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Fracture Characterization of Asphalt Mixtures with Reclaimed Asphalt Pavement

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Abstract: The use of recycled asphalt pavement (RAP) in hot-mix asphalt leads to significant environmental and economical benefits. The major benefits are realized through reduced demand for new or virgin aggregates and asphalt binders. A limited amount of research has been performed to investigate the effects of RAP on the low temperature fracture characteristics of asphalt mixtures. However, this is an important subject, since the inclusion of RAP in Hot-Mix Asphalt (HMA) has the potential to increase mixture stiffness and brittleness unless properly compensated for. Most design procedures for mixtures consisting of RAP recommend an asphalt binder grade adjustment to compensate for the aged binder through the use of a softer virgin binder. This study evaluates the validity of this grade adjustment procedure in the context of four RAP materials using mixture fracture testing. The RAP materials used in this study were chosen from a larger database of materials to represent a wide variety of binder aging levels. Various fracture tests for asphalt concrete were identified through literature review. The disk-shaped compact tension (DC(T)) test, as standardized in ASTM D7313-07b, was used in this study to characterize mixture fracture energy. DC(T) fracture tests were conducted on various asphalt mixtures, namely: a control mixture with no RAP, manufactured with PG 64-22 asphalt binder; four mixtures containing 30% RAP from different sources, with an adjusted virgin binder grade of PG 58-28, and; a reference mixture containing no RAP, manufactured using PG 58-28 binder. The test results indicate significant reduction in the fracture energy of asphalt mixtures with 30% RAP and no virgin binder grade compensation. The reduction in fracture energy was surprisingly consistent between the four RAP sources irrespective of the significantly different RAP binder stiffnesses that were determined to be present in these mixtures through binder recovery and testing. However, when the RAP mixtures were produced using a softer virgin binder (PG 58-28), the measured fracture energy was higher than the control mixture. The study provides some assurance that adequate cracking resistance can be maintained in mixtures containing 30% RAP when designed properly, and demonstrates how fracture testing with ASTM D7313-07b can be used in the design and control of RAP mixtures, particularly where cracking is of concern.

***Key words**: Disk-shaped compact tension test; Fracture characterization; Recycled asphalt pavement; Renewability; Sustainability.*

Introduction

The most prevalent use of reclaimed or recycled asphalt pavement (RAP) involves incorporating the asphalt pavement material obtained by milling an existing pavement as an ingredient in a newly produced mixture. The amount of RAP usage in asphalt pavements has been escalating significantly in recent years. The two primary motivational forces behind the utilization of RAP are cost savings and environmental benefits. Using RAP can result in cost savings to the producer and/or owner by reducing the amount of virgin materials required in the production of the new asphalt mixture, as reported by Bernard [1] and Chiu et al. [2]. The reduced requirements for new aggregates and asphalt binder in asphalt mixtures with RAP have a positive environmental impact. Huang et al. [3] have presented life cycle assessments (LCA) of various asphalt pavement rehabilitation strategies. Their evaluation includes the ecological costs and offsets in the LCA predictions, demonstrating the ecological benefits of using RAP and other recycled materials in pavements. Alkins et al. [4] have recently demonstrated cold in-place recycling as one of the alternatives towards sustainable pavement systems. They have reported greater than 50% reduction in the carbon dioxide emissions from using cold in-place recycling technique versus construction of new pavement with all virgin materials. As high as 23% reduction in ecological burden has been reported recently for use of RAP in hot-mix asphalt [2]. In summary, usage of RAP in pavement systems allows for an economical and environmentally friendly path towards pavements with greater sustainability and renewability factors.

The effect of aging usually leads to stiffening of the binder in the RAP material relative to its virgin state. Xiao et al. [5] reported that a significant increase in stiffness resulted in mixtures with as much as 15% RAP. Due to the stiffening effect, a major concern in pavements constructed with RAP is cracking. During the course of service, pavement undergoes aging which leads to stiffening and embrittlement of the material. These effects are most pronounced near the surface of the pavement. RAP material is typically manufactured from pavements that have been in service for a number of years (10 or more is common) and have deteriorated to the stage that the surface of the asphalt layer is required to be milled off. If no adjustments are made, the mixtures containing RAP may have inferior fracture properties when compared to mixtures with all virgin materials. Extensive research has been performed to characterize asphalt binder properties in the context of cracking. National Cooperative Highway Research Program (NCHRP) Project 9-12 [6]

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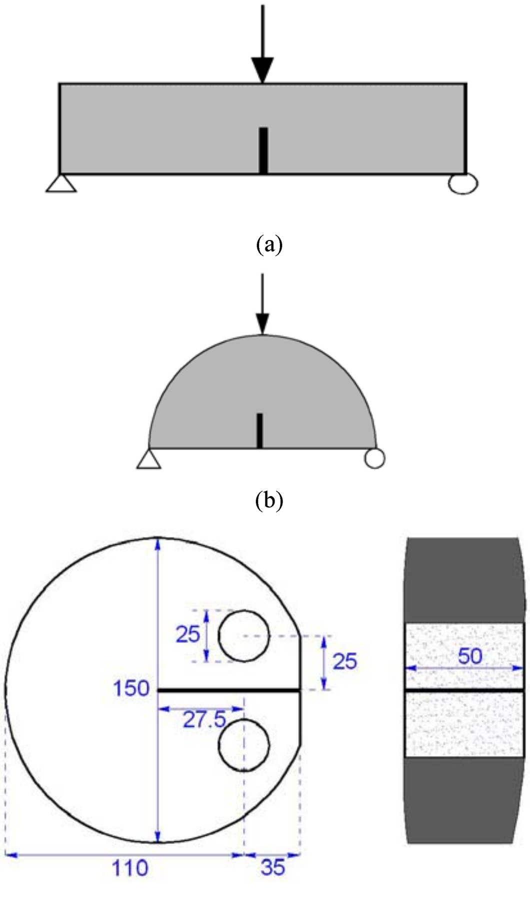


(a)

(b)

(c)

Fig. 1. Specimen Geometry of Various Fracture Tests (a) Single Edge Notched Beam, SE(B), (b) Semi-Circular Bend, SC(B), and (c) Disk Shaped Compact Tension, DC(T).

focused on binder testing of blends consisting of RAP binders, and reported inferior low temperature properties for such materials. A study by Lee et al. [7] further reinforced the findings of NCHRP 9-12 in the context of low temperature properties of RAP binder blends. However, the links between binder properties and field performance of RAP mixtures can be weak, since binder testing does not account for the fact that incomplete mixing of new and old binder can occur in mixtures containing RAP, nor does it account for aggregate effects (combined effect of recycled and virgin aggregates) or other mixture-related variables. Very little work has been performed using newly available mixture fracture tests to assess the effects of RAP on the low temperature fracture properties of asphalt concrete.

RAP sometimes consists of materials with relatively high variability [8]. It is important to acknowledge that when RAP is utilized in high amounts, variability in gradation, asphalt content, and binder stiffness is expected. One way to target this effect is to consider RAP material from various sources in the experimental design. In the current study, four RAP sources with significantly varying recovered binder stiffness were selected. This paper explores the effect of RAP on the low temperature fracture properties of asphalt concrete using a new mixture fracture energy test, and assesses the commonly held hypothesis that the use of a softer virgin grade as compared to the target binder grade will compensate for the aged binder properties present in the RAP.

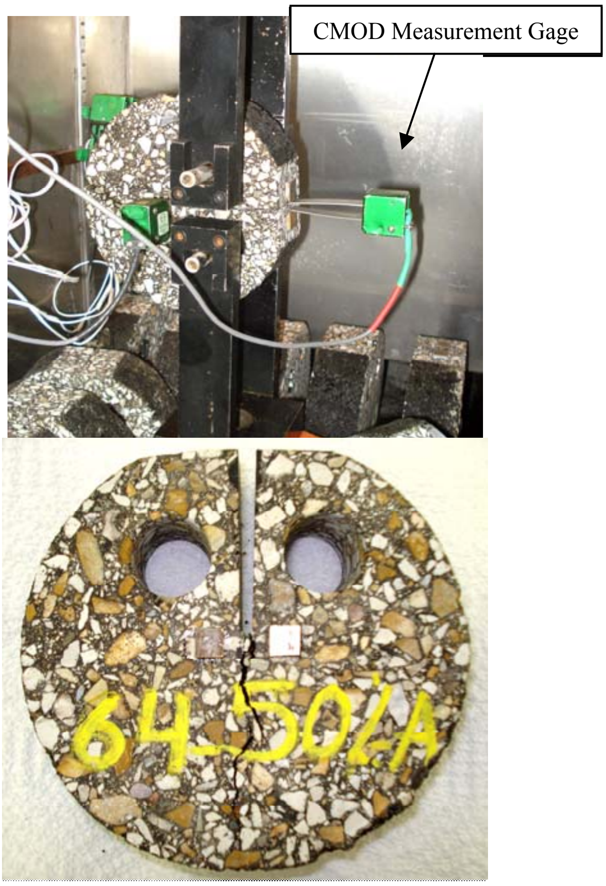
Experimental Methods

Test Selection

Fracture processes can be divided into three modes namely, Mode I (opening mode), Mode II (in-plane shear), and Model III (out-of-plane shear). For thermal cracking and reflective cracking under bending conditions the most critical mode to control is Mode I. A great deal of effort has been directed towards the development of Mode I fracture testing methods. There are three commonly used testing configurations for Mode-I fracture characterization of asphalt concrete: the Single Edge Notched Beam (SE(B)) [9], the Semi-Circular Bending (SC(B)) [10], and the Disk-Shaped Compact Tension (DC(T)) [11]. All of these test configurations are shown in Fig. 1. The SE(B) test has a simpler loading configuration and allows for a stable crack growth after crack initiation. Moreover, the mixed-mode (combination of tensile and shear opening) fracture testing by offsetting the notch on the bottom of the specimen is also possible with the SE(B) configuration [9, 12]. However, obtaining field specimens for SE(B) test may be difficult and not practical because of the extensive sawing requirements, necessary asphalt layer thickness (approximately 75*mm*) and damage to the pavement when field samples are required. Procurement and testing of in-place materials from the pavement is necessary, for example, to accurately simulate cracking and to perform calibration of crack prediction models. Since field cores obtained from constructed pavement layers are of cylindrical shape, a practical fracture test for asphalt concrete should be able to utilize cylindrical specimens with thicknesses equal or less than the asphalt concrete layer. The SC(B) is a convenient geometry for taking specimens from both gyratory compacted lab samples and from field cores. Two specimens can be obtained from the each field core for SC(B) testing, thereby reducing the required number of cored specimens to provide a representative sampling of test results. One of the drawbacks of SC(B) test configuration is its smaller fracture ligament area, $37.5cm^2$ for SC(B) versus $75cm^2$ for SE(B) and $55cm^2$ for DC(T). Due to the small ligament size greater test variability is expected, this effect is especially exaggerated for asphalt mixtures with coarser gradations.

The DC(T) geometry, has been applied to metallic materials (ASTM E399) for several years. Wagoner et al. [11] proposed a DC(T) test that is suited for fracture characterization of asphalt concrete. Amongst other modifications to ASTM E339 is the altered location of the loading holes to ensure cracking at the notch tip. The DC(T) test has been used for variety of research studies, including the study of reflective cracking by Paulino et al. [13], thermal cracking by Dave et al. [14-15], and aging by Apeagyei et al. [16]. The test has been standardized in ASTM D7313-07b. The disk-shaped compact tension geometry is a circular specimen with a single edge notch loaded in tension. Test specimens were fabricated in accordance with the dimensions shown in Fig. 1(c). Specimen fabrication, apparatus, instrumentation, and analysis procedures are explained in detail in ASTM D7313-07b.

Due to its simple geometry, DC(T) specimens can be obtained easily from field cores or lab compacted samples. In this study DC(T)



(b)

Fig. 2. Experimental Setup for DC(T) Testing (a) DC(T) Test Setup and (b) DC(T) Test Specimen after Test.

was selected as the fracture test, in order to ensure compatibility with cylindrical specimens and to allow a 19*mm* nominal maximum aggregate size mixture to be tested with sufficient fracture ligament area. The data analysis for DC(T) test is now briefly described, followed by a description of the experimental design used for this study.

The loading rate for the DC(T) test is controlled through opening displacement at the crack mouth. A constant crack mouth opening displacement (CMOD) rate of 1*mm/min* was used in this study in accordance with ASTM D7313-07. The CMOD gage mounted to the DC(T) is shown in Fig. 2(a). Fracture energy of the specimens is determined by calculating the normalized area under the Load-CMOD curve. Normalization is done to obtain the fracture energy required to produce a unit fracture area. The DC(T) test set up, the CMOD gage, and the loading fixture are shown in Fig. 2(a). A typical DC(T) specimen upon completion of the test is shown in Fig. 2(b). In accordance with the ASTM D7313-07 test procedure, the testing was conducted at temperature of -12ºC for the target binder grade of PG 64-22.

Experimental Design

Four RAP samples from distinctly different sources across the State of Illinois were used in this study. Fig. 3 shows a map of the State of Illinois with the approximate locations of the four RAP sources. Incomplete records were available to assess the original design and materials associated with these RAP samples, and thus, forensic testing was conducted. Extraction and recovery of asphalt binder was performed on all four RAP samples in accordance with the AASHTO T319 test procedure. Recovered binders were tested to determine the complex modulus using the Dynamic Shear Rheometer (DSR) as per recommendations of the Superpave specified procedure (AASHTO T315-03) for testing of short term aged Rolling Thin-Film Oven (RTFO) asphalt binder. Fig. 3 shows the DSR test results in the form of shear stiffness (G*/sin(δ)).

Using solvent extraction, the asphalt content of RAP materials was determined, as listed in Table 1. RAP binder extraction produces a clean aggregate sample that can be used to determine the RAP aggregate gradation. Sieve analysis was conducted to determine gradations of RAP materials (AASHTO T27-88). Gradation information for the RAP materials, virgin aggregates, and the designed RAP mixtures are presented in Figs. 4 and 5.

A 19-mm nominal maximum aggregate size mix with a target asphalt content of 5.9 and 30% RAP by weight of total mixture was

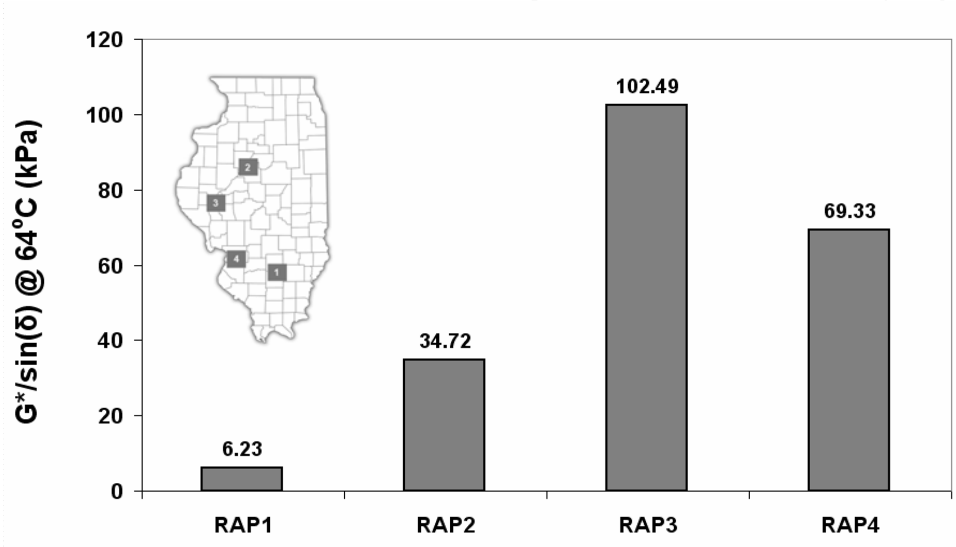


Fig. 3. DSR Test Results for Four Illinois RAP Sources.

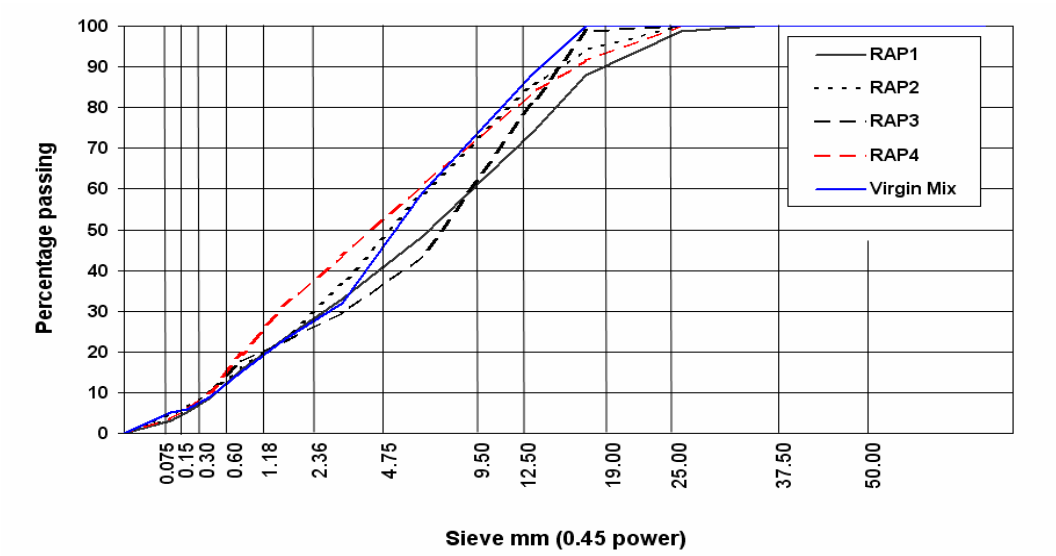


Fig. 4. Gradation of RAP Materials and Virgin Asphalt Mixture.

Table 1. Mix Design for RAP Mixtures.

Mix Type	Binder Content of RAP (%)	Mass of Constituents in the Mixture (*gm*) (Total Batch Weight = 5000*gm*)			
		RAP Binder	RAP Aggregate	Virgin Binder	Virgin Aggregates
PG64-22 /PG58-28	0.00	0.00	0.00	295.00	4705.00
RAP1	3.98	59.74	1440.26	235.26	3264.74
RAP2	4.28	64.20	1435.80	230.80	3269.20
RAP3	3.91	58.62	1441.38	236.38	3263.62
RAP4	4.07	61.07	1438.93	233.93	3266.07

Table 2. Job Mix Formula (Aggregate Blend Percentages) for Virgin Mixture.

Virgin Aggregate Type	Blend Percentage (%)
CM16	65.3
FM20	23.0
FM02	10.5
Mineral Filler	1.2

Table 3. Volumetric Properties of Virgin and Rap Mixtures (Maximum Theoretical Specific Gravity of Virgin Mixture, $G_{mm\text{-}Virgin}$, = 2.488).

RAP Mixtures	Bulk Specific Gravity (G_{mb})	Air Void %
MIX1-A	2.360	5.1
MIX1-B	2.380	4.3
MIX2-A	2.340	5.9
MIX2-B	2.375	4.5
MIX3-A	2.385	4.2
MIX3-B	2.376	4.5
MIX4-A	2.388	4.0
MIX4-B	2.364	5.0
0%RAP-A	2.380	4.3
0%RAP-B	2.371	4.6

selected for this study. Mixing was performed at 155°C using a standard bucket mixing procedure. Details regarding the amount of RAP and virgin constituents are presented in Table 1. The job-mix formula (aggregate blend percentages) for the virgin mixture is shown in Table 2. The volumetric properties of prepared RAP mixtures are shown in Table 3. The nomenclature used for the rest of the paper to indicate the virgin and RAP mixtures are as follows:

- Virgin Mixture: The mixtures are labeled as per the grade of asphalt mixtures, namely, PG58-28 and PG64-22, and;
- RAP Mixture: The mixture labels are selected according to the source of RAP material. For example, RAP1 indicates a mixture containing 30% of RAP1 material by weight of mix and a PG58-28 virgin binder.

Kandhal and Foo [17] suggest that mixtures with 15% or greater RAP by weight of mixtures should utilize a softer virgin binder grade in order to counteract the stiffness of the RAP binder. The Illinois Department of Transportation Materials and Design Specifications recommend the use of a softer PG binder grade for mixtures containing 20% or greater RAP materials [18]. The target binder grade of the virgin mixture was PG 64-22, thus for mixtures with 30% RAP, a PG 58-28 binder was selected as the virgin binder source. Two gyratory samples were prepared for each RAP mixture. From each gyratory sample, two DC(T) specimens were manufactured.

Results and Discussion

Typical Load-CMOD plots for three replicates of one of the study mixtures are presented in Fig. 6. In general, quasi-brittle materials exhibit a softening curve after the peak load instead of a sudden drop in material capacity in the post-peak region as exhibited by brittle materials. Other engineering materials that exhibit quasi-brittle failures include, concrete, rock, ceramics and fiber composites. The

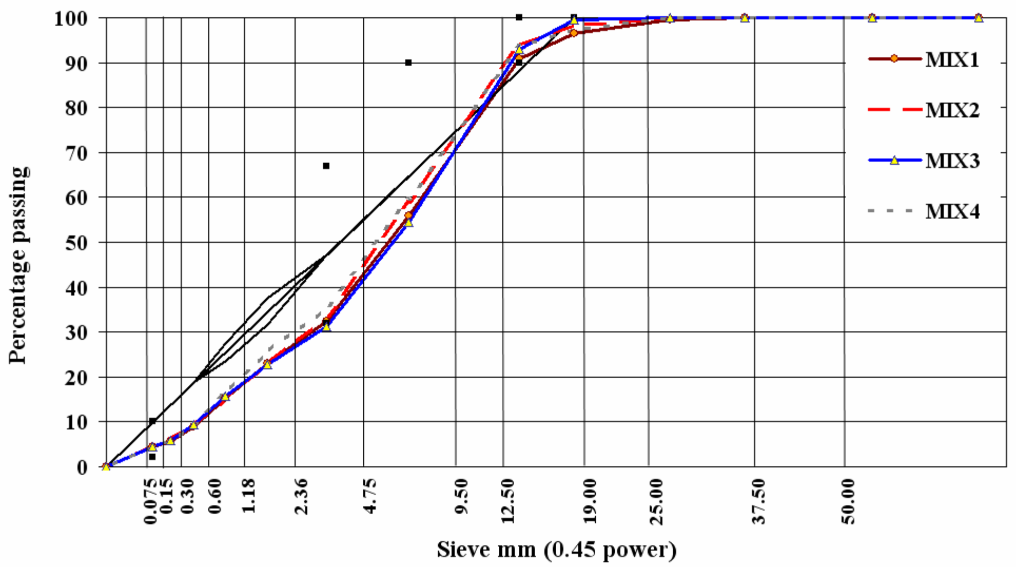


Fig. 5. Gradation of Mixtures Containing 30% RAP (Mix Number Corresponds to RAP Type).

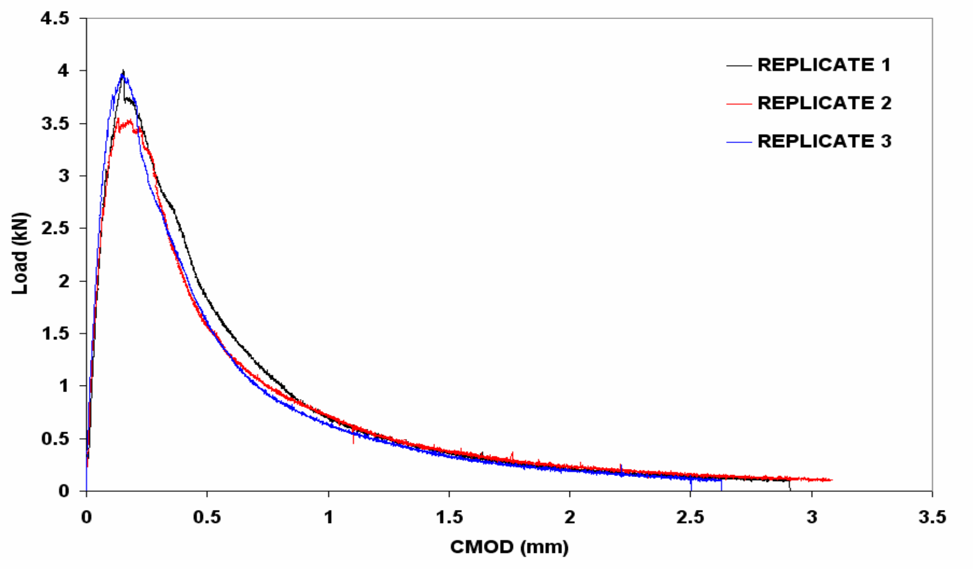


Fig. 6. Typical Load- CMOD Plots for Three Replicates for DC(T) Test.

softening portion of the plot represents the material state in the post-peak region after the onset of damage. Material softening occurs because of its ability to carry load due to aggregate bridging and interlocking and the ductile response of the binder coating on the aggregates in the fracture process zone ahead of the crack tip. This implies that material has capacity to carry load even after the stresses have exceeded the material strength, which gradually decreases with continued separation eventually leading to zero traction (load) across the cracked surface. It is important to accurately capture this complex material failure mechanism in both laboratory testing and computer simulations to accurately predict cracking in pavements through the use of non-linear fracture models. Methods such as the Cohesive Zone Model (CZM) can be used to handle this behavior efficiently [12].

Fracture energy results measured using the DC(T) test for mixtures containing 30% RAP from four sources are shown in Table 4. The test results for the virgin mixture are also shown in the same table. Based upon ASTM D7313-07b, a minimum of three test replicates were used to ensure adequate reliability of test results. Up to five test replicates were performed, depending upon availability of material. The coefficient of variation (CoV) was calculated for the test replicates in order to further ensure the quality of the results. Typically for fracture testing a maximum value of CoV should be restricted to 25% in order to ensure good data reliability [17]. For the results presented herein, the CoV ranged from 6 to 16%, which is quite good considering the size of aggregates used and presence of RAP in the mixtures tested. Fig. 7 summarizes the DC(T) test results of mixtures containing 30% RAP along with two reference mixtures containing 100% virgin materials, labeled: PG58-28 and PG64-22. Each bar represents the average of at least three DC(T) test results, with the error bars indicating the minimum and the maximum value obtained in the replicate tests.

The results reveal a significant decrease in the fracture energy for mixtures with 30% RAP and PG 58-28 binder tested at -12°C as compared to the virgin PG 58-28 reference mixture tested at the same temperature. A reduction of fracture energy of approximately

Table 4. DC(T) Test Results for Virgin and 30% RAP Mixtures.

RAP ID	Replicate #	CMOD Fracture Energy (J/m^2)	Average Fracture Energy (J/m^2)	CoV (%)
RAP 1	1	506	604	10.1
	2	597		
	3	644		
	4	611		
	5	664		
RAP 2	1	584	540	6.8
	2	558		
	3	511		
	4	509		
RAP 3	1	620	680	10.9
	2	636		
	3	679		
	4	785		
RAP 4	1	783	668	16.1
	2	569		
	3	654		
PG 58-28	1	1896	2021	6.8
	2	2000		
	3	2167		

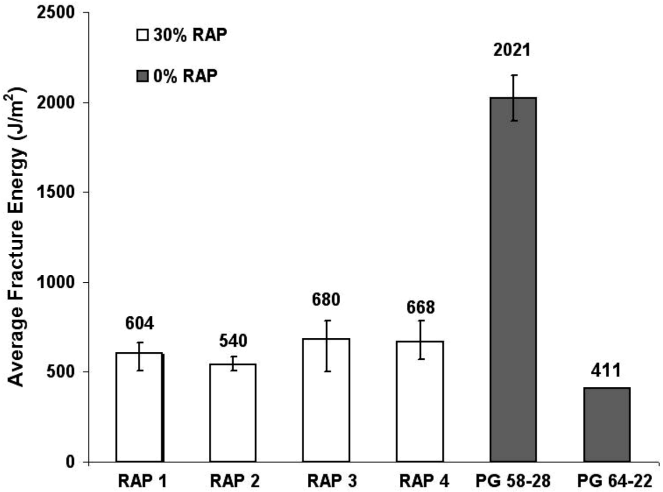


Fig. 7. Average Fracture Energies for Virgin and RAP Mixtures.

70% was observed with 30% addition of RAP. However, the more important comparison is between the RAP mixtures and the mixture produced with virgin materials at the target binder grade, or PG 64-22. It was observed that the average fracture energies of the mixtures containing 30% RAP and PG 58-28 binder were greater than those of the virgin mixture manufactured with PG 64-22 binder by about 50% on average. In this study, the mixtures containing RAP with adjusted lower binder grade have even better fracture resistance than virgin PG64-22 mixture. The virgin PG 64-22 mixture had fracture energy of 411J/m^2, while the RAP mixtures produced following the 'one binder grade softer' design philosophy had fracture energies ranging between 540 and 680J/m^2. Thus, the limited results obtained in this study suggest that the aforementioned design philosophy may have merit from the perspective of low temperature fracture properties. It can be deduced, therefore, that with proper design, RAP mixtures containing up to 30% RAP have the potential to achieve equal or superior crack resistance as compared to 100% virgin mixtures. The results also suggested that there was room for even higher RAP amounts before having to switch to an even softer binder grade from the standpoint of mixture fracture properties for the materials used in this study. This will vary from material set to material set, and furthermore, it should be kept in mind that the PG 58-28 binder grade used in this study was known to be softer than average PG 58-28 binders. This further emphasizes the need for mixture testing when higher levels of RAP are to be incorporated. The study also demonstrates the utility of the ASTM D7313-07b mixture fracture energy test for performance-based design of RAP mixtures where cracking is of concern, and the potential use of the test for quality control and/or assurance, and for pavement analysis and forensics.

Summary, Recommendations, and Remaining Challenges

Summary and Conclusions

This paper explored the effect of RAP on the low temperature fracture properties of asphalt concrete using DC(T) fracture energy test for asphalt mixtures. The practice of using a softer binder grade to compensate for the aged binder properties associated with RAP was assessed. Four RAP sources were studied with asphalt binder stiffness ranging over two orders of magnitude. Chemical extractions were performed to obtain the gradations of RAP materials and to make suitable adjustments to the mix design in terms of gradation and binder content. A set of mixtures were manufactured with 30% RAP content by weight of total mixture and PG58-28 binder. Virgin mixtures were manufactured and tested as control mixtures using both PG64-22 (target grade) and PG58-28 binder. DC(T) specimens were prepared from gyratory compacted samples of RAP and virgin mixtures.

DC(T) fracture tests were conducted at temperature of -12°C with at least three replicates for each material. The DC(T) test was found to be a suitable fracture evaluation method for RAP mixtures. In the current study the coefficient of variation was found to vary between 7 and 16%. The results demonstrated approximately 70% reduction in the fracture energy with 30% inclusion of RAP. That notwithstanding, these mixtures showed approximately 50% greater fracture energy than virgin mixtures produced with the design binder grade (PG 64-22). Consequently, the grade adjustment from PG64-22 to PG58-28 for mixtures with 30% RAP yielded favorable results from a fracture resistance point of view. The results also suggested that there was room for even higher RAP amounts before having to switch to an even softer binder grade from the standpoint of mixture fracture properties for the materials used in this study. No correlation was found between the high temperature RAP binder stiffness and the fracture resistance of RAP mixtures.

Recommendations

In order to extend the findings of this study, the following remaining challenges as identified through the present study should be addressed:

- The present study considered mixtures with 30% RAP from four sources within the State of Illinois. More RAP types and contents need to be tested for the evaluation of mixture fracture energy. In the future, a performance based design procedure for RAP mixtures may be possible.
- In order to relate the fracture energy measurements from the DC(T) test to field cracking performance, it is necessary to perform pavement cracking simulations. This will require the collection of additional low temperature material properties, such as creep compliance, tensile strength, and thermal coefficient of expansion.
- In addition to use of RAP, warm-mix asphalt (WMA) is an environmentally friendly alternative to traditional hot-mix asphalt production and can be combined with RAP. Future studies should involve fracture evaluations of WMA mixtures consisting RAP using the techniques presented herein.
- Previous researchers have shown that apart from cracking, another important source of deterioration for mixtures containing RAP is moisture damage. Following recently published work, one approach could involve the testing of moisture conditioned RAP and virgin mix samples in the DC(T) test configuration as a more fundamental alternative to the AASHTO T-283 procedure.

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