THE EFFECT OF SBS ASPHALT MODIFIER ON HOT MIX ASPHALT (HMA) MIXTURE CRACKING RESISTANCE

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ABSTRACT

This paper presents a laboratory investigation conducted to evaluate the effect of both radial and linear SBS modifiers on the cracking resistance of Hot Mix Asphalt (HMA) mixtures. Three types of asphalt mixtures composed by the same aggregate type and gradation but different asphalt binders (one unmodified and the others obtained by adding linear and radial SBS polymers to the unmodified one) were produced in the laboratory. The cracking performances of the mixtures were evaluated using a cracking model developed at the University of Florida called “HMA Fracture Mechanics Model”, based on the principles of visco-elastic fracture mechanics. The model requires only five tensile asphalt mixture properties which are obtained using the Superpave IDT: resilient modulus, creep compliance power law parameters, tensile strength, fracture energy and dissipated creep strain energy to failure.

All the results presented show the benefit of SBS modifiers to mixture’s cracking resistance in terms of reduced rate of damage accumulation (m-value) and increased tensile limits to failure (tensile strength, fracture energy and dissipated creep strain energy to failure). No influence was observed in the elastic response but rather on the time-dependent response. Finally, SBS linear polymers have shown to better improve cracking performances of HMA mixes than SBS radial ones.

Keywords: HMA mixtures, SBS polymer modifiers, Superpave IDT

1. INTRODUCTION

Cracking is one of the most influential distresses that governs the service life of asphalt concrete pavements. In order to improve the cracking performance of asphalt pavements it is important to acquire a better understanding of the cracking mechanism of asphalt pavements and to determine mixture's resistance to crack development and propagation.

In the last decades, several research efforts have investigated the use of asphalt modifiers to produce Hot Mix Asphalt (HMA) mixtures with sufficient cracking resistance as well as desirable rutting resistance. One of the most popular asphalt binder modifier is the Styrene-Butadiene-Styrene (SBS) block copolymer for its apparent capability in mitigating cracking of pavements in the field. Recent work conducted by Kim et al. (2003) showed that the SBS modified mixture generally has a lower m-value than unmodified one resulting in a reduced rate of micro-damage accumulation. However, it was not fully understood whether or not this benefit was uniquely associated with SBS modification rather than with age-hardening or further combined effects.

This paper presents a laboratory study focused on the evaluation of the influence of SBS asphalt modifier on HMA cracking performances. Three types of HMA mixes composed by the same aggregate type and gradation but different asphalt binders (one unmodified and the others obtained by adding linear and radial SBS polymers to the unmodified one) were investigated. The cracking performances of the mixtures were evaluated using a visco-elastic fracture mechanics-based cracking model recently developed at the University of Florida (Zhang et al. 2001; Roque et al. 2002). According to this framework, it was found that only five tensile mixture properties easily obtainable from the Superpave Indirect Tensile Test (IDT) are needed to control the cracking performances of asphalt mixtures, namely the m-value, the resilient modulus, the creep compliance, the dissipated creep strain energy to failure and the total energy to fracture.

The result presented show that both SBS radial and SBS linear modifiers appear to greatly improve the cracking resistance of asphalt mixtures, having more influence in the time-dependent response than on the elastic one.

2. MATERIALS

Three fine graded mixtures with the same aggregate type and gradation, but different asphalt binders were used in this study. All the mixtures are 12.5-mm nominal maximum size, produced with limestone and marly limestone, calcarenite and fine and coarse sand.

Three asphalt binders were involved in this study: one unmodified (N) graded as PG 58-22, and two polymer modified, RM3.5 and LM3.5 graded as PG 64-22 and PG 70-22 respectively. The RM 3.5 asphalt binder was obtained adding to the N unmodified one 3.5% of SBS radial cross-linked polymer, while the LM3.5 asphalt binder was obtained adding to the same N unmodified one 3.5% of SBS linear cross-linked polymer. The characteristics of asphalt binders are shown in Table 1.

The N unmodified mixture was designed according to the Marshall mix design procedure, while the two polymer modified mixtures were prepared using the same mix design parameters obtained for the N unmodified one.

Table 1. Asphalt binder properties

Asphalt binders	**N (unmodified)**	**RM3.5 (3.5% radial)**	**LM3.5 (3.5% linear)**
Asphalt grade	**PG 58-22**	**PG 64-22**	**PG 70-22**
UN-AGED ASPHALT			
Dynamic Shear (10rad/sec) G*/sinδ, kPa	2.58 @ 58°C	2.46 @ 64°C	1.40 @ 70°C
RTFO AGED RESIDUE			
Dynamic Shear (10rad/sec) G*/sinδ, kPa	4.77 @ 58°C	4.64 @ 64°C	2.35 @ 70°C
PAV AGED RESIDUE @100°C			
Creep Stiffness and m-value, 60 sec.	179 and 0.353 @ -22°C	130 and 0.335 @ -22°C	173 and 0.311 @ -22°C

2.1 Specimen preparation

For each mixture, one 4500 g aggregate batch was prepared to produce a total of 3-152 mm diameter cylindrical specimens. The aggregates, the asphalt binders and mixing equipment were heated for three hours at 150°C for the unmodified mix and at 175°C for modified ones to achieve appropriate uniform mixing temperature.

The batch was then mixed with the design asphalt content percentage and heated for another two hours at 135°C for short-term aging. According to the Marshall mix design the optimum asphalt content was estimated 5.2% for all the mixtures. The cylindrical specimens were obtained compacting the mixes to 6 (± 0.5) percent air voids into 152 mm diameter specimens using the Pine Gyratory Compactor.

After compaction and cooling of the specimens, volumetric analyses of the mixtures were performed (Table 2).

Each cylindrical specimen was sawn to obtain two effective plates, each 30 mm thick discarding the top and the bottom plates for reducing density gradient effects. For each mixture, three circular shaped specimens were used to perform The Superpave Indirect Tensile Test (IDT) according to the procedure developed by Roque and Buttlar (1992,1994).

Table 2. Volumetric properties of the three mixtures

Mixture	N	RM3.5	LM3.5
Asphalt content AC%	5.2	5.2	5.2
Theoretical maximum specific gravity G_{mm}	2.585	2.557	2.581
Bulk specific gravity of compacted mix G_{mb}	2.429	2.399	2.416
Bulk specific gravity of aggregate G_{sb}	2.632	2.632	2.632
Effective specific gravity of aggregate G_{se}	2.650	2.650	2.650
Percent VMA in compacted mix VMA	12.45	13.62	12.99
Percent air voids in compacted mix A_v	6.0	6.2	6.4
Percent VFA in compacted mix VFA	51.95	54.48	50.73

3. HMA CRACKING RESISTANCE PARAMETERS

Recent work conducted at the University of Florida had led to the development of a visco-elastic fracture mechanics-based framework, entitled “HMA Fracture Mechanics” (Zhang et al., 2001) capable to describe the fracture properties of HMA mixtures. The implication with this work is that it may not be sufficient to monitor changes in a single parameter such as strength or stiffness to evaluate the effects of micro- and macro-damage in mixtures. Rather, changes in stiffness and strength are typically accommodated by changes in the visco-elastic properties of mixtures, as well as strength and stiffness.

The core of this framework is the concept of the existence of a fundamental energy threshold which defines the development of macro-cracks at any time during either crack initiation or propagation. It was found that if the energy threshold is not exceeded, only healable micro-cracks not associated with crack initiation or crack growth occur; conversely, once the energy threshold is exceeded, non healable macro-cracks develop and propagate along the mixture.

As discussed by Roque et al. (2002), fracture (crack initiation or crack growth) can develop in asphalt mixtures in two distinct ways, defined by two distinct thresholds. The lower threshold is the Dissipated Creep Strain Energy (DCSE) limit which is associated with continuous repeated loading. In contrast, the upper energy threshold is the Fracture Energy (FE) which corresponds to that threshold required to fracture the mixture with a single load application. As shown in Figure 1 the Fracture Energy limit is determined as the area under the stress-strain curve, while the Dissipated Creep Strain Energy limit is the fracture energy minus the elastic energy at the time of fracture. It was also found that these parameters are fundamental HMA mixture properties, independent of specimen geometry and test configuration and not affected by polymer modification (Birgisson et al, 2007).

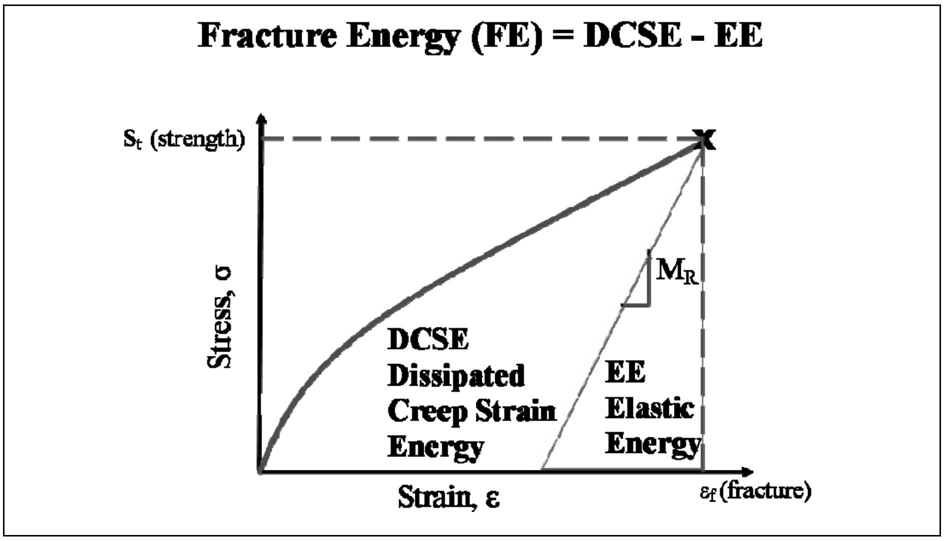

Figure 1. Lower and the Upper Threshold of Asphalt Mixes

A further parameter termed the Energy Ratio, which was derived by Jajliardo (2003) using the HMA Fracture Mechanics Model, was evaluated for representing the fracture toughness of asphalt mixtures. The Energy Ratio is defined as the dissipated creep strain energy threshold of the mixture divided by the minimum dissipated creep strain energy required ($DCSE_{min}$) which is function of the creep compliance power low parameters. Further details are discussed by Roque et al. (2004)

In order to evaluate mixture cracking performance using the HMA Fracture Mechanics Model the following tensile asphalt mixture properties are required:

- Resilient Modulus (M_R)
- Creep Compliance power law parameters (D_1 and m-value)
- Tensile Strength (S_t)
- Dissipated creep strain energy to failure ($DCSE_f$)
- Fracture energy

These properties can be easily determined from the Superpave IDT test as discussed by Roque et al. (2002).

4. TEST PROCEDURE

All the mixtures were tested at 10°C using the Standard Superpave IDT test to determine resilient modulus, creep compliance, m-value, D_1, tensile strength, failure strain, fracture energy and dissipated creep strain energy to failure. The cracking resistance of the mixtures were evaluated using the HMA Fracture Mechanics Model developed by Zhang et al. (2001)

The experimental setup of the Superpave IDT test is shown in figure 2.

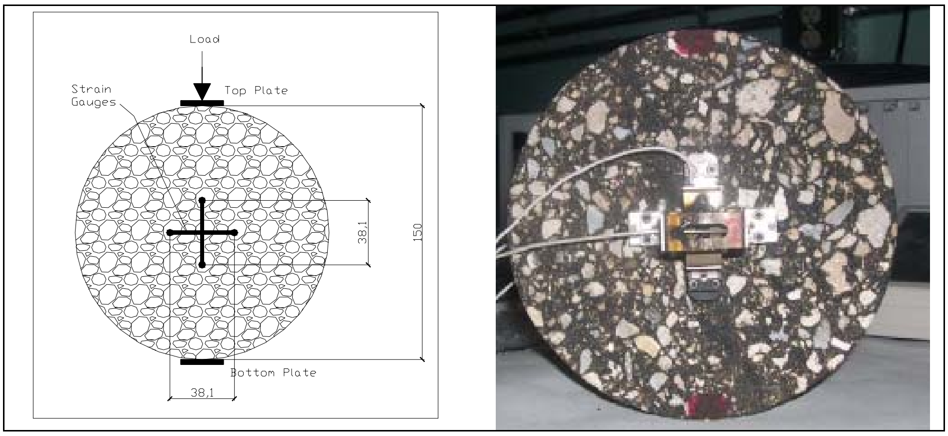

Figure 2. Superpave IDT

The top and the bottom loading plates are 25.4 mm wide and 50.8 mm long. Two strain gauges with a length of 38.1 mm are placed at the center of the specimen to measure vertical and horizontal deformations during loading. To take into account 3D effects, the procedure described by Roque and Buttlar (1992, 1994) and Birgisson, et al. (2003) was applied. According to this procedure, bulging correction factors are needed to correct the measured horizontal and vertical deformation to fit the deformation in a flat plane. These are then divided with the gauge length GL to obtain the average strain. Finally, center correction factors are used to correct the strain values at the center of specimen.

4.1 Resilient Modulus Test

The resilient modulus is defined as the ratio of the applied stress to the recoverable strain when repeated loads are applied. The resilient modulus test was performed in load control mode by applying a repeated haversine waveform load to the specimen for a 0.1 second followed by a rest period of 0.9 seconds for a total of 5 seconds to obtain horizontal strain between 150 and 350 micro-strains. The resilient modulus and Poisson's ratio are calculated by the equations developed based on three dimensional finite element analysis by Roque and Buttlar (1992, 1994).

4.2 Creep Test

Creep compliance is a function of time-dependent strain over stress. The creep compliance curve represents the time-dependent behavior of asphalt mixture, thus it is commonly used to evaluate the rate of damage accumulation of asphalt mixtures. As shown in Figure 3, three mixture parameters can be obtained from creep compliance tests: D_0, D_1, and m-value. Although D_1 and m-value are related to each other, D_1 is more descriptive of the initial portion of the creep compliance curve, while m-value describes the longer-term portion of the same curve. The m-value has proved to be related to the rate of damage accumulation and the fracture resistance of asphalt mixtures (Kim et al., 2003). In detail an asphalt mixture with a low m-value exhibits a low rate of damage accumulation. The creep test is performed applying a static load and then holing it for 1000 seconds. The loads and the deflections are recorded at different rates in function of time.

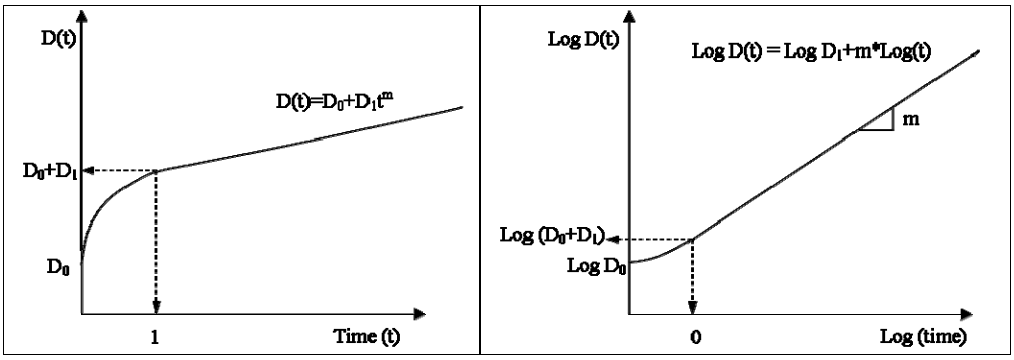

Figure 3. Power model of the creep compliance

4.3 Strength Test

Strength tests are used to determine failure limits as tensile strength, failure strain, fracture energy and dissipated creep strain energy. The strength test is performed loading monotonically the IDT specimen to failure applying a constant stroke of 50mm/min.

The tensile strength is calculated according to the Superpave IDT test procedure (Roque and Buttlar, 1992, 1994):

$$\sigma_h = 2P / \pi Dt \qquad \text{(Eq. 1)}$$

where:
σ_h = tensile stress at the center of the specimens,
P = load of the specimen,
D = diameter of the specimen,
t = thickness of the specimen.

As previously described, resilient modulus, fracture energy density and dissipated creep strain energy density are easily determined from the strength test.

5. RESULTS AND DISCUSSION

A summary of the test results and a detailed analysis of each mixture property is presented. The relationship between mixture properties and mixture cracking performance is also described. All the results obtained from the Superpave IDT test are listed in Table 3.

Table 3. Superpave IDT test results

Asphalt Mixture	N	RM3.5	LM3.5
Resilient Modulus (Gpa)	13.35	13.11	13.34
Creep Compliance @1000 seconds (1/Gpa)	4.23	2.07	2.13
m-value	0.55	0.46	0.51
D_1	6.309E-07	5.687E-07	4.203E-07
Tensile Strength (Mpa)	2.49	2.93	3.08
Failure Strain (10^{-6})	2061.3	2336.1	2450.1
$DCSE_f$ (kJ/m^3)	3.57	4.87	5.34
$DCSE_{min}$ (kJ/m^3)	2.33	1.32	1.32
Fracture Energy (kJ/m^3)	3.80	5.2	5.7
Energy Ratio	1.53	3.69	4.03

The Resilient Modulus is a measure of the material’s elastic stiffness. Figure 4 shows the values of Resilient Modulus for each of the mixtures. The results show that either the radial and linear polymer modifiers have no effect on resilient modulus. This indicates that, at small strain and/or short loading times, radial and linear polymers do not affect the mixture’s response.

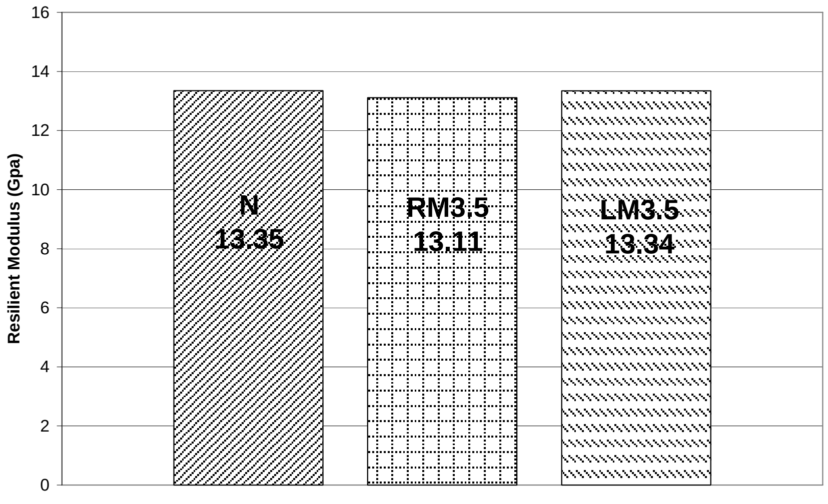

Figure 4. Comparison between the Resilient Modulus obtained for the 3 mixes

Creep Compliance is related to the ability of a mixture to relax stresses. As shown in Figure 5, the creep compliance curves varied significantly from unmodified to modified mixtures. The slope of the creep compliance curve at 1000 seconds is essentially a measure of the rate of permanent deformation : the higher the slope, the higher the rate of permanent deformation (Zhang et al. 2001). The crack growth process is governed by permanent deformations. Mixtures with high m-values or high creep rates exhibit higher crack growth rates. The results show that both radial and linear polymer modified mixtures exhibit a lower rate of permanent deformation thus a lower rate of micro-damage accumulation than the unmodified one. This means that either type of modifications have a greater influence on the time-dependent response than on the elastic response of the mixture. It must be pointed out that creep compliance values are almost the same for radial and linear polymer modified mixtures, while m-value and D_1 slightly differ.

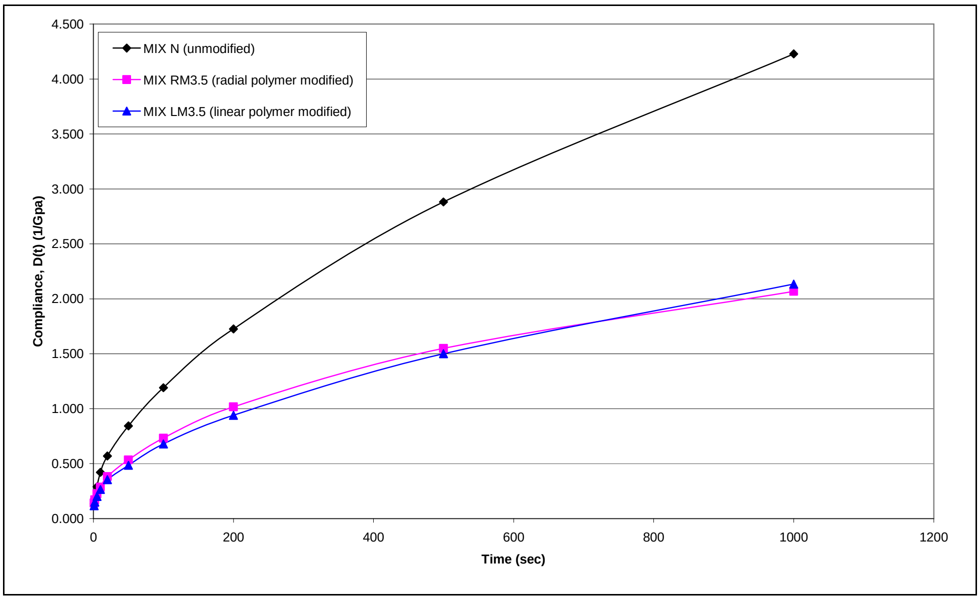

Figure 5. Creep Compliance curves for the 3 mixes

Tensile strength is the maximum tensile stress the mixture can withstand before failure (macro-crack initiation) while failure strain is the horizontal strain at first fracture. Fracture energy density is the energy per unit volume required to fracture a mixture, while the dissipated creep strain energy at failure is defined as the fracture energy minus the elastic energy. As shown in Figure 6, the modification slightly improved the tensile strength by 16.7% (radial polymer modification) and 23.7% (linear polymer modification).

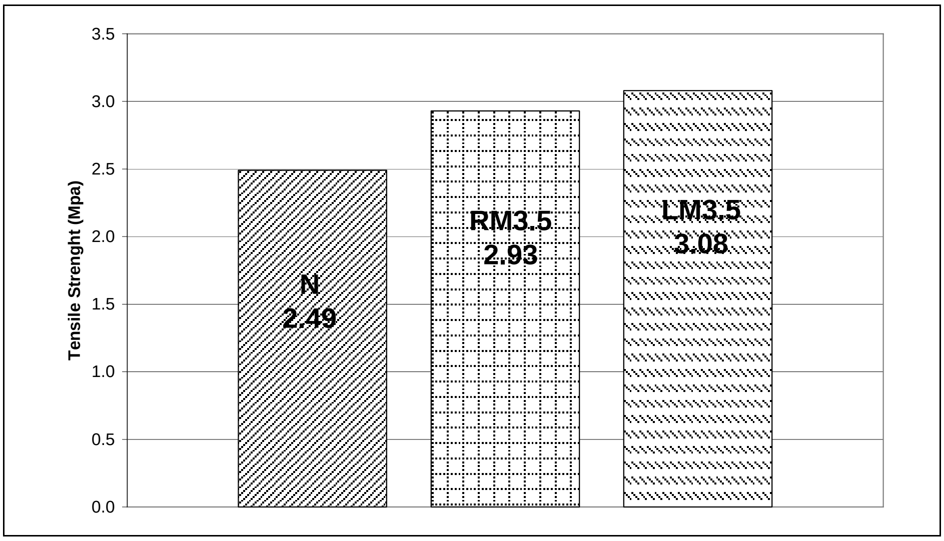

Figure 6. Comparison between the Tensile Strength obtained for the 3 mixes

Conversely, the dissipated creep strain energy to failure and fracture energy are strongly enhanced by the polymer modification, as well as failure strain (Figure 7). This means that both radial and linear SBS polymers are capable to increase the threshold energy required to crack the mixture. Besides, linear polymers seem to provide greater benefits in cracking resistance than the radial ones.

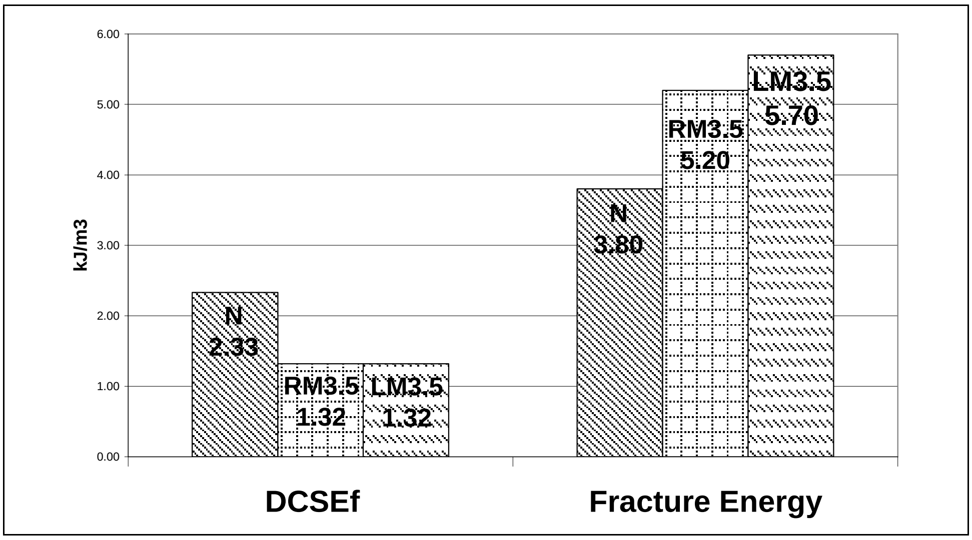

Figure 7. DCSE$_f$ and Fracture Energy obtained for the 3 mixes

The energy ratio is finally a dimensionless parameter which defines a single criterion for top-down cracking performance of all mixtures in pavement structures. It was found that for a mixture to be acceptable, the energy ratio should be greater than 1.0 (Roque et al. 2004). Obviously, the greater is the energy ratio the higher is the mixture resistance to top-down cracking. The results show that SBS polymer modified mixtures exhibit a better top-down cracking performance than the unmodified one. In particular, the SBS linear polymer modifier provides more benefits that the SBS radial one.

6. SUMMARY AND CONCLUSIONS

A laboratory investigation was conducted to evaluate the effect of SBS modifiers on HMA cracking performances. Both SBS radial and SBS linear polymer modified mixtures were tested using the Superpave IDT test, as well a control unmodified mixture. The cracking performances of the mixes were evaluated using the "HMA Fracture Mechanics" cracking model capable of describing the cracking behavior of HMA mixes regardless of the test configuration and independently from the level of polymer modification.

The results presented show that the polymer modification do not have any effect at small strain but allow for a lower rate of permanent deformation and micro-damage accumulation. Polymer modification has also shown to improve tensile failure limits of mixtures, slightly increasing tensile strength and enhancing both Dissipated Creep Energy to failure and Fracture Energy. It was also found that SBS polymer modified mixtures have a higher Energy Ratio than the unmodified one, resulting in a better top-down cracking performance. Finally, the results imply that linear polymers provide more benefits than the radial ones.

It can be concluded that SBS polymer modifiers have a greater influence on the time-dependent response than on the elastic response of mixtures, improving mixture resistance to crack initiation and propagation for both bottom-up and top-down cracking.

REFERENCES

B. Birgisson, C. Soranakom, J.A.L. Napier and R. Roque (2003) - "Simulation of Fracture Initiation in Hot Mix Asphalt Mixtures"- Transportation Research Record, Soil Mechanics, Issue 1849, pp 183-190.

Birgisson B., Montepara A., Romeo E., Roque R., Roncella R., Tebaldi G., (2007) – "Determination of Fundamental Tensile Failure Limits of Mixtures" - Journal of the Association of Asphalt Paving Technologists, Vol.76, in press.

Booil K., Roque R., Birgisson B. (2003) – "Effect of Styrene Butadiene Styrene Modifier on Cracking Resistance of Asphalt Mixtures" - *Transportation Research Record, Bituminous Binder,* Issue: 1829.

Buttlar W.G. and R. Roque (1994) - "Development and Evaluation of the Strategic Highway Research Program Measurement and Analysis System for Indirect Tensile Test at Low Temperatures" - Transportation Research Record Issue: 1454.

Jajliardo A. P. (2003) – "Development of Specification Criteria to Mitigate Top-Down Cracking" – Master Dissertation, University of Florida.

Roque R. and W.G. Buttlar. (1992) – "The Development of a Measurement and Analysis System to Accurately Determine Asphalt Concrete Properties Using The Indirect Tensile Mode" - Journal of the Association of asphalt Technologists. Vol.61, pp. 304-332.

Roque R., Birgisson B., Sangpetgnam B., Zhang Z., (2002) - "Hot Mix Asphalt Fracture Mechanics: A Fundamental Crack Growth Law for Asphalt Mixtures". Journal of the Association of Asphalt Paving Technologists, Vol.71, 2002, pp.816-827.

Roque R., Birgisson B., Drakos C., Dietrich B. (2004) – "Development and Field Evaluation of Energy-Based Criteria for Top-Down Cracking Performance of Hot Mix Asphalt.

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