Rheological Properties and Fatigue Resistance of Crumb Rubber Modified Bitumen

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ABSTRACT: This paper describes the results of a research program that was performed to evaluate the rheological properties and fatigue resistance of crumb rubber modified bitumen. Crumb rubber has been used in field of highway construction to enhance the performance of asphalt concrete pavements. Fundamental dissipated energy concept and finite element simulation were used to evaluate the rheological properties and fatigue resistance for crumb rubber modified and unmodified bitumen. Rheological tests were performed using a dynamic shear rheometer apparatus and finite element simulation was done using ABAQUS program. The conventional bitumen used in this research was AC (70/100) penetration grade, modified with crumb rubber at four different modification levels namely 3%, 5%, 7% and 10% by weight of the bitumen. It has been found that the fatigue life of the modified bitumen is about two times higher than conventional bitumen and the 3D finite element model shows good agreement with the dynamic shear rheometer result. In conclusion, at low rubber content 3% and 5%, the behaviour of the modified bitumen remains close to that of the conventional bitumen and the optimum crumb rubber content for good rheological properties and long fatigue life was found to be 10%.

KEY WORDS: Modified asphalt, asphalt rheology, fatigue, dissipated energy, finite element.

1 INTRODUCTION

Bitumen is a visco-elastic material, where temperature and rate of load application have a great influence on its performance. Bitumen exhibits both elastic and viscous components of response and display time-dependent relationship between applied stresses and resultant strains. At high temperatures under traffic loading asphalt is not able to maintain the original shape of the pavement, which leads to permanent deformation, known as rutting. At low temperatures asphalt gets brittle and tends to crack because the stiffer structure is not able to relax the internal stresses from the traffic load. Conventional bitumen has a limited capacity under heavy traffic volume and wide range of temperature. Therefore, binders need to be modified because the modified binders bring real advantages to the field of highway construction.

With the increasing of environmental concerns the disposal of waste tires is a growing problem all over the world. In order to improve the performance of asphalt concrete, highway engineers have modified conventional bitumen by adding crumb rubber from ground-up tires. Using crumb rubber as asphalt modifier contributes significantly to reduce the deposit of waste tires (Hanson, 1994). The advantages of using crumb rubber modified bitumen in hot asphalt mixtures include a higher viscosity than conventional bitumen. Mixing of crumb rubber with conventional bitumen improve the resistance to the development of permanent deformations, and fatigue cracking (Bahia and Davies, 1994; Bahia, 1995; Hanson and Duncan, 1995).

2 ASPHALT RHEOLOGY

Rheology is to study and evaluate of the time/temperature dependent response of materials, which are subjected to an applied force. The rheological properties of the bitumen have a major influence on the bond properties between asphalt and aggregate On the other hand, it is believed that asphalt pavement distress may be are related to the rheological properties of the used bitumen in asphalt concrete mixtures. The main rheological parameters are the complex shear modulus that can be defined as materials resistance to deformation and the phase angle which is the time lag between applied stress and resulting strain.

3 EXPERIMENTAL PROGRAM

The conventional bitumen used in this study was asphalt cement AC (70/100) penetration grade which is widely used for medium temperature locations. The crumb rubber was from recycled tires and the particle size is from 0 µm to 600 µm. The elastomeric compositions for crumb rubber are natural rubber 30%, styrene-butadiene-rubber (SBR) 40%, and butadiene rubber 30%. The physical properties for crumb rubber are presented in table 1.

Table 1: Physical properties of crumb rubber

Physical properties	Unit
Density	1320 kg/m^3
Young's modulus (E)	2600-2900 MPa
Tensile strength (σ_t)	40-70 MPa
Elongatian at break	25-50%
Melting point	200 °C
Price	0.25-0.50 €/kg

Two type of testing specimen plate geometries are used with the dynamic shear rheometer (DSR). The first specimen geometry is 25-mm diameter spindle with 1-mm testing gap used at high temperature for frequency sweep test. The second specimen geometry is 8-mm diameter generally used at intermediate temperature for time sweep test. The technology for measuring the rheological properties of asphalt binders is well developed. Devices, such as the dynamic shear rheometer DSR, are routinely used for measuring the dynamic shear modulus (G*) and the phase angle (δ) of binders, given the strain level and the temperature (Roberts et al. 1996). The rheological properties of crumb rubber modified bitumen and conventional bitumen were determined by evaluating the behaviour of the tested specimen subjected to oscillatory (sinusoidal) stresses. Two different types of tests were used in this study namely frequency sweep test and time sweep test. The fatigue test was performed on un-aged bitumen to study the effect of crumb rubber on fatigue resistance. The dissipated energy ratio concept was used to determine the fatigue life. The test conditions and specifications for frequency sweep test and time sweep test are presented in table 2.

Table 2: Dynamic shear rheometer test conditions

Test conditions	Frequency sweep test	Time sweep test	Units
Mode of loading	Stress Controlled	Stress Controlled	
Shear Stress (τ)	1000	10000-100000	Pa
Temperatures (T)	20,35, 45, 55	20	^{o}C
Frequencies (F)	0.1 to 100	10	Hz
Bitumen thickness (t)	1	2	mm
Spindle diameter (D)	25	8	mm

3.1 Frequency Sweep at Constant Stress

Frequency sweep test at constant stress is used to measures the main rheological parameter over a range of frequencies at constant temperature. The rheological parameter can be used to evaluate the viscous and elastic properties of the tested samples. On the other hand, the rheological parameters can be used as an input parameter in finite element model to evaluate pavement performance as well as to construct the stiffness master curve and black diagrams. Frequency sweep test is used to obtain the main rheological parameter complex shear modulus in Pascal and phase angle in degrees for the given test temperature and frequency for both modified and unmodified bitumen. In this research, the rheological tests for modified and unmodified bitumen were done according to the European standard (EN 14770).

3.2 Time Sweep Test

Time sweep test provides a simple method of applying repeated cycling of stress or strain loading at selected temperatures and loading frequency. The initial data collected were very promising and showed that the time sweep test was effective in measuring binder damage behavior under repeated loading in shear (Bahia et al. 1999). Numerous studies suggested that the fundamental dissipated energy concept is useful to characterize damage in viscoelstic materials (Bahia and Anderson 1993). Once the test was done the dissipated energy ratio can be calculated using the relation between dissipated energy and number of cycles. In the first stage of the time sweep test the energy dissipated per loading cycle remains constant. However, if the tested sample continues to be loaded and unloaded, the amount of the dissipated energy per cycle will change and then the failure point will be reached. The damage is characterized by a decrease in the energy dissipated per loading cycle and fatigue life of the bitumen is represented by the number where the straight line leave dissipated energy curve. The dissipated energy and the dissipated energy ration were outlined by (Pronk, 1995).

$$Wi = \frac{\pi \, \tau^2 \sin(\delta)}{G^*} \qquad \ldots\ldots\ldots\ldots (1)$$

$$DER=\frac{\sum_{i=1}^{n} Wi}{Win} \qquad \text{..............} (2)$$

$$N_f = K1\left(\frac{1}{Wi}\right)^{K2} \qquad \text{.................} (3)$$

where:

$W\ i$ = Dissipated energy per cycle

$W\ in$ = Dissipated energy at cycle n

τ = Applied Shear Stress (Pa)

G^* = Complex modulus (Pa)

δ = Phase angle in ^{o}

N_f = Number of load application to failure

The relation between the number of cycles to failure and the dissipated energy were plotted in a log-log scale and fatigue parameters k_1 and k_2 were determined to calculate fatigue life for asphalt binder at any input energy.

4 RESULTS AND DISCUSSION

In this research three replicate specimens for modified and unmodified bitumen ware tested. The rheological parameters such as complex shear modulus and phase angle values were determined for each specimen under the same test conditions and the average value was calculated. Stress sweep was done before the frequency sweep test to determine the linearity The result shows that 1000 Pa can be used as the constant stress, which applies for the frequency sweep test in the range of linear limits.

4.1 Frequency Sweep Test Result for CR-Modified Bitumen

Complex shear modulus and phase angle of crumb rubber modified bitumen were measured at four different temperatures 20 ^{o}C, 27 ^{o}C, 35 ^{o}C and 45 ^{o}C over a range of frequencies from 0.1 Hz to 50 Hz. The frequency sweep test result is illustrated in Figure 1. It is clear that the shear modulus (G*) increases with the testing frequency. On the other hand, phase angle tends to decrease with the increases of testing frequency. When the rubber was added to the conventional bitumen there is a decrease in phase angle, which directly affects the elastic recovery properties. In the same time complex shear modulus which represents the stiffness of the bitumen increases, the increase in stiffness is due to rubber, which absorbs oil from the conventional bitumen and produce harder bitumen. Figure 1 presented the rheological properties of modified and unmodified crumb rubber at 20 ^{o}C.

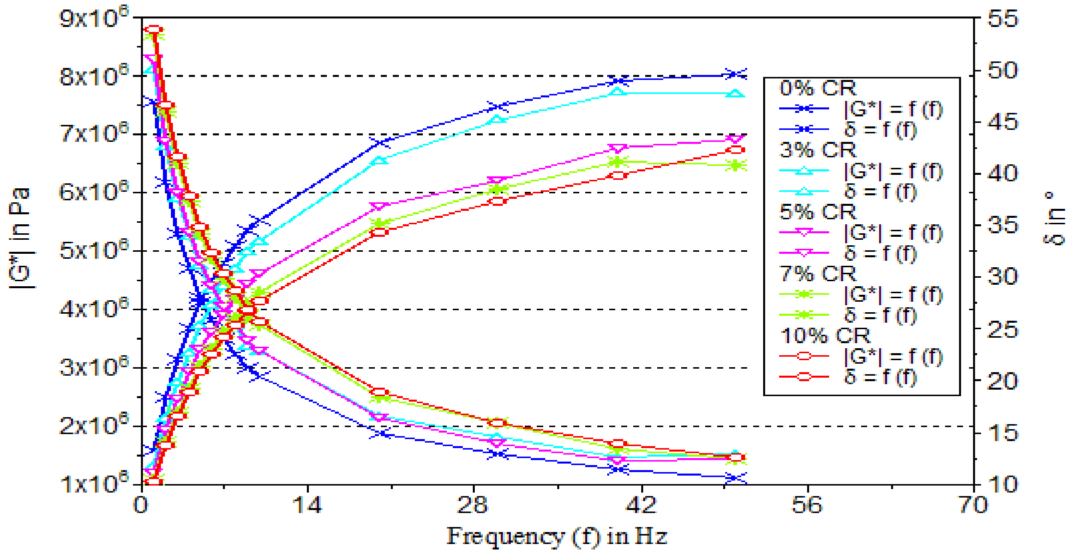

Figure 1: Complex shear modulus and phase angle versus frequency at 20 °C.

Crumb rubber modified bitumen showed different properties compared to the conventional bitumen and greater effect on the rheological properties were found. Using crumb rubber with different modification levels 3%, 5%, 7% and 10% helps to increase the stiffness of the Conventional bitumen by factors of 12%, 25%, 43% and 50% respectively at the same test conditions. In conclusion, the addition of crumb rubber as modifier to the conventional bitumen leads to produce hard and elastic bitumen.

4.2 Black Diagram

In the black diagram, dynamic complex shear modulus is plotted as a function of the phase angle containing no reference to temperature or frequency. Individual data points from the frequency sweeps test result at different temperature levels are simply plotted on the same graph which gives the change in phase angle with the change in complex modulus.

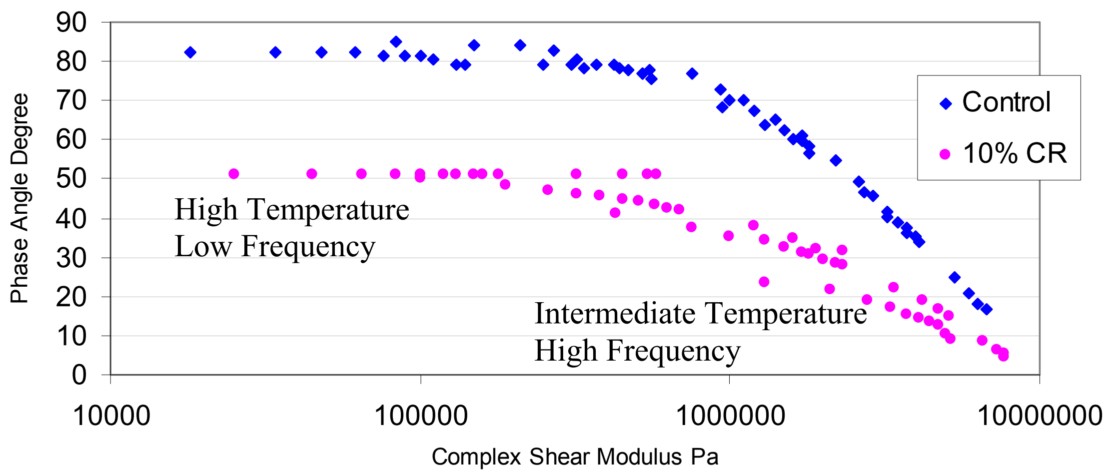

Figure 2: Black diagram relationship between phase angles versus complex modulus.

Crumb rubber modified bitumen show different behavior compared to conventional bitumen in the black diagram and it is clear that the modified bitumen has better performance, especially when high temperatures/low frequencies are considered. The modified bitumen has a lower phase angle than the unmodified bitumen at low temperature, indicating that it can be more resistant to cracking. At high temperatures the modified binder has a high complex shear modulus which is taken as reference for the stiffness that helps for resisting rutting.

4.3 Dissipated Energy for CR-Modified Bitumen

From the time sweep test results the dissipated energy and dissipate energy ratio can be calculated. In the first stage of the time sweep test the energy dissipated per loading cycle remains constant. However, if the tested sample continues to be loaded and unloaded, the amount of the dissipated energy per cycle will change and then the failure point will be reached. The value of the dissipated energy increases when fatigue damage is reached, which leads to a decrease in dissipated energy ration. The variation in the dissipated energy ratio versus cycles of loading for crumb rubber binder under cyclic stress controlled load at 10 kPa is presented in Figure 2.

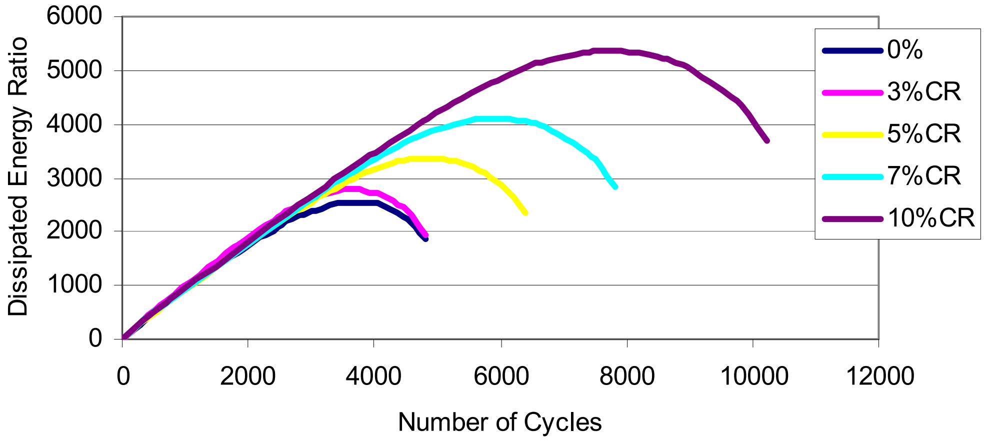

Figure 3: The variation in DER versus cycles of loading for crumb rubber modified bitumen at 10 kPa.

The relation between dissipated energy ratio and number of load cycles to failure were used to determine fatigue life parameter. It can be seen from figure 2 that all the binders show a steady behavior in terms of dissipated energy ratio for the first thousand cycles. However there is a certain point where dissipated energy ratio starts to decrease, this point is a sign of damage occurring in the tested sample. 10% crumb rubber has the highest number of load cycles to failure compare to the rest of modified and conventional bitumen.

4.4 Fatigue Life of Crumb Rubber Modified Bitumen.

Fatigue trends were used to fit linear relationship and estimate fatigue parameter k1 and k2 at each temperature for different modification level. After fatigue parameter determination, equation 3 can be used to predict the fatigue life for asphalt binder at different initial input energies. The comparison of the fatigue lives at 20 °C for different modification levels shows that the 10% crumb rubber modified bitumen performed better than the conventional bitumen. The fatigue life of the 10% modified crumb rubber is longer than 200% the fatigue life for the conventional bitumen.

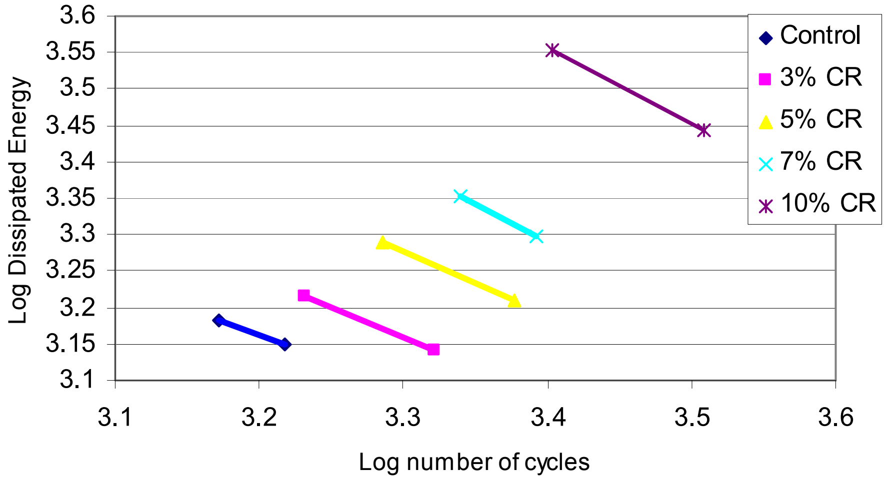

Figure 4: Relation between number of cycles and dissipated energy crumb rubber modified bitumen

In conclusion from laboratory fatigue tests for crumb rubber modified bitumen, the fatigue behavior of bitumen was found to be significantly improved compared to conventional bitumen. Crumb rubber modified bitumen with 10% has the higher fatigue life; followed by 7% crumb rubber as observed from laboratory fatigue test results, is nearly two times. On the other hand, 3% and 5% crumb rubber modified bitumen shows no significant effect in fatigue life.

5. FINITE ELEMENT MODEL

The disadvantage of using dynamic shear rheometer to evaluate fatigue resistance of bitumen that the test is costly and time consuming. 3D finite element model had been developed for dynamic shear rheometer that may be helpful to solve this problem. The DSR model is a circular specimen mounted between two circular plates. Figure 6 presents the Dynamic Shear Rheometer model using finite element program ABAQUS.

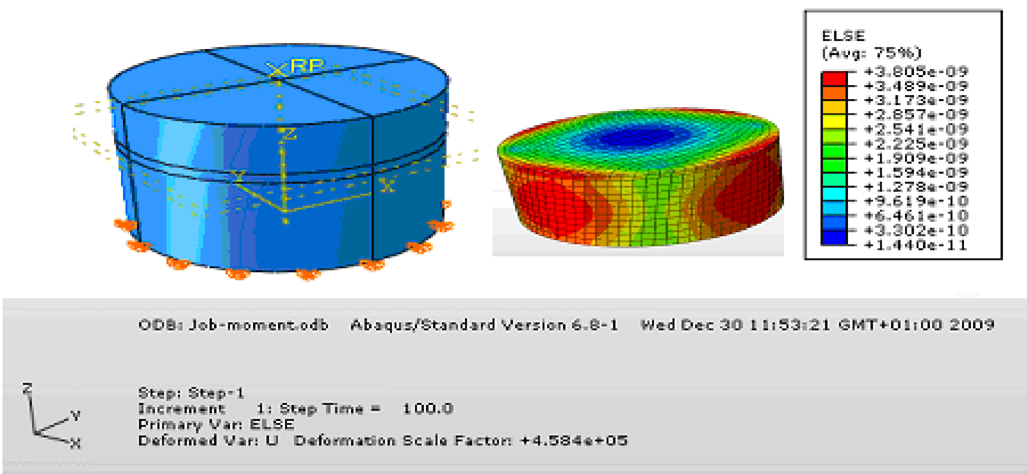

Figure 6: Strain energy distribution dynamic shear rheometer model

The model is generated using ABAQUS with all needed and necessary elements. A dynamic oscillatory load, where sinusoidal shear stress is applied and transfered to the specimen as torque thought to the upper plat. The boundary condition let the upper plate free to rotate around a vertical axis plate and in the same time the lower plate is fixed. The materials input parameters were taking from bitumen rheology (Khodary, 2010). Figure 7 illustrate the relationship between dissipated energy from experimental test and finite element model for conventional bitumen. The experimental result and finite element result shows excellent fit between dissipated energy for conventional bitumen at the same test condition. The DSR model for asphalt binder can be used to solve the problem of test time and cost. It seems appropriate to use DSR model to calculate dissipated energy for different bitumen types.

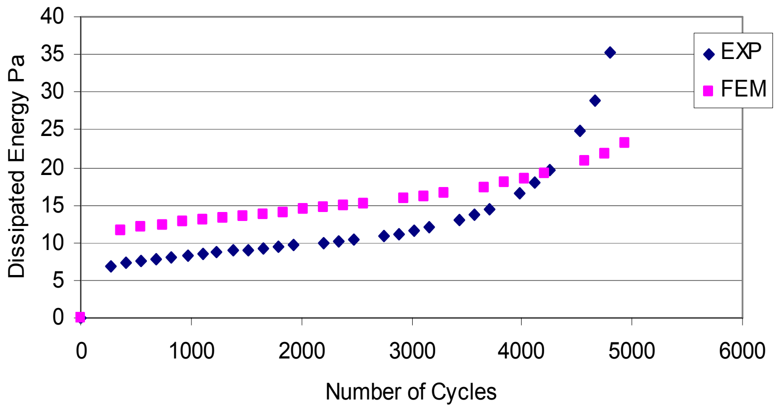

Figure 6: Dissipated energy result for conventional bitumen from laboratory results and DSR model.

6 CONCLUSIONS

A laboratory testing program was conducted on conventional and crumb rubber modified bitumen and after analyzing the test results, the following conclusions can be drawn:

- The result showed significant improvement in fatigue behavior of all modifier types used with compared with the control mixtures.
- At lower rubber content (3%) and (5%), the behaviour of the modified binders remains close to that of the conventional bitumen.
- 10% crumb rubber has higher fatigue resistance and it gives better rheology properties than Conventional bitumen.
- The amount of energy dissipated per volume from the bitumen specimen in dynamic shear rheometer fatigue test can be correlated with the amount of energy dissipated per volume from 3D finite element model.

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