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Effect of Aged Binder Distribution on the Fracture Tolerance of Asphalt Mixtures with Reclaimed Asphalt Pavement

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Abstract. This study investigated the effect of the distribution of aged binder from reclaimed asphalt pavement (RAP) on the fracture tolerance of recycled asphalt mixtures. Two RAP sources (one coarse, one fine), one virgin polymer-modified asphalt (PMA) binder, and four RAP contents (0, 20%, 30%, and 40%) were used to produce a total of seven mixtures. Fracture tolerance was assessed in terms of fracture energy density (FED) at three levels: binder, interstitial component (composed of effective binder and fine aggregate fraction), and mixture. Binder fracture energy tests were conducted to measure the FED of blends of virgin and recovered RAP binder. Interstitial component (IC) direct tension tests were employed to determine IC FED. Finally, Superpave indirect tensile fracture tests were performed to obtain the FED of RAP mixtures. FED decreased with increasing RAP content at the three levels (binder, IC, and mixture). More importantly, IC and mixture exhibited almost identical FED reductions in relatively terms, while the reduction was less significant at binder level. This finding indicates that the full blending scenario artificially created at the binder level did not occur at IC and mixture levels. Furthermore, the coarse RAP yielded greater FED than the fine RAP, which substantiates that RAP gradation controls the distribution of RAP binder in

recycled mixtures. Consequently, the lower content of aged RAP binder in the IC portion for mixtures with the coarser RAP resulted in better fracture tolerance. The application of a newly developed guideline for determining the maximum allowable RAP content in recycled mixtures confirmed that the coarser RAP used in this study allows for a greater RAP content than the finer RAP despite the stiffer RAP binder.

Keywords: Reclaimed Asphalt Pavement, Gradation, Binder Distribution, Fracture Tolerance, Recycling, Interstitial Component

1. Introduction

Employing reclaimed asphalt pavement (RAP) in pavement construction is a sustainable approach that brings in significant economic and environmental benefits.^{1,2,3} The latest survey conducted by the National Asphalt Pavement Association (NAPA) indicates that the amount of RAP used in asphalt mixtures was 89.2 million tons in the United States in 2019. This reduced the need for 4.5 million tons of asphalt binder and nearly 85 million tons of aggregate with a total estimated value of more than 3.3 billion US dollar, as well as about 41 million cubic meters of landfill space.⁴ However, the results of NAPA's survey also revealed that the average usage of RAP is still low; approximately 21% by weight of aggregate for mixtures produced for state departments of transportation.

Oxidative aging during service life increases the viscous and elastic properties of the binder, leading to a global hardening (i.e., stiffening) of the material.⁵ RAP contains aged asphalt binder, which typically requires the use of a softer virgin binder to account for a potential reduction in mixture cracking performance resulting from increased binder stiffness.⁶ The existing design guideline, AASHTO M 323 Standard Specification for Superpave Volumetric Mix Design, assumes that RAP binder fully blends with virgin binder in the new mixture (also known as white rock scenario). This assumption maximizes the contribution of RAP binder.⁷ However, some research supports the complete opposite assumption that RAP binder does not blend at all with virgin binder in the new mixture, i.e., RAP particles act like a black rock. Nowadays, it is a common understanding in the asphalt community that neither full blending nor zero blending between virgin and RAP binder occurs in actual mixes.^{8,9} Researchers reported a blending scenario where only part of the RAP binder reacts with the virgin binder, which yields a cluster phenomenon.^{10,11} Several studies emphasized that the agglomeration of RAP is one of the most important factors affecting the performance of cold

recycled asphalt mixture, which is produced in field without the heating process used in hot asphalt mixture recycling.^{12, 13}

Current consensus in the asphalt community is that virgin binder selection should be based on RAP binder properties, such as binder performance grade (PG), penetration value, or softening point, and the effective RAP binder content that contributes to the total binder content of the mixture. Extensive research has been performed to characterize blending and to quantify the effective RAP binder content in mixes. A coating study that involved fixed sizes of RAP particles and virgin aggregates was conducted to determine how much RAP binder can transfer from the former to the latter after mixing.¹⁴ In a separate study, virgin binder was added to samples of the coating study and an equation was proposed to calculate the degree of blending between virgin and RAP binders.¹⁵ Of note, both studies employed gap-graded RAP sources, which facilitates the separation of RAP and virgin aggregate after mixing. Another study evaluated the interaction and extent of blending between virgin and RAP binder by using atomic force microscopy (AFM).¹⁶ Uniform microstructural properties in blends of virgin and RAP binder were observed, which indicates a completely blended new material. Recent studies used titanium dioxide powder and nanoparticles to trace the presence of virgin binder in chemical microanalysis in an attempt to determine the degree of blending between virgin and RAP binders in mixes.^{17,18,19} Nevertheless, there is not yet a well-accepted and practice-ready methodology to accurately determine effective RAP binder content, which affects both mixture performance and the economic competitiveness of the recycling process.

RAP aggregate, which usually receives less attention than RAP binder, can also have a strong impact on mixture performance. According to the current design guideline AASHTO M 323⁷,

RAP aggregate must meet the same quality specifications as virgin aggregates, including coarse aggregate angularity, fine aggregate angularity, and flat and elongated requirements. During the mix design process, RAP is treated like another aggregate stockpile that is combined with the virgin aggregate to achieve the desired mix gradation. This approach is appropriate as long as all RAP binder separates from RAP aggregate and then fully blends with virgin binder, which do not occur in actual mixes. In fact, the size of RAP particles could strongly affect the level of blending. Nguyen²⁰ reported that the smaller the RAP particle size, the better the distribution of RAP in the mix and, consequently, the better the interaction between RAP and virgin binder. Better interaction can also increase the stiffness of recycled mixtures. Salianni et al.²¹ concluded that coarse RAP particles had a higher binder content than fine RAP particles, but when mixed with virgin aggregate, more RAP binder transferred from coarse RAP particles to virgin aggregate than from fine RAP particles. In another study, mixtures with coarse RAP exhibited greater energy ratio values (an indicator of mixture cracking performance at intermediate temperatures) than mixtures with fine RAP, despite the fact that the coarse RAP was much stiffer than the fine RAP.^{22, 23} Salianni et al.²⁴ also reported that coarse RAP mixtures outperformed fine RAP mixtures, and concluded that RAP particle size had a considerable effect on RAP binder contribution to total binder content, aggregate skeleton of the mix, and ultimately, mix performance (rutting, fatigue cracking, and thermal cracking). Recognizing that full blending does not occur in real asphalt mixes, there is a strong need to gain further understanding on the effect of the distribution of RAP binder —potentially governed by RAP gradation— on mixture performance, particularly on cracking performance at intermediate temperatures for being one of the most dominant pavement distresses in mild climates.

2. Objective and Scope

The objective of this research was to study the effect of the distribution of aged binder on the cracking potential of asphalt mixtures with reclaimed asphalt pavement. Cracking performance was evaluated in terms of the fracture tolerance at intermediate temperatures. The distribution of aged binder was varied by using two RAP sources with distinct gradations: a coarse RAP (aged binder is more likely to remain in the coarse fraction of the RAP mix) and a fine RAP (aged binder more likely to stay in the fine fraction of the RAP mix).

3. Materials

Both RAP sources (fine and coarse) were subjected to trichloroethylene for binder extraction, followed by binder recovery by means of the rotavapor apparatus. Recovered RAP binder and RAP aggregate were collected for determination of binder properties and aggregate gradation, respectively. The coarse RAP (RAP-C), with a slightly lower asphalt binder content than the fine RAP (RAP-F), was found to contain a notably stiffer binder than RAP-F, as shown by a lower penetration and a greater viscosity. Table 1 shows the properties of the binder recovered from each RAP source.

Table 1. Properties of extracted RAP binder

RAP source	RAP-C	RAP-F
Asphalt content (%)	4.6	4.8
Penetration number (0.1 mm)	9	15
Viscosity (poise)	624000	98400
Continuous grade (°C)	104.2-14.1	94.2-24.1

Besides the two RAP fractions, granite and local sand were used as virgin aggregate, and a PG 76-22 polymer-modified asphalt (PMA) as virgin binder. These materials were used to produce 12.5-mm nominal maximum aggregate size (NMAS) Superpave mixtures with different RAP contents: 0% (reference mixture), 20%, 30%, and 40% by total weight of

aggregate. Figure 1 plots the aggregate gradation of both RAP sources and the reference mixture. The two RAP gradations in Figure 2 refer to the size distribution of the extracted and recovered RAP aggregate, which can be entitled as the ‘white curve’. The gradation of RAP particles, i.e., the ‘black curve’, is typically coarser than that of RAP aggregate due to agglomeration or clustering. The ‘white curve’ of RAP aggregate was used for mix design. All RAP mixtures were designed to match the aggregate gradation of the reference mixture, which was achieved by adjusting the virgin aggregate components.

Fig. 1. Aggregate gradation of two RAP sources and prepared RAP mixtures

The design asphalt binder content of all mixtures was determined following the Superpave mix design method to achieve a 4% air void content at 75 gyrations. Table 2 summarizes the total binder content and RAP binder replacement rate (i.e., percent of RAP binder divided by the total binder content) for each mixture.

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Table 2. Details of RAP content in mixtures

	RAP content (%, by weight of aggregate)	RAP binder content (%)	Virgin binder content (%)	Total binder content (%)	RAP binder replacement rate (%)
Reference	0	0.0	5.2	5.2	0
RAP-C	20	0.9	5.0	5.9	15
	30	1.4	4.5	5.9	23
	40	1.8	3.8	5.6	33
RAP-F	20	0.9	4.3	5.2	18
	30	1.5	3.6	5.0	29
	40	1.9	3.0	4.9	39

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4. Research Approach

155 The experimental plan consisted in performing fracture tests at three different levels to
156 investigate the effect of aged binder distribution on fracture tolerance, expressed in terms of
157 fracture energy density (FED). The three levels included: (i) binder level, (ii) interstitial
158 component (IC) level, and (iii) mixture level. The binder level was used as a reference to
159 represent the effect of RAP binder without RAP gradation effects, i.e., a full blending
160 scenario. On the other end of the spectrum, the mixture level was employed to capture the
161 effect of RAP binder and RAP gradation in the actual blending scenario. In addition, the IC
162 level was introduced to determine whether the interstitial component can effectively capture
163 the actual blending conditions of the mixture level, but with significantly less material needs
164 and less specimen preparation effort. According to the dominant aggregate size range-
165 interstitial component (DASR-IC) model, the IC is defined as the combination of fine
166 aggregate (passing 1.18-mm sieve size), effective binder, and air voids that fill in the space
167 between the interstices of the primary structural network (i.e., load carrying structure) formed
168 by interactive coarse aggregate particles (Figure 2). While the Bailey method links gradation
169 to mixture volumetrics²⁵, the DASR-IC model was developed to link gradation characteristics
170 to mixture performance validated from numerous field sections. It has been reported that the

IC is mainly associated with the fracture resistance and durability of asphalt mixtures.^{26,27}

Therefore, IC FED can provide more insight regarding the effect of RAP gradation and aged binder distribution on the fracture resistance of RAP mixtures.

Fig. 2. Conceptual depiction of dominant aggregate size range and interstitial component model

Table 3 summarizes the three material levels evaluated and the testing method for each level.

For comparison purposes, IC and mixture FED were measured on short-term aged samples since no long-term aging protocol is yet available for IC specimens. Conversely, binder FED, which captures RAP binder presence but not RAP binder distribution, was measured on rolling thin film oven (RTFO) plus pressure aging vessel (PAV) samples. More details on the test method for each level are provided in the next sections.

Table 3. Three tested asphalt material phases and testing methods

Material Level	Test Method	Testing Temperature	Aging Level
Binder	Binder fracture energy (BFE) test	15°C	RTFO ⁽¹⁾ + PAV ⁽²⁾
Interstitial component	IC direct tension (ICDT) test	10°C	STOA ⁽³⁾
Mixture	Superpave IDT fracture test	10°C	STOA ⁽³⁾

Note: (1) RTFO: Rolling thin film oven, (2) PAV: Pressure aging vessel, and (3) STOA: Short-term oven aging

4.1 Binder fracture energy (BFE) test

The binder fracture energy (BFE) test was conducted on blends of virgin and recovered RAP binder to determine binder FED at intermediate temperatures following the AASHTO provisional standard TP 127. The BFE test is performed at 15°C by applying a constant displacement rate of 500 mm/min until fracture. Binder FED was shown to be independent of testing temperature in the range of 0°C to 20°C,^{28, 29} which allows comparing binder results at 15°C with IC and mixture fracture properties typically obtained at 10°C. Figure 3 illustrates the BFE test components, including the equipment for specimen preparation, testing setup, and a view of a specimen before and after fracture testing. For each binder blend, three replicates were tested after RTFO+PAV conditioning. Time, force, and displacement data were collected during test, and the measured force and displacement were converted to true stress and true strain at the middle section of specimen where fracture occurs. Binder FED is defined as the area under the true stress-true strain curve up to the true stress peak. Details on the BFE testing procedure and specimen preparation can be found elsewhere.^{29, 30}

Fig. 3. Specimen preparation and testing setup for binder fracture energy test

4.2 Interstitial component direct tension (ICDT) test

The interstitial component direct tension (ICDT) test was performed to determine FED at the IC level³¹. Figure 4 shows the ICDT test specimen preparation and testing setup. ICDT test

specimens contain asphalt binder and batched IC aggregate. The IC aggregate for all mixtures was determined as the fine aggregate passing the 1.18 mm sieve based on analyses performed according to the DASR-IC model. The amount of IC aggregate and binder was calculated from the relative volume of effective binder and IC aggregates in the corresponding mixture.

Fig. 4. Specimen preparation and testing setup for interstitial component direct tension test

Loose IC mixes were compacted in a dog-bone shaped mold to obtain a geometry that ensures failure consistently occurs at the middle section of the specimen. This allows an accurate definition of the strain field on the failure plane. The target air void content for ICDDT specimens was 0% at this stage to minimize the effect of void structure, which is typically considered as a mixture level variable. A prior study reported that the measured air void content of the central portion of an ICDDT specimen was below 0.3% and no air voids were detected on the failure plane by X-ray computed tomography.³² Three replicate ICDDT specimens were tested for each mix type at 10°C and a displacement rate of 50.8 mm/min. Recorded load magnitude was used to calculate the stress on the failure plane using the load divided by area, whereas the displacement data was used to determine the strain based on a relationship between displacement and average strain developed by means of finite element analysis.³² Subsequently, IC FED was calculated as the area under the stress-strain curve.^{31, 32}

4.3 Superpave indirect tensile (IDT) fracture test

Mixture FED describes fracture tolerance before failure and it can be determined from a Superpave IDT fracture test.^{32,33} Superpave IDT test specimens were obtained by slicing a 4.5-kg Superpave gyratory pill (150-mm in diameter) using a masonry saw. The target specimen thickness was 38.1 mm and the target air void content for the test specimen was $7\pm0.5\%$ to simulate the air void content typically required in the field. Two gauge points were attached on each face of the sample to measure strain on the failure plane. Figure 5 illustrates the specimen preparation (compacted pill, slicing, and attaching the gauge points) and testing setup for Superpave IDT tests. Specimens were placed in an environmental chamber for 12 hours before testing to assure they reached the testing temperature. Three replicate specimens were tested for each mixture type at 10°C by applying a 50.8 mm/min displacement rate until the specimen failed. Mixture FED is defined as the area underneath the stress-strain curve up to failure. Data analysis was conducted using the Superpave Indirect Tension Test for Low Temperatures program. Details on Superpave IDT test procedures can be found elsewhere.³³

Fig. 5. Specimen preparation and testing setup for Superpave IDT mixture tests

5. Results and discussion

5.1 Fracture energy density results

Figure 6 plots average FED values for each evaluation level. Overall, all three levels (binder, IC, and mixture) exhibited a reduction in FED with increasing RAP content. Figure 6a shows that binder blends with the coarser RAP yielded greater FED than those with RAP-F within

the range of binder replacement rates studied. Despite the drop in fracture tolerance caused by the presence of RAP, the FED values above 6000 kJ/m³ observed for the highest binder replacement rates still exceeded those measured on unmodified and rubber-modified binders in prior research.²⁹ This suggests the blends evaluated in this study still show some improved elastic response derived from the presence of polymer in the virgin PMA binder. IC FED results in Figure 6b show a similar trend, although RAP-C yielded a lower FED value than RAP-F when 40% RAP was incorporated. At the mixture level, RAP-C also yielded a greater FED values than RAP-F, except for the highest binder replacement rate (Figure 6c). In this case, it was observed that fracture of the 40% RAP-C mixture specimens occurred mostly through coarse limestone aggregate present in the RAP. Therefore, the relatively large percentage of weak limestone aggregate seems to explain the drop in FED for the 40% RAP-C mixture.

a. Binder level (3 replicate specimens)

b. Interstitial component level (3 replicate specimens)

c. Mixture level (4 replicate face results)

266 Note: error bars represent standard error of the mean

267 **Fig. 6.** Fracture energy density results at three different levels

Although RAP-C appeared to contain a more aged and brittle binder given its higher viscosity and temperature continuous grade, mixtures with RAP-C exhibited greater FED than those with RAP-F. Figure 7, which depicts the content of RAP (aggregate plus binder) in the IC portion of each mixture, clearly reveals that mixtures with the finer RAP contained twice as much RAP in the fine fraction as the mixtures with the coarser RAP. Since RAP aggregate gradation controls the distribution of RAP binder in the mix and full blending does not occur, finer RAP sources tend to increase the proportion of aged and brittle binder in the fine portion of the mixture that governs fracture response, thereby resulting in lower fracture tolerance.

Fig. 7. RAP content in the interstitial component of mixtures with two different RAP sources

5.2 Comparison of normalized FED results

Figure 8 shows FED values normalized with respect to the results with no RAP at each level. Although increasing RAP content reduced FED at the three levels for both RAP sources, the reduction in FED was almost identical for the mixture and the IC levels. Conversely, binder blends exhibited a considerably lower reduction in normalized FED. This finding substantiates that blending level, and not only RAP binder content, impacts fracture tolerance. It is believed that the presence of areas of stiffer and more brittle aged binder

derived from a non-full blending scenario introduced localized areas of stress concentration and increased failure potential. While this effect appears to be captured at IC and mixture level, the full blending scenario between RAP and virgin asphalt artificially created at binder level does not. Again, the drop in normalized FED of the 40% RAP-C mixture is likely to be associated with the weak limestone aggregate present in this RAP source.

Fig.8. Normalized FED of binder, IC, and mixture: a) RAP-C and b) RAP-F

5.3 Application of guideline to determine maximum allowable RAP content

The results shown in Figure 6c substantiate that the existing design guidelines for RAP mixtures based only on RAP binder content and RAP binder properties are insufficient to capture the impact of RAP gradation on RAP binder distribution and, ultimately, on cracking performance. To further confirm this concept, the results obtained in this study were compared with the new design guideline developed in a concurrent study.^{34, 35} As depicted in Figure 9 the new design guideline considers RAP binder stiffness (expressed in terms of high-temperature continuous grade) and RAP fineness (aggregate percentage passing the 1.18-mm sieve size) to determine the maximum allowable RAP content in mixtures with virgin PMA binder. This new design guideline was developed and verified using RAP sources covering a broad range of RAP characteristics. Based on the range of RAP characteristics used, nine zones were generated in a combination of three levels of RAP

binder stiffness (high, intermediate, and low stiffness) and RAP fineness (coarse, intermediate, and fine). The C-H zone refers to coarse RAP sources with high binder stiffness, while the F-L zone represents fine and low stiffness RAP. Depending on the RAP characteristics in each zone, a maximum allowable RAP content in PMA mixtures was defined in the new design guideline from fracture tolerance results. For example, the coarse and low stiff RAP (C-L group) allows up to 40% RAP (the maximum value in the design guideline) whereas all fine RAP sources can be used up to 20% in PMA mixtures because of the lower fracture tolerance measured. According to the new design guideline, RAP-C falls in the C-I zone (coarse gradation, intermediate binder stiffness). Similarly, RAP-F belongs to the I-L zone (intermediate fineness, low binder stiffness). As a result, the recommended maximum allowable RAP contents are 35% for RAP-C and 30% for RAP-F. It should be noted that the actual maximum allowable RAP content for RAP-C may be greater than 35% since this RAP is significantly coarser than the 30%-60% calibration range used in the development of the new design guideline. Figure 9 supports that the coarser gradation of RAP-C will lead to a greater maximum allowable RAP content than RAP-F, even though RAP-C has a stiffer RAP binder. Therefore, the effect of RAP gradation on mixture cracking resistance is critical, and the characteristics of RAP gradation should be carefully considered when determining RAP content in PMA mixtures.

Fig. 9. Maximum allowable RAP content for RAP-C and RAP-F based on the newly proposed design guideline

6 Conclusions and recommendations

The experimental investigation conducted in this study to evaluate the effect of aged binder distribution on the fracture tolerance of RAP mixtures revealed that for a similar binder replacement rate, a mixture with a coarser RAP exhibited greater fracture energy density (FED) than a mixture with a finer RAP, despite the notably stiffer binder of the coarser RAP. The mixtures produced with the finer RAP contained twice as much RAP in their interstitial component, which is believed to embrittle the fine fraction of the mixture that governs fracture tolerance. This means that since full blending between RAP binder and virgin binder does not take place in real mixtures, RAP gradation controls the distribution of RAP binder within the mixture. Consequently, very fine RAP sources may lead to recycled mixtures with a high content of aged and embrittled binder in their most critical fraction from the standpoint of cracking performance. The application of a newly developed guideline for determining the maximum allowable RAP content in recycled mixtures confirmed that the coarser RAP used in this study will allow a greater RAP content than the finer RAP, despite the stiffer RAP

binder. Since IC results seemed to capture the effect of RAP gradation effectively and efficiently, it is recommended that further research be conducted to develop an appropriate long-term conditioning method for IC samples and to incorporate the effect of the air void structure on IC testing results (perhaps by means of a modeling effort) for predicting asphalt mixture cracking performance.

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