the TB scenario at 2.5% RAS as compared to the BR scenario at the same RAS content. As expected, increasing the RAS content to 5.0% further decreased N_f, indicating an increase in the brittleness of the mixture.

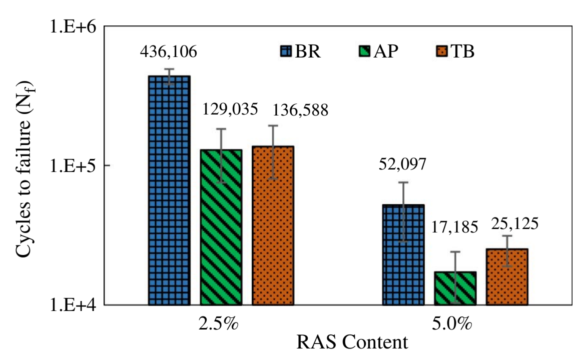

Fig. 1. Cycles to failure as a function of RAS content for the three scenarios.

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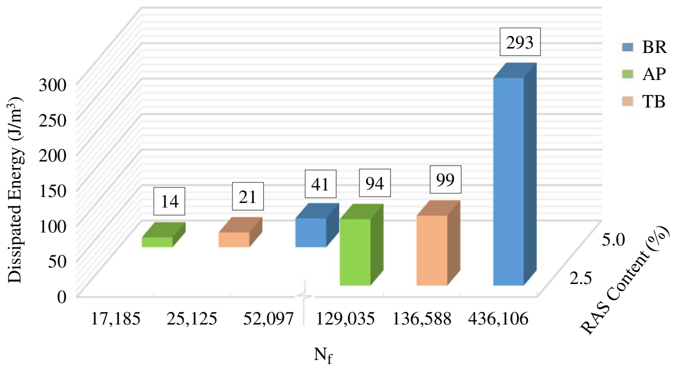

Fig. 2. Dissipated energy in specimens under fatigue life tests.

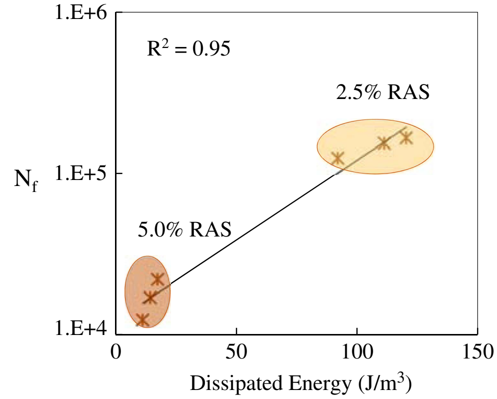

Fig. 3. Regression relationship between N_f, RAS content, and dissipated energy for the AP scenario.

At both levels of RAS content, the behavior of the mixtures in the AP scenario was more similar to the TB scenario than the BR scenario. Based on the statistical analysis over the range of RAS contents, there was not a significant difference in the number of cycles to failure between the TB and AP scenarios. This suggests that, in practice, the aged binder of the incorporated RAS blends with the virgin binder in the asphalt mixture. Although mixing temperature and time in a mixing plant would probably not be sufficient to allow for the total physical blending of RAS binder with virgin asphalt binder, the results for the bulk properties of RAS-containing mixtures in this study indicate that binder blending does occur. In another study, it was reported that partial blending of aged RAS binder and the virgin binder of the asphalt mixture does take place (Zhao et al. 2013).

Fig. 2 shows the dissipated energy in the HMA specimens as a function of RAS content and cycles to failure for each of the three blending scenarios. For the BR scenario at 2.5% RAS content, the average dissipated energy of the specimens was approximately 300 J/m^3. When the RAS content was increased to 5.0%, the average dissipated energy dropped to approximately 40 J/m^3 (an 85% reduction). The dissipated energy of an asphalt mixture is a function of the asphalt binder content of the mixture and the flexibility of the mixture. At 2.5% RAS content, there is enough virgin binder to maintain a somewhat flexible mixture. However, with an RAS content of 5.0%, which caused the BR scenario to have an effective binder content of 4.2%, the mixtures demonstrated brittle behavior. This brittleness reduced the area under the force-displacement diagram and, therefore, significantly decreased the dissipated energy. This behavior will be discussed further subsequently.

For the TB scenario at 2.5% RAS content, the dissipated energy was approximately 100 J/m^3, which was 66% less than in the BR scenario with the same RAS content. In the TB scenario, the extracted aged and stiffened binder was mixed with the virgin binder, which made the final mixture stiff and brittle. As expected, increasing the RAS content to 5.0% further decreased the dissipated energy, which indicates further brittleness.

Based on the statistical analysis, there was not a significant difference between the results for dissipated energy in the TB and the AP scenarios at 2.5% RAS. The same trend held true when the RAS content was at 5.0%. This shows that for the dissipated energy of asphalt mixtures under cyclic fatigue loading, performance under actual practice conditions is more similar to the total blending scenario than to the black rock scenario. This supports the notion that RAS binder acts as if it is fully blended with the virgin binder in an RAS-containing HMA.

The AP scenario is the most realistic representation of the field. Therefore, this scenario was selected for fatigue model development. Fig. 3 shows the relationship between the laboratory-measured fatigue life N_f and the dissipated energy, replicated at two different RAS contents.

Traditionally, the fatigue life of HMA N_f has been correlated with the tensile strain at the bottom of the HMA layer and the stiffness (Finn et al. 1977; Shell International Petroleum Company Limited 1978; Asphalt Institute 1982). However, in this study a more holistic modeling approach was adopted, which correlates N_f to the laboratory-measured dissipated fatigue energy. In addition, because the focus of this study was on RAS-containing HMA, the RAS content was also included in the model, as follows:

$$N_f = 2{,}560 \times (\mathrm{DE})^{0.941} \times (100 \times \mathrm{RAS\ content})^{-0.366} \quad (1)$$

where DE = dissipated energy in an RAS-containing HMA specimen in J/m^3; and RAS content is given as a percentage. The coefficient of determination R^2 of the proposed equation was 0.95, which indicates that the model does a good job of describing the trend given the variabilities in the data. The model presented in Eq. (1) suggests that by increasing RAS content, the fatigue life of the mixture decreases. This can be attributed to the highly aged and stiffened asphalt binder of the RAS, which makes the mixture brittle and more vulnerable to fatigue deterioration. Obviously, with more data the proposed model presented in Eq. (1) could be more refined, and more importantly, calibrated with field data.

The results for the initial and final stiffness values of all the specimens are presented in Fig. 4. For the BR scenario mixtures with 2.5% RAS content, the average initial stiffness was approximately 6,000 MPa. By increasing RAS content to 5.0%, the initial stiffness increased by 8% and reached approximately 6,500 MPa. Under the BR scenario, only the virgin binder was used in the mix, and by increasing the RAS content, which in this scenario was solely represented by the aggregates, the effective binder content was reduced. This slightly increased the stiffness of the mixture.

For the TB scenario, the initial stiffness values of the specimens at 2.5% and 5.0% RAS content were equal to 6,714 and 7,182 MPa, respectively; these values were significantly higher than those in the BR scenario. Under the TB scenario, the stiffened and aged RAS binder was recovered and physically blended with the virgin binder, making the mixture more stiff. These findings were in agreement with the work of previous researchers (McGraw et al. 2007). In addition, the increase in RAS content made the mixtures even more stiff. These results match the results presented in other studies, in which the incorporation of 5.0% RAS was reported to significantly increase the stiffness of asphalt mixtures (You et al. 2011; Tavassoti-Kheiry et al. 2016).

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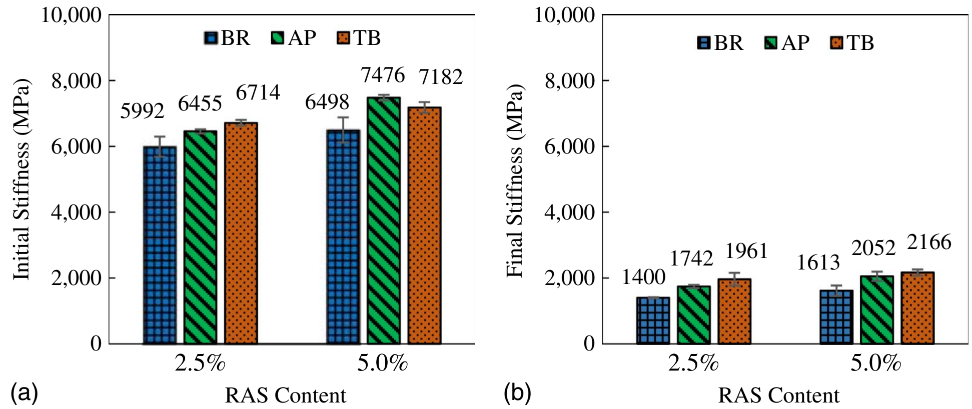

Fig. 4. (a) Initial stiffness; and (b) final stiffness before and after approximately 18,000 loading cycles.

The results of the statistical analysis showed that at both RAS content levels the initial stiffness of the AP and TB scenarios were not significantly different; however, they were significantly different from the BR scenario. Again, this supports the notion that the RAS binder acted as if it was fully blended when RAS was incorporated into the asphalt mixture, resulting in a stiffer mix.

The results for final stiffness showed that increasing the RAS content slightly increased the stiffness of the specimens. In addition, the statistical analysis suggests that the AP scenario matched the TB scenario more closely than it matched the BR scenario. When comparing initial to final stiffness, it was observed that, under all three scenarios and across RAS contents, there was a significant drop in the stiffness of the specimens after applying approximately 18,000 load cycles [Fig. 4(b)]. This may reflect the development of microcracks in the asphalt specimens caused by cyclic loading, decreasing the overall stiffness or load-carrying capacity.

Fracture Potential of Asphalt Mixtures

Fracture energy is often utilized for characterizing the cracking potential of HMA. The results from the SCB tests are presented in Fig. 5. For all the three scenarios, increasing RAS content from 2.5% to 5.0% decreased the fracture energy. This suggests that at higher RAS contents, asphalt mixtures have lower resistance against cracking.

Although the Fig. 5 data may appear to suggest that there could be a difference between the fracture energy for the various mixing scenarios, the results of the statistical analysis revealed that there was not a significant difference between them, and this held true at both low and high RAS contents. This could be the result of the severe laboratory-induced aging protocol, which may have masked a pre-rigid-binder to rigid-binder transition zone. Further research on the impact of laboratory-induced aging protocols on RAS-containing asphalt mixtures may be warranted.

The flexibility index is an additional important parameter that can be obtained from the SCB tests described in AASHTO TP124. The FI is calculated using the fracture energy and the slope of the force-displacement diagram in the post-peak region, which represents the average crack growth rate. The FI provides a means for identifying brittle mixes that are prone to premature cracking (Ozer et al. 2016).

The results for FI are presented in Fig. 6. For the BR scenario, increasing the RAS content from 2.5% to 5.0% decreased FI by 55%. This can be attributed to the decrease in the effective binder content in the BR scenario, which reduces the flexibility of the mixture. At the 2.5% RAS content, FI for the TB scenario was significantly less than it was for the BR scenario. This was the result of incorporating aged and stiffened binder into the mixture in the TB scenario. As expected, increasing RAS content from 2.5% to 5.0% further decreased the FI of the mixtures.

The decrease in the FI of the mixtures may indicate that RAS-containing asphalt mixtures are susceptible to early cracking (Abbas et al. 2013). Therefore, some researchers have recommended using softer asphalt binders in the production of RAS-containing HMA (Abbas et al. 2013; Zinke and Mahoney 2015).

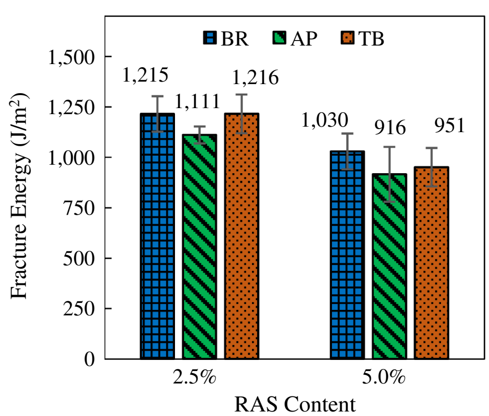

Fig. 5. Fracture energy of specimens obtained from SCB tests.

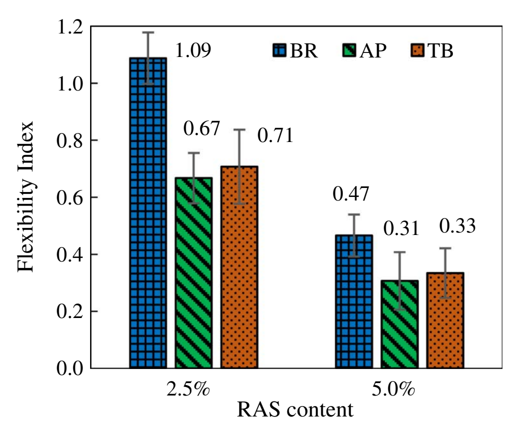

Fig. 6. Flexibility index obtained from SCB tests.

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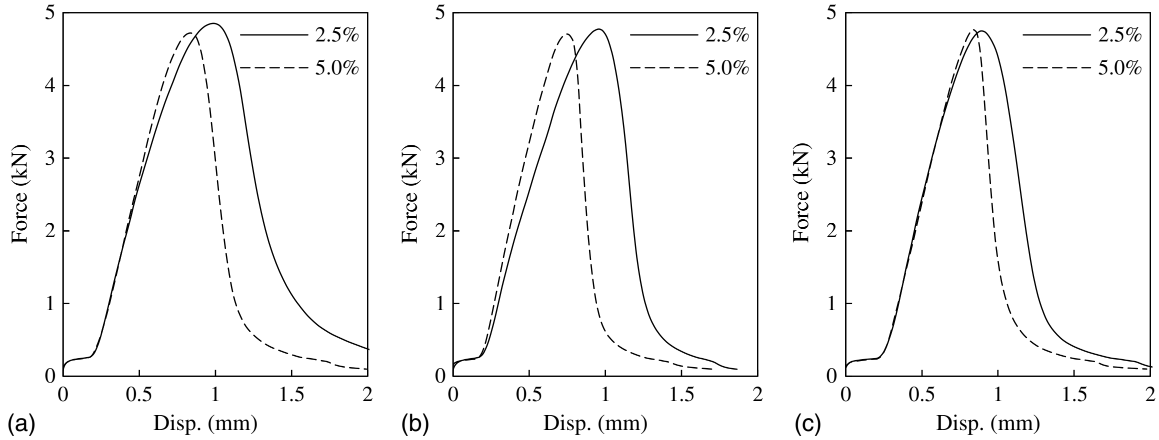

Fig. 7. Force-displacement relationship for each blending scenario and for cases of 2.5% and 5.0% RAS content: (a) BR; (b) AP; and (c) TB.

Based on the statistical analysis, there was not a significant difference in FI between the AP and TB scenarios for either the 2.5% or 5.0% RAS mixtures. Again, this appears to support the notion that RAS binder blends with the virgin binder, which results in a stiffer HMA. At 5.0% RAS content, there was no statistically significant difference between the BR, TB, and AP scenarios—likely due to the very low FI values.

The force-displacement data for all of the specimens are presented in Fig. 7. As the results show, for all blending scenarios, increasing RAS content from 2.5% to 5.0% did not significantly change the peak load; however, it decreased the corresponding displacement at the maximum load. Reaching a similar load level at a lower displacement level means that the stiffness of the specimen has increased. Other studies have shown that the incorporation of RAS increases the stiffness of asphalt mixtures (McGraw et al. 2007; Abbas et al. 2013). For the BR scenario, the increase in stiffness can be attributed to a decrease in effective virgin binder content due to additional demand from a higher aggregate surface area.

The area beneath the force-displacement graph presents the energy that was dissipated during fracture. In all three binder blending scenarios, the RAS-containing HMA demonstrated a shift toward a higher brittleness, which confirms the stiffening impact of adding RAS. This inference is in good agreement with the inference that was made based on the fatigue life data (Fig. 2).

Conclusions and Future Research

The goal of this study was to determine the degree to which the aged binder of RAS blends with virgin binder in asphalt mixtures containing RAS. The study included two extreme scenarios: black rock, which represented a no-binder-blending condition; and total blending, which represented full physical blending of the RAS binder with the virgin binder. In addition, a third scenario was examined, which was called actual practice (AP); this scenario was intended to replicate actual field practice conditions, in which RAS is added directly to asphalt mixtures with some binder blending expected. The results of the laboratory experiments demonstrated that the performance of specimens prepared under the AP scenario tended to be closer to that of specimens prepared under the TB scenario. This suggests that the highly stiffened and aged binder of RAS blends—or acts as if it blends—with the virgin binder of the asphalt mixture. Therefore, special consideration should be given to modifying the grade or physical properties of virgin asphalt binder in asphalt mixtures containing RAS. In addition, increasing RAS content decreased the flexibility index of the mixtures, making them more vulnerable to cracking. Higher RAS content decreased the laboratory-measured fatigue performance of the study asphalt mixtures. An energy-based fatigue model was proposed in this study, and it proved to be effective in predicting the impact of RAS content on the laboratory-measured fatigue life. More work needs to be conducted to measure the short-term and long-term performance characteristics of RAS-containing asphalt mixtures. It is also important to investigate the effects of various levels of asphalt aging as opposed to focusing only on the most severe cases of laboratory-induced aging.

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