The Improvement of Thermal Cracking Resistance and Fatigue Life of RAP-Incorporated Asphalt Mixtures with the Aid of epoxidized methyl soyate (EMS)

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ABSTRACT

In this study, an asphalt binder was modified with epoxidized methyl soyate (EMS) that was engineered at Iowa State University. The binder modification was accomplished in an asphalt terminal, and the resulting binder was used for reversing the undesired effects of reclaimed asphalt pavement (RAP) in a mixture containing 30% of this reclaimed material. The modified mixture was produced in an asphalt plant for a pavement demonstration project that occurred in November 2017. The EMS-modified mixture with 30% RAP and a control mixture containing only 18% RAP were used for paving a 7-mile stretch of a high-volume roadway in O'Brien County, Iowa, U.S. About 6.6 miles of the roadway was paved with the control low RAP mixture that is traditionally used for paving roadways in Iowa, and the remaining 0.33 miles was paved with the high RAP EMS-modified mixture. To predict the field performance of the mixtures, the low-temperature cracking and fatigue cracking resistance of the mixtures were evaluated using disc-shaped compact tension (DCT) and push-pull fatigue tests, respectively. The results revealed that the EMS restorative reactive modifier (RRM) used in this study results in reversing the undesired effects of RAP and improving the low-temperature cracking and fatigue resistance of the asphalt mixture containing 30% RAP.

INTRODUCTION

Sustainability in the context of pavements refers to achieving the design goals; preserving/restoring the surrounding ecosystems; using human, financial, and environmental resources in an economical fashion; and meeting the basic human needs (Van Dam et al. 2015). Pavement sustainability is an aspirational goal, as it is unlikely that a fully "sustainable" pavement will be constructed in the near future; therefore, the sustainability should be viewed as progressive movement toward this ultimate goal. In the context of asphalt pavements, the use of reclaimed asphalt pavement (RAP) aggregates and bio-renewable modifiers can increase the speed to achieve a high level of sustainability, if not the ultimate goal. RAP when incorporated into asphalt mixtures decreases the depletion rate of virgin aggregates and reduces the amount of virgin asphalt binder needed for producing mixtures. Bio-renewable modifiers, i.e., the modifiers made of organic materials with recent biological origin, when used in asphalt binders obviate the need for using analogues obtained from petroleum resources.

It is known that RAP results in premature pavement failure at low and intermediate temperatures. The asphalt binder in RAP has a poor relaxation ability due to its continuous oxidation throughout the pavement service life. Therefore, when RAP aggregate is replaced with virgin aggregate, the resulting mixture becomes stiffer and more brittle and more prone to failure due to environmental and traffic-related loads. A myriad of recycling agents has been produced to restore the properties of RAP binder to address this drawback (Zaumanis et al. 2014). These agents are often formulated to return an oxidized binder's ratio of asphaltenes /maltenes to its unaged stage (Romera et al. 2006). The asphalt binder's rheology depends largely on the quantity of asphaltenes as they are more viscous than both resins and oils. During the oxidation process, resins transform into asphaltenes while saturates/oil and aromatics transform into resins. Such transformation increases the quantity of asphaltenes and therefore the hardening of asphalt materials (Wu et al. 2007). The recycling agents containing saturates/oils can restore an aged/oxidized asphalt binder to its original viscoelastic state, but the quality of such restoration depends on the formulation of such modifiers and their application method (Podolsky et al. 2018). Among all the available modifiers, bio-renewable soybean oil-derived recycling agents have lately drawn the attention of researchers (Chen et al. 2019; Pouranian et al. 2019), as they are less expensive and more environmentally friendly.

The objective of this study is to investigate the low-temperature cracking and fatigue performance of a high RAP asphalt mixture produced with an asphalt binder modified with epoxidized methyl soyate (EMS) that is a soybean oil-derived recycling agent. To this end, disc-shaped compact tension (DCT) and push-pull fatigue tests are used for evaluating the mechanical performance of two types of mixtures: a control mixture containing only 18% RAP, and a mixture containing 30% RAP and modified with EMS.

MATERIALS AND METHODOLOGY

Project description. The paving project occurred in O'Brian County, Iowa, U.S in November 2017. Two different mixture types were used: a low RAP mixture - containing 18% RAP - and a high RAP mixture - containing 30% RAP modified with epoxidized methyl soyate (EMS). The low and high RAP mixtures were used for paving, respectively, 6.63 and 0.33 miles of U.S. 18. If no EMS was used the whole pavement section would be paved with the low RAP mixture. Using the EMS, being a reactive restorative modifier (RRM), allowed the incorporation of 30% RAP for paving the remaining 0.33 miles. Hereinafter, the unmodified low RAP mixture traditionally used in the State of Iowa would be referred to as control mixture, and the high RAP mixture would be referred to as EMS-modified mixture. The asphalt mixtures used in this study were obtained from a mobile asphalt plant "six pack" located near the project site.

Asphalt binder. The grading for asphalt binders was conducted based on the method provided by the Combined State Binder Group (CSBG) (*Combined State Binder Group: Method of Acceptance for Asphalt Binders* 2020). The CSBG consist of the State Departments of Transportation of Iowa, Minnesota, North Dakota, South Dakota, Wisconsin, and Nebraska. In the performance grade (PG) system, the Superpave rutting parameter ($G^*/\sin\delta$) is measured by applying an oscillating load to the asphalt binder at a very low strain level to capture the permanent deformation of this material (AASHTO M 320-17). However, low strain levels fail to accurately represent the rutting resistance of polymer modified binders, because the polymers, when not subjected to deformation at higher strain levels would act as fillers – i.e., only increase the stiffness of the binder. To overcome this shortcoming, the MSCR test was introduced to not only evaluate the change in binder stiffness due to polymer modification, but also measure the non-recoverable creep compliance (J_{nr}) and the percent elastic recovery (R) (Moraes, R. et al. 2017). By using higher levels of strain and stress, the MSCR test enables capturing the delayed elastic behaviors in addition to evaluating the stiffening effect of polymers. The main difference between the new MSCR specification and the conventional Superpave high temperature specification is how the grade bumping is achieved. Previously, to increase the rutting resistance, the grade bumping was accomplished by increasing the binder test temperature and maintaining the $G^*/\sin\delta$ above the specification minimum requirements through polymer modification. However, many polymers soften very quickly at high temperatures, and, in reality, the pavements are unlikely to experience such high temperatures during their service lives. Using the MSCR test, the high temperature grading is performed at the high environmental temperature in the location that the pavement is expected to rut – e.g., in this research the high environmental for both projects was 58 °C, as the project was located in O'Brian County, Iowa. Based on the J_{nr} parameter obtained from the MSCR test performed at the high environmental temperature, the PG is graded as either standard (S), heavy (H), very heavy (V) or extremely heavy (E). These letters indicate the volume of traffic that an asphalt mixture made with these binders can withstand during the pavement service life. The CSBG has taken this grading system to the next level as it uses the elastic recovery value in addition to the non-recoverable creep compliance value, and grades the asphalt binder based on the most conservative grade, e.g., S, H, V or E, that is obtained.

Based on the CSBG grading system, the base binder used in this project graded as PG 58-34H. Due to high amount of RAP, e.g., 30%, used in this project, a grade bump down of PG 58-38H to PG 52-40H was required. This requirement was achieved in an asphalt terminal through the modification of the base binder with EMS at a dosage rate of 3.6% based on the binder weight. EMS, being an RRM (Podolsky et al. 2018), was used to restore the undesired effects of RAP and improve the mechanical performance of RAP-incorporated mixture at intermediate and low temperatures.

Aggregates. The virgin aggregates used in the project were obtained from Hallett Materials Co. and Concrete Materials Co. located in Iowa, and the RAP aggregates were provided by the contractor in charge of the project. Table 1 presents the aggregate gradations used for control (or low RAP) and EMS-modified (or high RAP) mixtures.

Table 1. Aggregate Gradation for Each RAP Replacement Content.

Sieve Size (mm)	18 % RAP			30% RAP		
	Lower Tolerance (%)	Combined Gradation (%)	Upper Tolerance (%)	Lower Tolerance (%)	Combined Gradation (%)	Upper Tolerance (%)
25	100	100	100	100	100	100
19	100	100	100	100	100	100
12.5	83	90	97	88	95	100
9.5	76	83	90	78	85	92
4.75	64	71	78	54	61	68
2.36	37	42	47	31	36	41
1.18		26			22	
0.6	14	18	22	12	16	20
0.3		11			9.3	
0.15		5.9			5.5	
0.075	2.3	4.3	6.3	2.3	4.3	6.3

Fabrication of asphalt mixture specimens. The control and EMS-modified asphalt mixtures procured from the asphalt plant were heated to 150 °C and then compacted using a gyratory compactor to obtain specimens with 7±0.5% air void content for performing disc-shaped compact tension (DCT), dynamic modulus and push-pull fatigue tests. After the compaction, the DCT specimens with a height of 50 mm and a diameter of 150 mm were cut and drilled to a obtain a face, a pair of holes, and a notch (ASTM D7313-13). The face allowed gluing gage points and placing a clip-on gage, the holes enabled mounting the specimen in the device using a loading clevis, and the notch allowed guiding the crack propagation through, or in the proximity, of the ligament area during the test. For performing the push-pull test (AASHTO TP 107-18), it was needed to first obtain specimens with a diameter of 100 mm and a height of 150 mm to perform dynamic modulus test (AASHTO T 342-11). The first step before performing push-pull tests is to measure the dynamic modulus ($|E^*|$) and phase angle (δ) values to then allow the calculation of pseudostiffness (C) and the damage parameter (S) values. After obtaining these values, the dynamic modulus test specimens were trimmed to 130 mm and then glued to loading platens for performing the push-pull fatigue test.

Characterization of low temperature cracking performance. According to a national pooled fund study, part of which was led by the asphalt research team at Iowa State University, the DCT test can give an acceptable estimation of the low temperature cracking performance of asphalt mixtures in the field (Marasteanu et al. 2012). Therefore, in this study, the low temperature cracking resistance of the mixtures was evaluated using a DCT device. The temperature selected for performing the DCT test was -24°C, a temperature 10 °C higher than the low temperature grade of the base binder, e.g., PG 58-34H, used in the project. All the DCT specimens were conditioned at -24°C for at least 12 hours to reach thermal equilibrium (Arabzadeh and Güler, 2014). After mounting the specimens in the DCT device, the specimens were pulled using the DCT loading crevice at a constant rate of crack mouth opening displacement (CMOD) of 0.017 mm/s. The load-CMOD data logged during the test were used for calculating the fracture energy (Equation 1).

$$G_f = \frac{AREA}{B.(W-a)} \quad (1)$$

where: G_f is the fracture energy (J/m^2); AREA is the area (m^2) under the load versus CMOD curve; B is the specimen thickness in m; and W-a is the ligament length (m).

Characterization of fatigue performance. A universal testing machine (UTM) was used for performing the push-pull test. The test temperature was selected based on the project location. This temperature was determined as the average of the high-and-low PG temperatures minus 3°C resulting in a test temperature of 21°C. Therefore, all the push-pull fatigue tests were performed at a room temperature of 21±1°C, obviating the need for running the UTM's environmental chamber in a temperature-controlled mode. The loading mode was controlled actuator displacement (Wang 2019), or controlled crosshead (Keshavarzi and Kim, 2016). To obtain different fatigue life data, e.g., N_f, the mixtures were subjected to different strain levels ranging from 250 to 500 με. The strain levels increased at increments of 50 με, but the specimens with significant deteriorated signals obtained from linear variable displacement transducers (LVDTs) were discarded when performing the fatigue analyses. The $|E^*|$ and δ values acquired during the dynamic modulus test together with the data obtained during the push-pull test were fed to the FlexMAT™ program currently under development by the asphalt research team of North Carolina State University. The FlexMAT™ was used for calculating the C and S values as well as developing the damage characteristic curves using the following model (Equation 2):

$$C = 1 - C_{11}S^{C_{12}} \quad (2)$$

where C_{11} and C_{12} are the model coefficients. The relationship between the C and S has proven to be a fundamental material property (Etheridge et al. 2019; Wang et al. 2018). In other words, this relationship is independent of testing temperature, loading mode and loading amplitude.

RESULTS AND DISCUSSION

Low temperature cracking analysis results. The presence of EMS in the high RAP asphalt mixture resulted in a slight increase in the fracture energy when compared with the performance of the control, or low RAP mixture (see Table 2). The EMS being a reactive restorative modifier (RRM) allowed the increase of RAP content from 18% to 30%. Therefore, due to the reaction of EMS with the binder and restoring the undesired effects of RAP, this recycled material could be incorporated at a higher rate without sacrificing the low temperature cracking performance of the asphalt mixture. It is know that the fracture energy is representative of the strain tolerance (Braham et al. 2007), and the slight increase in the fracture energy in the mixture containing 30% RAP and modified with EMS proves the effectiveness of this RRM used at a dosage rate of 3.6% in this study. The behavior observed, indicate the possibility of increasing the EMS content to then increase the RAP content even above 30%. However, increasing the RRM and RAP contents, for improving the low-temperature cracking performance, requires further investigations to evaluate the mixture behavior at high and intermediate temperatures. At high and intermediate temperatures, respectively, the rutting and fatigue cracking are the dominant distress types.

Table 2. The DCT Test Results

Mixture Type	Fracture Energy (J/m²)		Coefficient of Variation (%)
	Per Replicate Value	Average	
Control	595 601 538 628	590.5	6.41
EMS-Modified	601 603 604	604.0	5.75

Fatigue performance analyses results. Figure 1 presents the relationship between the pseudostiffness (C) - or the material integrity - and the damage parameter (S) that were calculated based on the viscoelastic continue damage (VECD) theory. The relationship between C and S is independent of loading mode. In other words, performing the test at different temperatures, loading rates or amplitudes, or in either controlled stress, strain, or actuator displacement modes does not influence the relationship between C and S (Wang, 2019). The C value of 1 indicates the intact state of the material before loading. The C value starts to decrease when subjected to cyclic fatigue loading. The S parameter is representative of the damage accumulated during the cyclic fatigue loading. This value stars at 0 and begins to increase with the increase of fatigue cycles.

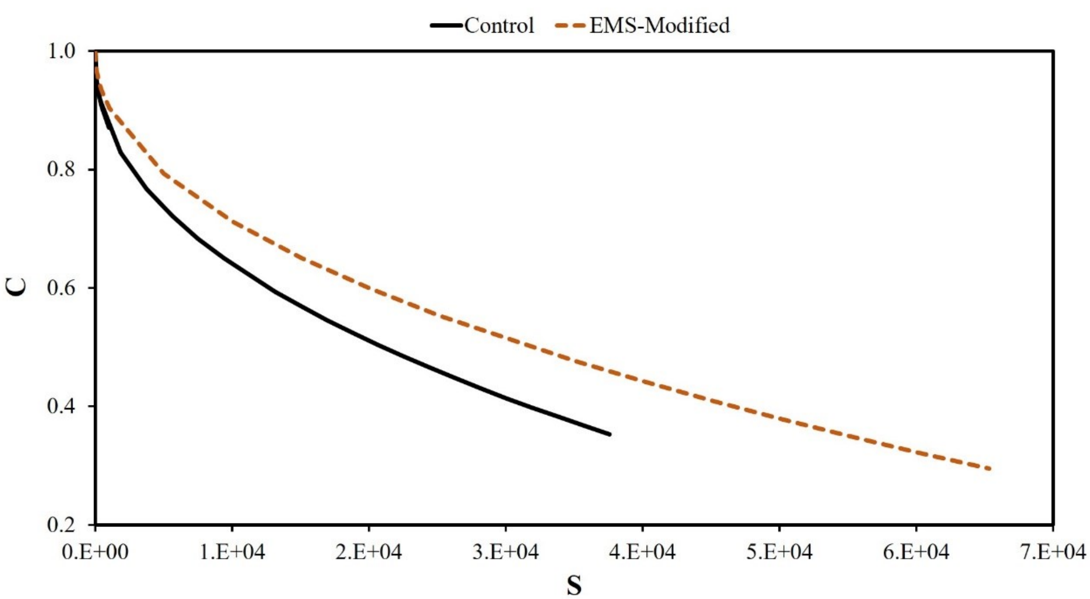

Figure 1. Damage characteristic curves.

According to Figure 1, when compared with the low RAP control mixture, the modification of asphalt binder with the RRM used in this study results in obtaining a curve with higher C values. These higher values indicate the higher material integrity of the high RAP EMS-modified mixture. However, this finding is in contradiction with the findings of (Sabouri et al. 2016) who investigated the influence of recycling agents on the fatigue behavior of warm mix asphalt mixtures through comparing the damage characteristic curves. They found that, recycling agents, softening the mixtures, result in the decrease of C values. The reason for not observing the same behavior, e.g., reduced C values due to the presence of EMS, can be attributed to the higher percentage of RAP used in the EMS-modified mixture. Unlike Sabouri et al., Ozer et al. (2013), who studied the characterization of asphalt mixtures at high asphalt binder replacement with recycled asphalt shingle (RAS), did not observe a consistent trend when comparing the damage characteristic curves of their mixtures with different stiffnesses – their mixtures contained 2.5, 5 and 7.5% RAS. In the existing literature, there are many other examples with different interpretations for the damage characteristic curves. According to (Wang & Kim, 2019), the reduction in the value of C to a critical value cannot be a reliable fatigue criterion due to the high variability in asphalt mixtures. The C and S values calculated based on the VECD are able to only quantify the initiation and propagation of microcracks. There are many other different criteria or methods for characterizing the fatigue behavior of asphalt mixtures. In addition to the reduction of C to a critical value, the reduction in modulus values up to 50%, drop in phase angle values, "experimental failure", the number of cycles required to reach plateau value, dissipated energy concept, etc. are among many other methods for identifying the fatigue life of asphalt mixtures (Gudipudi and Underwood 2016; Reese 1997; Shen and Carpenter 2005; Zhang et al. 2013). These methods require testing a considerable number of specimens to either experimentally identify or numerically predict the fatigue life of asphalt mixtures. Wang (2019) who recently developed a framework for the performance-engineered mixture design for asphalt mixtures, proposed using the D^R failure criterion. The D^R averaging the reduction in C up to failure, can be a trustable energy-based failure criterion that is based on the simplified VECD theory. The D^R is obtained through performing linear regression on cumulative (1 – C) and fatigue life data through using a linear model that passes through the origin of coordinates (see Table 3 and Figure 2).

Table 3. The Results obtained from the FlexMAT™ Program.

Mixture Type	Strain Level (με)	Fatigue Life (Cycles)	Cumulative (1 – C)
Control	250	5690	2480
	300	2190	1055
	400	1230	546
EMS-Modified	300	4680	2643
	300	7160	3253
	500	270	151

The reduction in the number of coefficients, e.g., excluding the intercept, results in the reduction of specimens required for identifying the fatigue failure criterion of asphalt mixtures. The slope of the linear line fitted to the data can be defined using Equation 3:

$$D^R = \frac{\int_0^{N_f}(1-C)dN}{N_f} \tag{3}$$

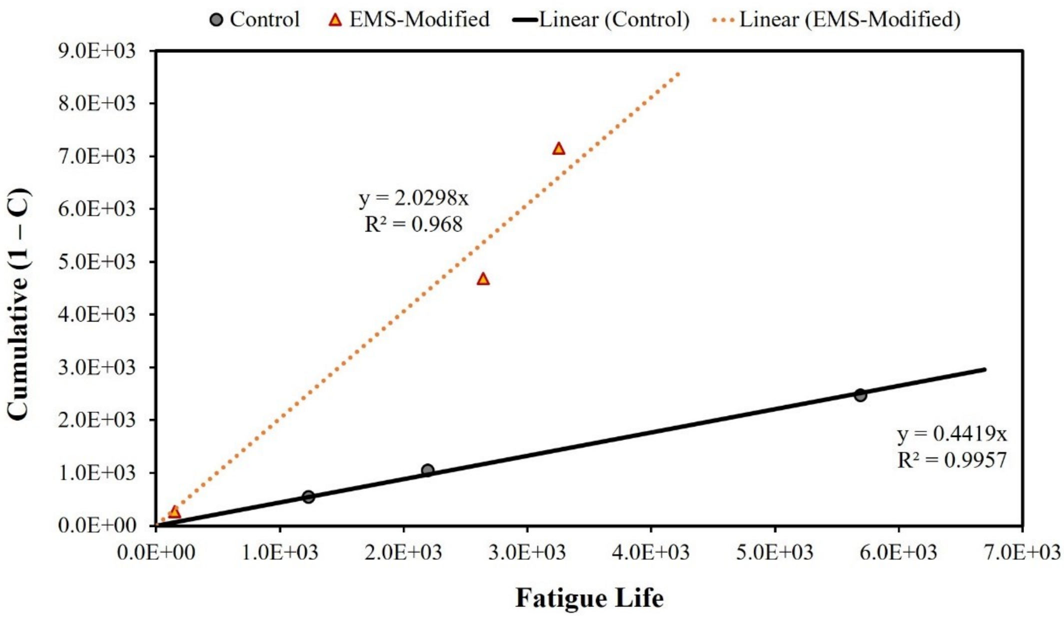

Figure 2 The procedure followed for the calculation of D^R.

In addition to reducing the number of tests required to characterize the fatigue behavior of asphalt mixtures, this criterion allows the prediction of fatigue failure in an arithmetic scale reducing the extrapolation-related errors (Wang 2019). The D^R being a material-specific value determines the resistance to fatigue, and the higher the D^R, the greater the resistance of a material to fatigue cracking (Wang et al. 2018). As it can be seen in Figure 2, the modification of the high RAP mixture with EMS resulted in a significant improvement in the fatigue performance of the mixture that can be attributed to the high reaction quality of the EMS with the binder. Due to the addition of EMS, the D^R value of the high RAP mixture became 2 that is considerably higher than that of the low RAP control mixture that resulted in a D^R of 0.44. The use of EMS at a dosage rate of 3.6%, therefore, can be an alternative method for reducing the occurrence likelihood of fatigue cracking in the asphalt mixtures containing high amounts of RAP op to 30%.

CONCLUSIONS AND RECOMMENDATIONS

In this study the mechanical performance of an asphalt mixture containing 30% reclaimed asphalt pavement (RAP) and modified with epoxidized methyl soyate (EMS) was compared with that of a control mixture containing only 18% RAP. This comparison was made through performing disc-shaped compact tension (DCT) and push-pull fatigue tests to investigate the influence of EMS on improving the low-temperature cracking and fatigue resistance in a mixture containing more RAP than the control.

The DCT analysis results revealed that the modification of asphalt binder with 3.6% EMS slightly increases the fracture energy and hence the low-temperature cracking resistance. This can be attributed to the high degree of the reaction of the EMS, and its ability to reverse the undesired effects of RAP. According to the damage characteristic curves obtained from the fatigue analyses results, the modification of asphalt binder with EMS results in a mixture with a higher material integrity, compared with the control mixture. The fatigue criterion, D^R, used in this study for the comparison of the control and EMS-modified mixtures, revealed that the EMS significantly improves the fatigue performance. The reason for the improved fatigue performance can also be attributed the high degree of reaction of EMS with the binder.

It can be concluded that, the modification of asphalt binder with EMS at a low content of 3.6% allowed increasing the RAP content up to 30% and achieving a low-temperature performance comparable to a control mixture containing only 18% RAP. Also, in terms of fatigue, this modification resulted in allowing the incorporation of RAP at a higher content of 30% and achieving a much-improved performance. For future studies, there is a need to compare the results obtained from the pavement distress surveying conducted on the sections paved with control and EMS-modified mixtures to further verify the results obtained from the lab investigations.

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