Quantitative evaluation of low-temperature performance of sustainable asphalt pavements containing recycled asphalt shingles (RAS)

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HIGHLIGHTS

• The results supported the use of RAS modified mixtures in warm climates.
• The warmer embrittlement temperatures due to RAS is critical in cold climates.
• Nodules of RAS form due to partial blending between the RAS and virgin binders.
• RAS nodules accumulate damage first and thus govern the embrittlement temperature.
• Higher RAS content leads to higher peak loads and lower fracture energy in DC(T) test.

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Abstract

The low-temperature cracking characteristics of asphalt concrete materials containing varying amounts of recycled asphalt shingles (RAS), 0–12.5%, and mixed at three different temperatures are investigated using the Disk-shaped Compact Tension (DC(T)) and acoustic emission (AE) tests. The specimens’ AE activities were monitored during cooling from room temperature to −50 °C to determine their embrittlement temperatures. It was observed that the mixtures containing RAS had lower DC(T) fracture energies, higher DC(T) peak loads, and warmer embrittlement temperatures than the control mixture. Results also showed that higher mixing temperatures appear to lower embrittlement temperatures for mixtures containing RAS.

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1. Introduction

In the United States, about 96% of approximately 2.4 million miles of paved roads are surfaced with asphalt concrete [1]. The sustainability of these roads is of crucial importance, and the utilization of recycled materials has become a very economical and environmentally-friendly approach. A variety of recycled materials have been incorporated into hot mix asphalt (HMA) mixtures, including reclaimed/recycled asphalt pavements (RAP), reclaimed concrete, blast furnace slag, crumb rubber from scrap tires, glass, fly ash, bottom ash, batter cases, polypropylene containers, and recycled asphalt shingles (RAS) [2–4]. The emerging practice of incorporating RAS into HMA mixtures is worthy of attention and is the focus of this study.

According to the EPA, over 11 million tons of asphalt shingles are added to landfills in the United States each year [5–7]. This waste derives from both post-consumer and post-manufactured sources. Post-consumer asphalt shingles removed from old roofs—often referred to as tear-off scrap shingles (TOS)—account for over 10 million tons of this waste [5,8]. The remaining 1 million tons of waste come from flawed shingles and excess material from punch-out tabs produced by manufacturers, which is usually called manufacturers waste scrap shingles (MWSS) [5,9,10]. The high
availability of this recycled resource has the potential to abate the consumption of virgin materials while simultaneously reducing landfill dumping, thus providing economic and environmental gains. For example, recycling shingles into pavements would eliminate the landfill dumping fee, which has been reported to be as high as $100/ton [11,12]. Additionally, the asphalt binder content used in roofing shingles can be as high as 30–40% by weight of the total mixture, which is significantly greater than the 5–6% by weight of the total mixture binder content that is typical for paving applications. The percent asphalt content of aged shingles may be even greater due to a loss of mineral aggregate from weathering [13]. Although reclaimed post-consumer roofing material is often highly variable from source to source and it is comprised of deleterious constituents, the high binder content makes the inclusion of RAS in HMA pavements even more desirable from a sustainability standpoint. Also, some of the granular material and fibers in the shingle waste may act as aggregate and/or filler in the HMA mixture. Brock [11] estimated that the cost per ton of HMA could be reduced by about $7 by introducing 5% RAS, which corresponds to an annual savings of nearly $1 billion if all the shingle waste was incorporated in HMA mixtures.

Although a fair amount of research has been conducted on HMA mixtures containing RAS, most efforts have only addressed the inclusion of RAS in HMA pavements for applications in warm climates. Funded by the SHARP IDEA Program, an AE-based approach was developed in the Nondestructive Testing and Evaluation Laboratory at the University of Illinois at Urbana-Champaign to estimate the low-temperature embrittlement properties of binders and conventional HMA and RAP mixtures. Here, this AE-based approach is extended to estimate the embrittlement temperatures of mixtures containing RAS, which are of primary concern due to the brittle nature of the hardened asphalt from shingles. Disk-shaped Compact Tension (DC(T)) tests are also conducted to further evaluate low temperature performance.

### 1.1. Constituents of asphalt roof shingles

Typically, the amount of aggregate granules in shingles ranges from 40% to 70%, the asphalt content ranges from 20% to 40%, and fibrous base material ranges from 1% to 25% [6,10,13]. There are different types of granular material used in shingles: crushed rock particles coated with ceramic metal oxides, headlap granules (typically ground coal slag), backsurfer sand, and mineral filler [10]. Granular material is placed on both the top and bottom sides of shingles. The exposed top surface is covered with a protective layer of the headlap granules and the ceramic-coated granules that are typically colored for aesthetic purposes; the back surface is dusted with the fine, natural sand to prevent the shingles from sticking together when packaged [14]. Additionally, mineral filler, such as powdered limestone, is often used to stabilize the shingle’s asphalt to prevent flow when subjected to high temperatures [10]. Often, asphalt is applied to both sides of the base material to ensure waterproofing and adhesion of the granules [10]. Both types of asphalt are typically air-blown to increase viscosity; this further prevents flow at high temperatures and produces an asphalt binder that is harder and stiffer than those used in HMA pavements [2,10]. For example, the asphalt used in shingles in Illinois normally has a performance grade around PG112 + 2, which is a substantially stiffer grade than that of the state’s most commonly used asphalt for pavement application (PG64-22) [14]. In general, the base material is either organic (such as cellulose felt) or inorganic (such as fiberglass). Newcomb et al. [10] provides a discussion regarding two existing standards: ASTM D225 and ASTM D3462 for organic felt shingle and for glass felt shingle specifications, respectively. These specifications are quite broad, so the specific properties of the shingles are dependent on the manufacture. Additionally, the post-consumer TOSS material often contains deleterious materials—such as wood, nails, paper, asbestos, soil, metal, glass, rubber, brick and plastic—which may be incorporated into the reclaimed material when the shingles are removed [7,15]. Because of this debris and the inconsistencies in the manufacturing processes, there is a high variability in RAS from source to source, which is important to consider when evaluating the effects of RAS on HMA pavements.

### 1.2. Processing RAS materials to be used in HMA pavements

Most TOSS is acquired from re-roofed buildings that are not regulated by the National Emission Standard for Hazardous Air Pollutants (NESHAP), such as non-commercial facilities and single-family homes [14]. Because the majority of TOSS is from these unregulated sources, the material must be screened for asbestos, which was sometimes used as the base material for shingles manufactured before the early 1980s. When used, the carcinogenic material was typically less than 1% of the product, and thus asbestos is very rarely found in quantities over the 1% threshold to be considered an asbestos-containing material [16]. Regardless, TOSS is still required to first be tested for asbestos before further processing. The content of the MWSS, on the other hand, is known and regulated, so this RAS material does not require such an impurity screening.

Both types of RAS materials are typically shredded using large wood chippers. The RAS material tends to blend better with the HMA mixture when the nominal size of the processed material is relatively small (<12.5 mm) [11]. Once ground to specifications the RAS material is sent to the HMA plant where the material is generally stockpiled. However, particularly in hot climates, the stockpiled RAS particles may start to conglomerate due to the high asphalt content. Sand is sometimes introduced during shredding to lower the percentage of asphalt binder, thus mitigating this effect [3,11]. Watering has also been used to prevent shredded pieces from clumping together; however, this is not ideal since drying the material would be required before use [6].

After processing, the RAS material can usually be fed directly into the HMA mixture using the same methods that most HMA plants have in place for incorporating RAP. Mixing times should be increased when incorporating RAS to ensure proper blending. Batch plants and plants using a continuous double barrel mixer are both well suited for incorporating RAS; however, plants using counterflow drum mixers with imbedded burners are not ideal for producing mixtures containing RAS. The short mixing time in the counterflow drum is not long enough to appropriately melt and mix the RAS, unless the RAS material is shredded an even smaller size (<6.5 mm) [11]. Although the production of mixtures containing RAS is relatively straightforward, it is essential to carefully consider the amount of RAS, the type of RAS, and the mixing temperature and time.

### 1.3. Evaluation of HMA mixtures containing RAS – a review

One of several consensuses emerging in the literature is that the addition of RAS increases the net stiffness of the blended HMA mixture. During processing, the asphalt for shingles is exposed to oxygen to increase viscosity and decrease temperature susceptibility in a process called air-blowing [8,10]. The asphalt is thus pre-aged and stiffened significantly via oxidative hardening. Furthermore, the type of asphalt used in shingles is a blend of saturant and coating asphalts, which are both harder and stiffer than conventional pavement binders [10]. The stiffening effect on
various studies on HMA mixtures containing RAS discussed below. The economic and environmental value of using applications. Another emerging conclusion is that incorporating issues may arise when using the stiff RAS material in pavement projects. The results showed that mixtures containing RAS had a high resilient modulus when the binder extracted from the roofing material with a reduced amount of a softer grade virgin binder. For example, virgin binder of low viscosity served to increase the resilient modulus, tensile strength, stability, and air void content. The results suggested that mixtures containing RAS tend to have reduced temperature susceptibility at cold temperature. The effect was more pronounced for the MWSS mixtures than for the TOSS mixtures. When increasing the RAS content to 7.5%, the mixture stiffness generally decreased at intermediate and high temperatures without improvement in temperature susceptibility. Moisture sensitivity was gleaned from the comparison of the mixture's unconditioned (dry) resilient moduli and tensile strengths to its corresponding conditioned (wet) properties. For the felt-backed MWSS mixtures containing either binder grade, the ratio of conditioned to unconditioned moduli and strength did not change much when RAS content increased, thus the moisture sensitivity was not influenced much by this type of RAS. The results for the fiberglass MWSS mixtures were inconclusive and the author recommended additional field and laboratory testing. For the TOSS mixtures containing either binder grade, conditioning resulted in a greater reduction of moduli and strength as RAS content increased (most noticeably in the 7.5% RAS modified mixture with the softer binder). The results suggest that too much TOSS may be detrimental to moisture sensitivity. Low temperature behavior was determined via an indirect tension test reporting the maximum tensile strength and the corresponding strain. For both binder grades, addition of RAS decreased the specimens' low temperature maximum tensile strength. The inclusion of felt-backed MWSS either improved or had little influence on the specimen ability to strain at cold temperatures, suggesting a potential improvement in low-temperature performance. The other hand, there was a general reduction in the strain at the maximum strength for the fiberglass MWSS and the TOSS. There was a negative correlation between the amount of RAS content and the strain for the TOSS specimens, but no such consistent dependency was observed for the fiberglass MWSS. Regardless, neither of these RAS materials had any benefits to low-temperature performance as did the felt-backed MWSS. Finally, static creep compliance test results indicated the mixtures' susceptibility to permanent deformation performance. At high temperatures, the creep compliance of the mixtures containing the softer binder decreased with increasing RAS content, implying improved resistance to permanent deformation. This improvement, however, was not observed for the mixtures containing the harder binder. Overall, the report concluded that the effect of RAS is highly source-dependent, and despite the drawbacks mentioned, the inclusion of RAS generally resulted in reduced optimum binder contents for both dense-graded and SMA mixtures whose properties were similar, if not better than, conventional mixtures.

In 1998, the Georgia Department of Transportation reported on the state's experience with RAS. Watson et al. [15] evaluated two test sections of HMA pavements constructed with 5% RAS in 1994 and 1995. From visual inspection, the sections of pavement containing RAS showed little indication of distress and compared well to the unmodified control sections. From laboratory testing, the gradation and volumetrics of the modified section were similar to the control sections, indicating that introducing the RAS did not significantly alter target properties. However, one property that did show notable variation was viscosity. The results indicated that the addition of RAS caused mixtures to harden at a faster rate; when compared to the viscosities measured during initial mixing at the plant, the viscosity increased more for mixtures containing RAS than for the control mixtures. An increase in hardness/stiffness may likely positively influence high temperature performance while negatively influencing low temperature performance. Due to Georgia's warm climate, this implied improvements in terms of permanent deformation, and thus the study supported the use of up to 5% RAS in HMA pavements.

In 1999, Foo et al. [13] evaluated the effects MWSS in conventional HMA mixtures. The team analyzed specimens with 0% (control), 5%, and 10% RAS for two surface mixtures and a binder course mixture of similar gradations. Results from indirect tensile testing showed that the average tensile strength of the specimen generally decreased with an increase in RAS content, which corresponds to a greater susceptibility to fatigue cracking. Despite this concern, the results from dynamic creep tests and rutting tests showed that the addition of RAS reduced permanent deformation and increased rutting resistance. This improvement may correspond to a bump in the high temperature PG grade and is a consequence of increased net binder stiffness and/or the presence of hard, sharp granules of the shingle aggregate. This improved high temperature performance may come at the cost of degraded low temperature performance and fatigue life; therefore, the use a suitably softer virgin binder was recommended. Additionally, it was concluded that the volumetric properties of HMA mixtures with RAS do not significantly differ from those of the conventional mixtures.
In a 2011 study of low-temperature binder properties, You et al. [17] evaluated various asphalt binders, one of which being extracted RAS modified binder. Samples containing 5% and 10% RAS (added to a PG52–34 virgin binder) were evaluated using the Superpave Bending Beam Rheometer (BBR) tests and the new Asphalt Binder Cracking Device (ABCD). The results showed the net creep stiffness of the samples increased with increasing RAS content, which is due to the highly-oxidized nature of the asphalt in the shingles. The results show that the stiffening effect from RAS modification can potentially improve the high temperature grade, but at the expense of the low temperature performance.

In 2011, Watson et al. [15] assessed the combined use of RAS and RAP. The study considered the effects of both TOSS and MWSS, and the performance of two field projects in Minnesota from 2008 was evaluated. One project monitored the condition of three 500 foot (152.4 m) sections of pavement. The recycled materials used in each mix design are as follows: 5% MWSS + 15% RAP, 5% TOSS + 15% RAP, and 20% RAP. All three mixtures used PG58–28 as the virgin binder. Rutting was not a prominent issue in any of the sections. All sections, however, experienced transverse cracking, most of which occurred near curbs, gutters, and utilities (manholes, sewers, etc.). This observation made it difficult to associate the damage with solely the presence of recycled materials. Nonetheless, the 15% RAP + 5% TOSS section performed the best in terms of the quantity and linear length of longitudinal and transverse cracking. The 20% RAP section performed similarly, but had slightly more cracking; and the 15% RAP + 5% MWSS section performed the worst. The other project considered 500 foot (152.4 m) sections of a variable thickness, high-speed rural highway that was resurfaced with a 2 inch (50.8 mm) lower layer containing no recycled additives and a 2 inch (50.8 mm) surface layer containing 25% RAP and either 3% or 5% MWSS. Both layers used PG 64–34 virgin binder. It was observed that the RAS pavement sustained a significant amount of reflective cracks and was very brittle in appearance after the first winter in service. There was also more transverse cracking in the RAS pavement than in the control section, but no sever rutting was reported for any pavement section. The authors claim that the poor performance could have been due to other factors such as “long haul times and late season paving,” which speaks to the importance of maintaining the proper compaction temperature. So although the sections performed well at high temperatures, low temperature performance remains a crucial concern.

Another part of the study by Watson et al. [15] involved extracting binder from various laboratory mixtures that included RAP and RAS. It was found that the addition of RAP and/or RAS increased the high and low temperature grades of the binder. The increase in the low temperature grade can be detrimental, so the use of a softer base binder was recommended for colder climates. The TOSS modified mixtures had a better grade for both high and low temperatures compared to the MWSS. The difference between the TOSS and MWSS was also seen in asphalt mixture testing. Dynamic modulus tests showed a general stiffening effect for all the mixtures containing recycled material; however, the TOSS mixtures were stiffer than the MWSS mixtures. This could be due to a higher amount of aging or greater binder participation from the shingle waste. In summary, the utilization of RAP and RAS in HMA mixtures was recommended in controlled quantities.

1.4. Importance of this research

Although a fair amount of research has been conducted on HMA mixtures containing RAS, its effects on the low-temperature performance of HMA mixtures is not fully understood. This study employs an acoustic emission (AE) based approach to estimate the embrittlement temperatures of asphalt mixtures containing increasing amounts of RAS. This AE-based approach to estimate embrittlement temperatures has the potential to replace the AASHTO-TP1 and AASHTO MP1A protocols because of its many advantages, including the potential for portable instrumentation and rapid field testing [18–20]. The embrittlement temperature \( T_{emb} \) is estimated by observing the AE event response caused by increasing thermal stresses, which develop as the specimen cools because of the different coefficients of thermal expansion between the aggregates and the binder. When the magnitude of the tensile stresses reach the local binder strength, cracks occur, releasing strain energy in the form of transient stress waves, i.e., acoustic emission events, which are detected using piezoelectric sensors. The temperature corresponding to an event with energy equal or above \( 4 \times 10^7 \) µs is termed the mixture’s embrittlement temperature. The low-temperature properties of mixtures containing RAS are of primary concern due to the brittle nature of the oxidized, i.e., hardened, asphalt from shingles. Although research has repeatedly shown that the inclusion of RAS is beneficial to high temperature performance, a thorough understanding of its effects (and of the RAS mixing temperature) on the low-temperature performance is essential to confidently utilize this sustainable resource in cold climates.

2. Experimental procedure

Gyratory compacted specimens containing 0.0% (control), 2.5%, 5.0%, 7.5%, 10.0%, and 12.5% of RAS by total weight of the mixture, were prepared using three different mixing temperatures, i.e., 120 °C, 155 °C, and 200 °C, for a total of 18 pre-cut specimens. Three different mixing temperatures were used to study the effect that mixing temperature has on the blending between the virgin binder and the RAS binder. Although 200 °C is quite warmer than mixing temperatures typically used in producing HMA (135–165 °C), this high temperature was used to accentuate differences in the results for the different mixing temperatures. The specimens were compacted at 135 °C with a compactive effort of 100 gyrations. Each of the gyratory compacted specimens was cut into two DC(T) specimens, see Fig. 1, and each half of a broken DC(T) specimen was used as one AE test specimen. As a result, there were a total of 36 DC(T) test specimens and 72 AE test specimens.

A 19 mm nominal maximum aggregate size (NMAS) was selected, and the aggregate blend consisted of aggregates from four different stockpiles: 65% of coarse aggregate (CM16), 23% of manufactured sand (FM20), 10.5% of manufactured sand (FM02), and 1.5% of mineral filler (MF). The PG64–22 binder was utilized as the base binder. The target total binder content (either virgin binder alone, or the modified virgin binder with the RAS asphalt binder) was 5.8% by weight of the total mixture. The type of RAS used was post-consumer TOSS, and the performance grade of the binder extracted from the RAS was found to be PG136–94. The RAS material was shredded to assure that the nominal maximum size was smaller than 9.5 mm. It was assumed that 100% of the estimated 25% RAS binder content participated in the mixture, i.e., 100% RAS binder availability. The theoretical maximum specific gravity \( G_{ma} \) and the bulk specific gravity \( G_{mb} \) of the mixture were determined to be 2.445 and 2.34, respectively. The percent voids in mineral aggregates (VMA) of the mixture was measured to be 13.7%. The target height of the compacted specimens was 150 mm, which resulted in pre-cut gyratory specimens of 150 mm in diameter and 150 mm in height. These values are typical of mixtures that meet the target air void percentage of 4% after being subjected to 100 gyrations in a gyratory compactor.

2.1. Disk-shaped Compact Tension DC(T) test

To evaluate the fracture characteristics of asphalt mixture samples containing different percentages of RAS, Disk-shaped Compact Tension (DC(T)) tests were performed for all samples in accordance with ASTM D7313 [19,20]. Two DC(T) test samples were cut from the center region of each gyratory compact specimen to avoid edge effects. The DC(T) sample geometry and loading consists of a circular specimen with a single edge notch, see Fig. 1. The loading rate for the DC(T) tests was controlled through opening displacement at the crack mouth. A constant crack mouth opening displacement (CMOD) rate of 1 mm/min was utilized. The DC(T) testing setup and DC(T) specimen geometry is shown in Fig. 1. Previous studies showed that RAS mixtures can develop thermal cracks at around –8 °C. As a result, the tests were not performed at –12 °C as recommended by the standards, (i.e., +10 °C higher than the PG low temperature grade of the asphalt binder). Instead, the testing temperature was chosen as 0 °C to keep the DC(T) test samples above their embrittlement temperature, i.e., to prevent thermal cracks because of the RAS presence, see Table 1. Fracture energy of the specimens was determined by calculating the normalized area under the load-CMOD curve.
Normalization was done by dividing the area under the load–CMOD curve by the ligament length and width of the fracture area to obtain the fracture energy required to produce a unit fracture area.

2.2. Acoustic emission testing

Each of the two broken halves from each DC(T) test sample served as one AE test sample. The asphalt concrete embrittlement temperatures were estimated by recording the AE test samples' acoustic emission response to thermal cooling from 15 °C to −50 °C. Fig. 2a and b represent the cooling chamber, and a typical AE test sample cooling rate. Fig. 2c and d represents the time domain of one AE event and the corresponding power spectral density curve. Wideband AE sensors (Digital Wave, Model B1025) with a nominal frequency range of 50 kHz–1.5 MHz were coupled to the test specimen using high-vacuum grease. The AE sensors were conditioned in the cooling chamber to eliminate the events that arise due to the different rates of thermal expansion of the sensor’s materials. To reduce extraneous noise, the signals from the AE sensor were pre-amplified by 20 dB using a broadband pre-amplifier. The signals were then further amplified 21 dB (for a total of

Table 1

<table>
<thead>
<tr>
<th>AC mixtures containing a percentage of RAS</th>
<th>Results from DC(T) tests</th>
<th>CMOD fracture energy (J/m²)</th>
<th>AE-based embrittlement temperatures (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAS (%) Mixing temp. (°C)</td>
<td>Peak load (kN)</td>
<td>Average peak load (kN)</td>
<td>CMOD fracture</td>
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<tr>
<td>0.0</td>
<td>120</td>
<td>3.187</td>
<td>3.1</td>
</tr>
<tr>
<td>155</td>
<td>3.076</td>
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<td>472</td>
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<tr>
<td>2.5</td>
<td>120</td>
<td>3.069</td>
<td>3.1</td>
</tr>
<tr>
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<td>7.5</td>
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<td>373</td>
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<td>431</td>
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</tbody>
</table>

Table footnote: a Average of four AE test specimens, each AE test specimen consist of half of each of the two broken DC(T) specimens, which were cut from one gyratory compacted sample, see Fig. 1.

*Fig. 1. Disk-shaped Compact Tension (DC(T)) test; (a) test setup, and (b) geometry and recommended dimensions for the DC(T) sample.*
41 dB) and filtered using a 20 kHz high-pass double-pole filter. A threshold voltage of 0.1 V was used. The signals were digitized using a 16-bit analog-to-digital converter using a sampling frequency of 2 MHz. The temperature was monitored and recorded using a K-type thermocouple, which was connected to the one of the parametric inputs channels on the AE system unit via a K-type thermocouple adapter. To eliminate noise, all signals with an energy lower than 4 V²/µs were filtered out. For additional information regarding AE-based estimation of embrittlement temperatures the readers are referred to references [18–20].

Fig. 2. Acoustic emission testing; (a) cooling chamber, (b) typical plot of test sample temperature vs cooling time during acoustic emission (AE) testing, (c) typical acoustic emission signal associated with an AE event, and (d) corresponding power spectral density curve.

Fig. 3. DC(T) test results for lab compacted samples made with increasing percentage of RAS at the different mixing temperatures of 120 °C, 155 °C and 200 °C: (a) fracture energy, (b) peak loads; (c) corresponding DC(T) average load vs crack mode opening displacement curve (CMOD), and (d) schematic representation of the DC(T) load–CMOD showing the increase in peak load with increasing % of RAS along with shifting down of the softening of the load–CMOD curve. The error bars in (a) and (b) indicate the maximum and minimum of the experimentally obtained values.
3. Experimental results and discussion

The peak loads and fracture energy numerical results obtained from the DC(T) tests are presented in Table 1. Fig. 3a and b also shows the DC(T) fracture energy and peak loads, respectively, for the samples made with increasing percentage of RAS. Fig. 3c shows the DC(T) load versus crack mode opening displacement (CMOD) for mixtures with increasing percentage of RAS, while Fig. 3d schematically illustrates the increase of peak load while the softening curve is shifted down and to the left with increasing percentage of RAS. The decrease in CMOD fracture energy with increasing RAS content is intuitive. The addition of oxidized RAS material results in a more stiff and brittle mixture, and brittle mixtures result in lower CMOD fracture energies. The increase in stiffness inferred from the results shown in Fig. 3 are consistent with findings of other authors that the inclusion of RAS in HMA can be beneficial to high temperature performance [6–8,12,13,15]. While the peak load was insensitive to changes in the mixing temperature, the embrittlement temperatures are significantly affected by the presence of RAS. Even the presence of a small percentage of RAS significantly reduces the embrittlement temperatures. Using the mixture temperature of 155 °C, the mixture without RAS has an embrittlement temperature of –18.90 °C while the corresponding mixture with 2.5% RAS has an embrittlement temperature of –10.97 °C. The warmer embrittlement temperatures in the presence of RAS occurs because even when the mixtures are prepared at 200 °C, localized regions of RAS (or RAS nodules) still exist within the test sample as it is illustrated in Fig. 5. During cooling of the test samples, these RAS nodules are the first to accumulate damage by cracking at warmer temperatures, which leads to warmer embrittlement temperatures of the overall mixture. Fig. 4a also indicates that mixing at warmer temperatures has a small mitigating effect upon the loss of low-temperature performance, i.e., warmer embrittlement temperatures, due to the presence of RAS. Fig. 4b shows that the AE event energy distribution for the specimens with 0% RAS (mixed at 155 °C) have more distinct maxima when compared to the HMA with 10% RAS mixed at 120 °C and 200 °C. The HMA with 10% RAS mixed at 120 °C and 200 °C have only about 39% and 13%, respectively, of the total event energy of the mixture with 0% RAS. Fig. 4b shows that the partial blending of the stiffer and lower-viscosity (i.e., highly-oxidized) asphalt from RAS with the virgin binder increases with the mixing temperature. This increase in blending with temperature of the oxidized asphalt from RAS with the virgin binder leads to mixtures with a blended binder that has lower levels of adhesion than the virgin binder, which results in lower AE energy events.

The improvement in the embrittlement temperature observed at the 10% and 12.5% levels of RAS, see Table 1 and Fig. 3, may be due to the inhomogeneity in the distribution of the RAS material and small temperature gradients throughout the specimen. Recall that nodules of RAS were observed in the cross-sections of most of the specimens, see Fig. 5. Again, these RAS nodules are the weakest link in the system because they represent local regions with warmer embrittlement temperature; therefore, they are the first regions to develop damage accumulation during cooling. As the specimens are cooled, the surface of the specimens will cool first. Consequently, there is a small temperature gradient such that the interior of the specimen is warmer than the exterior. Therefore, the location of the RAS nodules will have an effect on the embrittlement temperature. The thermocouple monitors the temperature of the surface of the specimen. So if the RAS nodules are near the surface, the nodules would produce AE events when the thermocouple records the embrittlement temperature and the estimate would be accurate. However, if the nodules are more towards the center of the specimen, the embrittlement temperature would be underestimated because the surface temperature is lower than the actual temperature near the center of the specimen. If the two binders had been completely blended (i.e., no RAS nodules), a gradual warming of the embrittlement temperature with increasing RAS content is expected. Without complete blending, however, more RAS nodules would form with increasing RAS content, thus introducing more weak links in the mixture and limiting the use of larger amounts of RAS. Regardless, the warming of the embrittlement temperature for any amount of RAS compared to the virgin binder is clearly observed in this study.

Please note that the RAS binder has a performance grading of PG136–04. The low-temperature performance of (–4 °C) was estimated based upon its rheological properties obtained via the BBR test. The embrittlement temperatures using AE are estimated by recording the temperature at which low-temperature cracking occurs, which makes the AE-based embrittlement temperatures more accurate. Furthermore, the AE-based approach typically provides lower embrittlement temperatures (consistently about 5–6 °C lower) than the low-temperature cracking (i.e., behavior) estimated.

### Table 1

<table>
<thead>
<tr>
<th>RAS Percentage</th>
<th>DC(T) Fracture Energy</th>
<th>Peak Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>10%</td>
<td>120°C</td>
</tr>
<tr>
<td>2.5%</td>
<td>155°C</td>
<td>200°C</td>
</tr>
</tbody>
</table>

Fig. 4. Acoustic emission test results; (a) embrittlement temperatures versus percentage of RAS for mixtures prepared at 120 °C, 155 °C, and 200 °C, and (b) frequency distribution of acoustic emission event energy for the standard mixture. The error bars in (a) indicate the maximum and minimum of the experimentally obtained values.
using the rheological properties extracted via the BBR method. The variability of the embrittlement temperatures observed in Table 1 is mainly attributed to: (1) small temperature gradients in the test sample, (2) increase in blending of the asphalt binders (i.e., of the RAS binder with the virgin binder) with the mixing temperature, (3) random location of the RAS nodules within the test sample, and (4) variability in the RAS binder caused by different levels of oxidation. and (5) the more accurate evaluation of the embrittlement temperatures of the AE-based method as compared to the embrittlement temperatures estimated using the rheological data extracted from the BBR tests.

4. Conclusions

Asphalt concrete specimens were made with increasing amounts of recycled asphalt from shingles (RAS). It was observed that the presence of RAS affects the peak load and fracture energy results from the DC(T) tests. The observed increase in the peak load with an increase in the RAS percentage is consistent with observations from other investigators, and indicates that the presence of RAS does not lower the high-temperature performance in HMA. However, it was observed that even a small percentage of RAS significantly affects the mixture’s embrittlement temperatures; for example, for the mixing temperature of 155 °C, the presence of 2.5% RAS increases the embrittlement temperature from −18.90 °C (for the mixture without RAS) to −10.97 °C. Higher mixing temperatures also appear to have a mitigating effect regarding warming of the embrittlement temperatures for mixtures containing RAS. For example, the embrittlement temperatures for the mixture with 12.5% RAS, mixed at 120 °C and 200 °C, were estimated at −8.61 °C and −13.34 °C, respectively. This warming of the embrittlement temperatures is most likely due to the partial blending of the highly oxidized asphalt from the shingles with the virgin binder and to the current practices of mixture preparation, which indicates that additional research may be necessary regarding mixture preparation in the field before mixtures containing RAS are used in cold environments. The AE-based approach to estimate embrittlement temperatures of the HMA mixtures containing RAS may prove useful to study the embrittlement temperature dependence upon the RAS percentage and different mixing preparation including different mixing temperatures.

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References


Fig. 5. Cross-sections of gyratory compacted samples with 5% RAS using a mixture temperature of 120, 155, and 200 °C. The figure shows nodules of RAS in the test samples, (some nodules circled in red), and illustrates the difficulty in blending the oxidized asphalt extracted from the RAS in the test samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)