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Research Report: Jerry Leifheit Memorial Scholarship

Presented to IAPA Scholarship Board

Illinois Asphalt Pavement Association

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The contents do not necessarily reflect the official views or policies of the Illinois Center for Transportation, the Illinois Department of Transportation, or the Federal Highway Administration. This report is a summary of the work performed by the author during the R27-128 project and does not constitute a standard, specification, or final project report. This report should not be used as a reference document and for more information please refer to the R27-128 report from of the Illinois Center for Transportation.

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INTRODUCTION

During the last decade, multiple efforts has been made to protect natural resources by increasing the amount of recycled material used to produce common products such as cardboard, paper, and others. The pavement engineering field has implemented several sustainability alternatives with the goal of replacing virgin asphalt concrete (AC) components with Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS). As a result, there is a substantial reduction in the required amount of new mineral aggregates and barrels of asphalt used. A recent review of recycling practices in Illinois indicates that an average mile of construction in 2013 contained nearly four times more recycled content than in 2009 (Lippert et al. 2015). For AC, the increased specified allowances of (RAP) in the past few years, and the introduction of RAS in 2011, have greatly contributed to the increase in the recycled tonnage used. The outcome of this has been the reduction of landfills space that would have been used for this material, as well the decrease in the overall asphalt mixture costs.

One of the most urgent challenges of incorporating RAP and RAS is the increased brittleness of the asphalt mix. As a result, low temperature and fatigue cracking become a major problem, leading to early failure during service life. Currently, there is a gap in the literature to guide the asphalt industry on reliably measuring the changes in AC performance when using recycled and reclaimed materials. As a result, the Illinois Department of Transportation (IDOT), Federal Highway Administration (FHWA) and Illinois Center for Transportation (ICT) launched the R27-128 project, “Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS”. The main goal was the creation of a testing protocol to be used as part of the mix design acceptance specifications and production testing. This protocol would be able to identify changes in the susceptibility of cracking in AC with high levels of ABR.

During fall, 2014, I joined a team of four research assistants guided by Dr. Imad L. Al-Qadi, Dr. Hasan Ozer and Dr. John Lambros. The work has continued to date with the support of the previously mentioned agencies. This research report will provide a summary of the tasks and outcomes that I worked on, and where the Illinois Asphalt Pavement Association collaborated to provide additional support to my research this last year. The main tasks performed include:

- Laboratory Design of Asphalt Mixtures
- Complex Modulus Test
- Semicircular Bending Test (SCB) for laboratory mixtures.
- Development of the Flexibility Index

This work will enable engineers to characterize the mechanical behavior of mixtures with high ABR. Using the results of the mixture characterization, a suitable test that can distinguish between the mechanical responses of mixtures was selected. As mentioned before, the selected test was the Illinois Semicircular Bending Test (IL-SCB) to calculate the Flexibility Index (FI).

ASPHALT MIXTURE DESIGN

Before selecting an appropriate test, the effect of RAP and RAS in asphalt mixtures needs to be understood. For this reason, 16 plant mixtures were collected during the initial stage of the project form multiple IDOT projects. These mixes were used in the development of the test protocol because they had distinct mix design characteristics, which enabled the effect of various types and levels of ABR to be evaluated. However, one of the limitations of these mixes was that they did not have constant Voids in Mineral Aggregate (VMA) or asphalt binder content. As a result, my initial task in the project (along with Punit Singhvi) was to design 10 laboratory mixtures to understand the effect of ABR on the mechanical performance under constant volumetric conditions.

The mixtures were designed according the Illinois modified AASHTO M 323 specifications and the Bailey method. To evaluate the effect of ABR, the mixtures were designed for a 6 ± 0.1% binder content, 15.3 ± 0.1% VMA and 4% air voids. During their preparation, a special control on the volumetric properties was done to keep all the properties similar and only modify one variable per design. This made it possible to understand how each variable affected the fracture properties of the mixtures. A summary of the laboratory mixtures that were designed during this stage is presented in Table 1:

Table 1 Characteristic of Laboratory Designed Mixtures.

Mix ID	Mix Name	Binder Grade	RAP (%)	RAS (%)	ABR (%)	AC (%)	VMA (%)
L3	N90-0[1] CG[2]	70-22	—	—	—	6.0	15.3
L4	N90-0 CG	64-22	—	—	—	6.0	15.3
L5	N90-30 CG S1[3]	70-22	—	7	29.8	6.0	15.3
L6	N90-30 CG S1	58-28	—	7	29.8	6.0	15.3
L7	N90-20 CG S1	58-28	—	5	21.2	6.0	15.3
L8	N90-10 CG S1	64-22	—	2.5	10.5	6.0	15.3
L9	N90-30 CG S2[4] AS[5]	58-28	11	5	30.5	6.0	15.2
L10	N90-60 CG S2 AS	52-34	40	7	60.8	6.1	15.2
L11	N90-0 CG AS	64-22	—	—	—	6.0	15.3
L12	N90-30 CG S2[4] AS[1]	58-28	—	7	30.6	6.0	15.2
L13	N90-30 CG S1[3] AS[1]	58-28	—	7	29.8	6.0	15.3

[1] N90-0, N90-20, N90-30, and N90-60 indicate N-design and ABR percentage

[2] CG: Coarse graded

[3] S1: RAS source

[4] S2: RAS source

[5] AS: Mixture with 1% anti-strip added to virgin binder

Once the mix designs were completed, five representative mixtures were tested for Hamburg Wheel Tracking Test (WTT) and the Indirect Tensile Strength (IDT). The Hamburg WTT enabled us to identify the designs that were prone to rutting. At this step, all the mixtures designed passed the Hamburg WTT. The IDT test was performed to calculate the tensile stress ratio (TSR). This parameter is used to evaluate the susceptibility of the mixture to moisture damage in the field. The results of the TSR suggested that anti-striping agents should be incorporated in the mixtures to avoid moisture damage. For this reason, the mixtures L9-L13 were designed with the use of an antistripping agent.

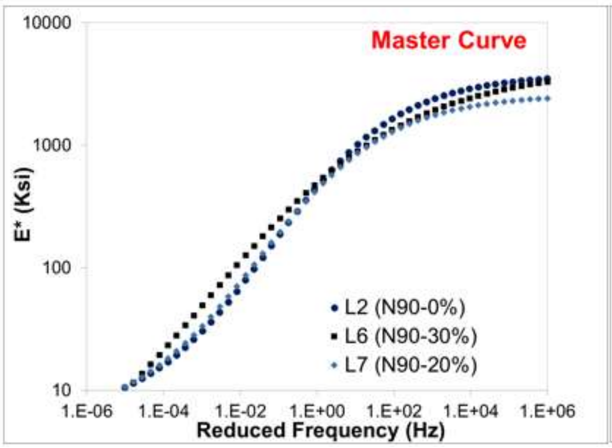
COMPLEX MODULUS

After the design of the mixtures, their mechanical performance needed to be understood. One of the most common parameters to characterize it is the Complex Modulus. The laboratory mixtures were tested for the Complex Modulus in accordance with the AASHTO TP 79-15. The complex modulus is a parameter that relates the stress and strains in a linear viscoelastic material when is tested against a sinusoidal load (Similar to the function of the elastic modulus on elastic materials). In practice, it is used for pavement design in the Mechanistic Empirical Pavement Design Guide (MEPDG) and can also be used to model the pavement response for multiple situations. The Complex Modulus is increasingly recommended for comprehensive characterization of AC because of its effectiveness in comparing different mixtures (Witczak et al. 2002; Bonaquist et al. 2003; Carpenter 2007; Vavrik et al. 2008; Ye et al. 2009; Braham et al. 2011; Ozer et al. 2012).

During this task three, laboratory design mixtures composed of 0, 20 and 30% ABR (L3, L6, and L7) were tested. Testing is conducted on cylindrical specimens of 100-mm (3.94-in) diameter and 150 mm (5.91-in) height as shown in Figure 1 a) Complex Modulus Testing equipment, b) Modulus Master curves, c) Phase Angle Curve. Measured strains are collected using strain gauges placed around the specimen's circumference. Testing is conducted at temperatures of –10°C (14°F), 4°C (39°F), 21°C (70°F), 37°C (99°F), and 55°C (131°F), and at frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz. The obtained modulus values are used to produce a complex modulus master curve that presents the modulus results for each frequency and a similar curve is produced for the phase angle. The phase angle is an indication of the degree of elasticity in the material. Higher phase angles indicate a viscoelastic behavior and smaller ones an elastic response.

a)

b) c)



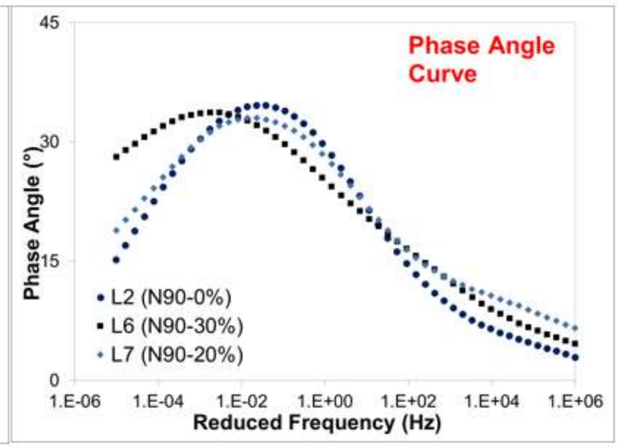


Figure 1 a) Complex Modulus Testing equipment, b) Modulus Master curves, c) Phase Angle Curve

Figure 1(b) and (c) shows the obtained curves for the complex modulus (E*) and the phase angle for the three mixtures respectively. In this test, the three selected mixtures contained 0, 20 and 30 % ABR (Mixes L3, L6, and L7 respectively). The mixtures with 0% ABR used a PG 70-22 binder while the 20% and 30 % ABR used a PG 58-28. The binder bumping was done to decrease the increment in the brittleness of the mixture due to the ABR. As a result when we compare the modulus curves of L3, L6, and L7 the mixtures do not appear to be any different from each other. This can be the result of the use of a softer binder (PG 58-28) for the mixtures with 30% ABR (L6). Usually, research shows that the addition of RAS and RAP significantly impacts the complex modulus of asphalt materials. Ozer et al. (2012) evaluated plant AC mixes with varying amounts of RAP and RAS and found that modulus increases with increasing RAS content at high testing temperatures and low frequencies. Finally, the results of the complex modulus master curve provided us with the parameters to model the mechanical response (stress-strain relationship) of the laboratory design mixtures.

SCB TESTING AT LOW AND INTERMEDIATE TEMPERATURES

The semi-circular bending beam test was performed to characterize the effect of ABR on the crack resistance of the laboratory mixtures according to the AASHTO TP 105-13. The semi-circular bending beam (SCB) test has been used to calculate the fracture energy derived from a load-displacement curve. The test is typically performed at two temperatures, 25°C and -12°C. These temperatures characterize the mixture behavior at intermediate and low temperature conditions, respectively. The test was conducted using a custom-designed SCB fixture placed in a servo-hydraulic asphalt testing machine (as shown in Figure 2). During each test, a load is applied over a three point bending semicircular asphalt sample. Then a load versus displacement curve is recorded and the SCB fracture energy, strength, and flexibility index (FI) parameters calculated and recorded for each mix. Fracture energy was calculated using the work of fracture method by finding the area under the load-displacement curve and dividing by the crack propagation area.

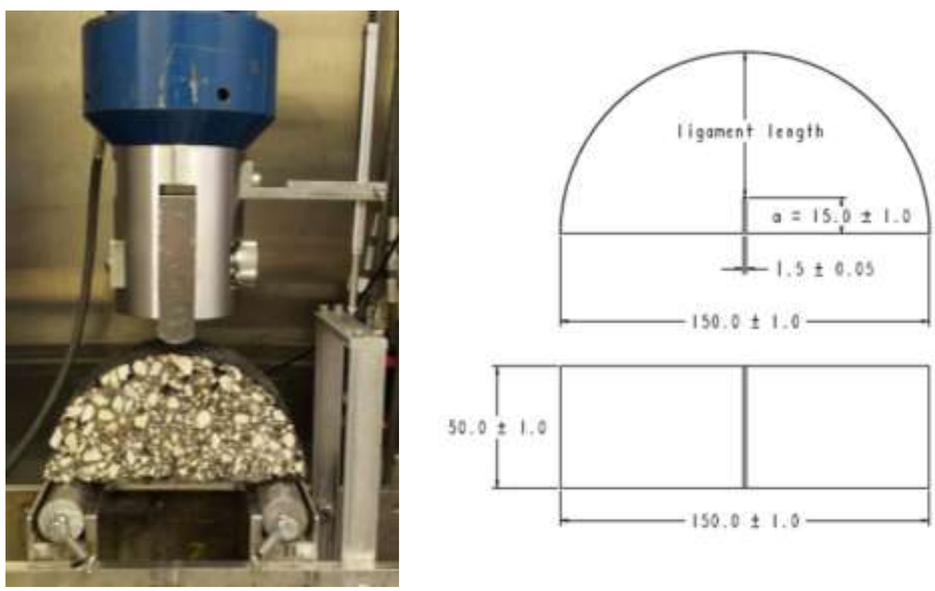


Figure 2 SCB test fixture and configuration (left) and geometry of specimen and fixture (right) with an external linear variable differential transformer (LVDT, based on the submitted AASHTO Provisional Standard Test Method)

The result from the SCB test at intermediate temperature suggest that there is a noticeable reduction in the fracture energy as ABR increases up to 60% as shown in Figure . Fracture energy values ranged from 967 to 2226 J/m2, a range of 1253 J/m2. In general, these results provide a better distinction between AC mixes. The reduction in the Fracture Energy indicates an increase in the cracking potential of the mixture in the field.

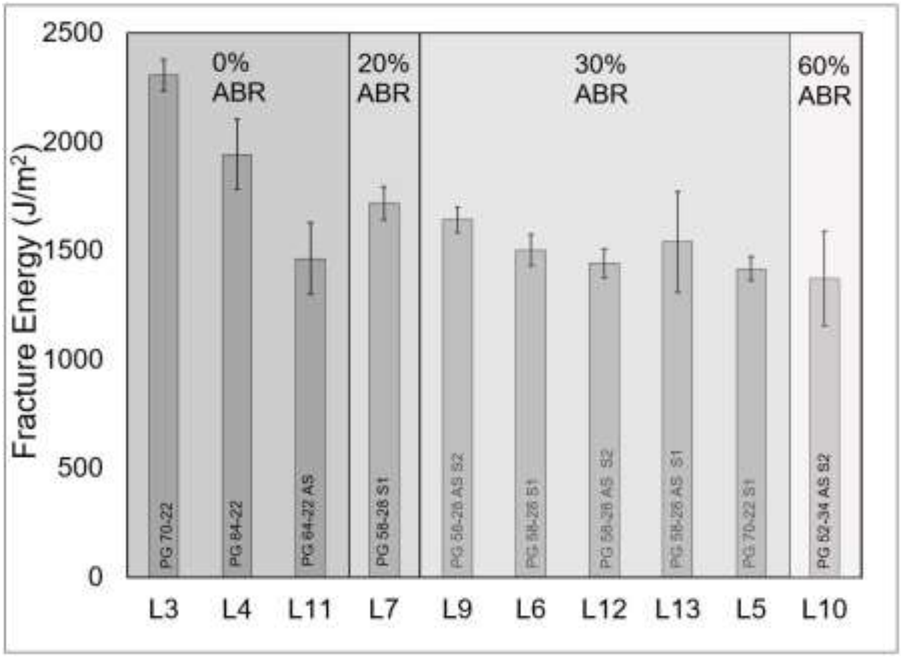


Figure 3 Intermediate-temperature (25°C [77°F]) SCB results for laboratory mixtures tested at a 50 mm/min (2 in/min) displacement rate.

FI DEVELOPMENT

One of the limitation of the traditional SCB output parameters is the inability in describing the shape of the load-displacement curve. The fracture energy indicates the overall energy dissipated from the mix, but it doesn’t necessarily indicate that the mixture can be stiff and prone to cracking. During this study, two mixtures with different ABR composition gave a similar fracture energy as shown in Figure . But, the load-displacement curves for each one indicated a different crack propagation behavior.
The fracture energy is a function of both the strength (defined by peak load) and ductility (defined as the maximum displacement at the end of the test) of the material. If the material displays a high peak load, it may compensate its fracture energy by its lack of ductility in the post-peak region of the load-displacement curve as shown in figure Figure . This is a potential explanation of why brittle AC mixtures with high amounts of recycled content may display similar or sometimes higher fracture energy values than their counterparts with no recycled materials. As a result, the fracture energy alone cannot determine the susceptibility of cracking.

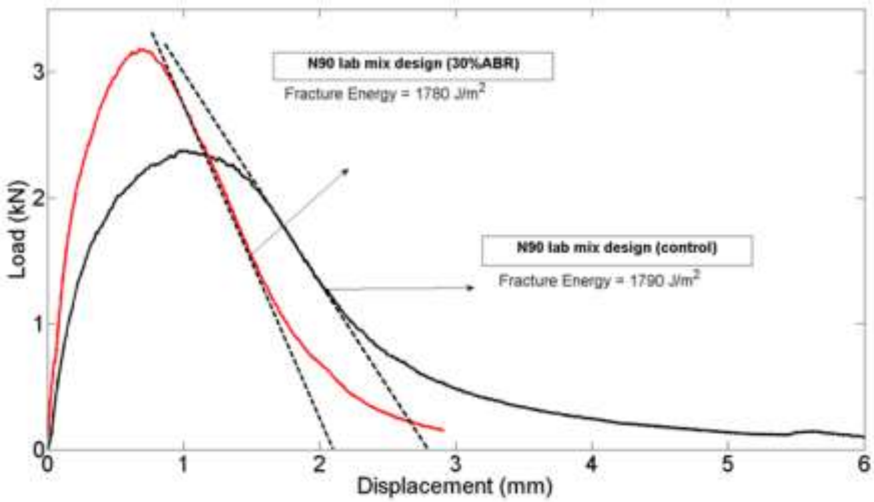


Figure 4 Major characteristics derived from load-displacement curves from IL-SCB tests conducted at 25°C (77°F) and at 50 mm/min (2 in/min) displacement rate illustrating the potential effects of ABR.

After a comprehensive study, our research group proposed the Flexibility Index as the main indicator to determine the damage potential of AC mixes. The FI is the fracture energy divided by the slope of the post-peak curve at the inflection point as shown in equation 1:

$$FI = A \times {G_f}/{abs(m)} \quad (1)$$

- G_f is fracture energy (joules/m^2)
- m is the slope of the post peak curve at the inflection point (kN/mm)
- Coefficient A is a unit conversion factor and scaling coefficient and is taken as 0.01

Figure shows the normalized FI result for the laboratory mixtures that were tested under the IL-SCB test. The Flexibility Index typically ranges from 1 to 20, and the higher the FI, the more ductile is the mixture and less prone to cracking. In the figure, the FI result was normalized with the control mixture L4 and the reduction of the FI with the increment of ABR in the mixture was noticeable. As a result, the increment in the ABR indicates a reduction in the ductility of the mixtures, and although the mixes are able to resist high load but, they fail more catastrophically due to a faster crack propagation.

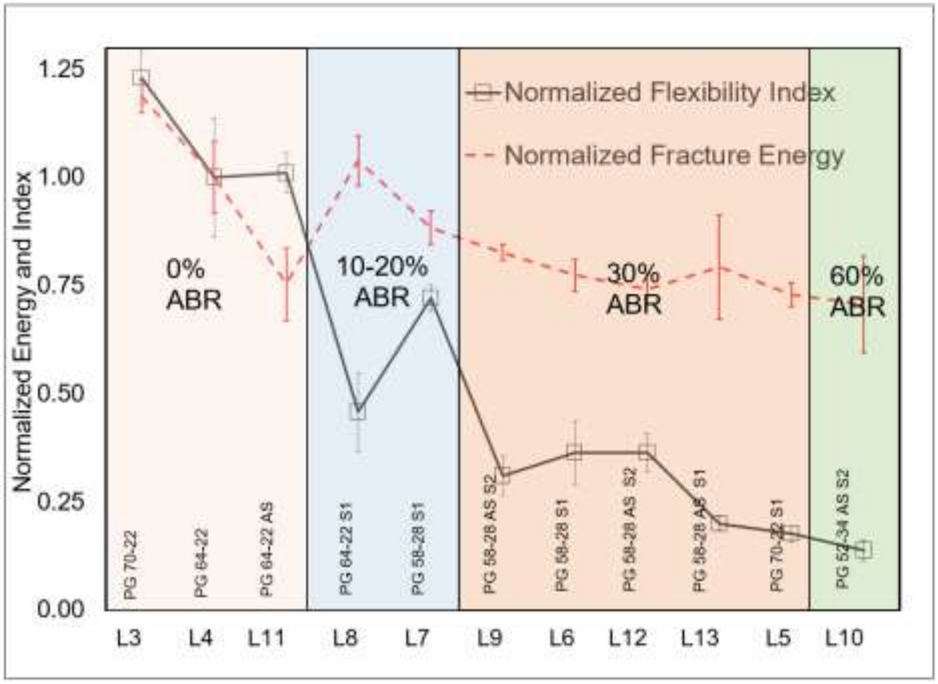


Figure 5 Normalized FI Results for the ICT Designed Plant Mixtures (FI Normalized based on mix L4)

CONCLUSION

During the last year, the IAPA scholarship has been able to support the work that I done with Dr. Imad Al-Qadi's research team to develop the Flexibility Index. There is a high expectation that this new parameter will be able to classify the asphalt mixtures prone to cracking. The development of this index is part of the efforts done by the Illinois Department of Transportation to incorporate recycled materials without compromising the pavement behavior. This index has being supported by a theoretical and practical approach. As previously explained, during the test and index development, several existing tests were evaluated along with the modulus and cracking tests. In addition, Plant, laboratory, and Field AC specimens were used at different stages of the study to validate the selected test. Tests were conducted at various temperatures and displacement rates to identify an optimum combination of temperature and displacement rate to allow a meaningful and consistent separation of the AC mixtures.
The IL-SCB test with the Flexibility index was the best testing scheme that is able to discriminate between the performances of the mixtures. The FI was finally defined from the load-displacement response curve incorporating fracture energy and slope after the crack begins to propagate. The FI was shown to correlate very well with another independent cracking test, which was tested on a full scale. Finally, during the following years it is expected that the FI become a tool to the typical mixture acceptance criteria, not just only in Illinois but, nationwide.

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