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Investigation of the Effect of Rubber on Rheological Properties of Asphalt Binders using Superpave DSR

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Abstract

The main objective of this study was to investigate the effect of the rubber additive on the rheological properties of asphalt binders including Superpave rutting parameter, fatigue parameter, storage modulus at six rubber percentages: 0.0, 2.5, 5.0, 7.25, 10, and 15%. The Superpave Dynamic Shear Rheometer (DSR) was used to measure the complex shear modules value and the phase angle for the fresh asphalt binder and the rubber-modified asphalt binders using DSR strain-controlled tests. The DSR tests were conducted at one loading frequency of 10 rad/sec (1.59 Hz) and five temperatures: 58, 64, 70, 76, and 82°C. A 12 percent constant strain was applied in these tests according to the Superpave specifications. The rubber additive improved the complex shear modulus value of asphalt binder at all temperatures. Findings of the study showed that the rubber additive resulted in an increase in each of: the complex shear modulus value, the rutting parameter, the fatigue parameter, and the storage modulus ($|G^*|$, $|G^*|/\sin\delta$, $|G^*|\sin d$, and $|G^*|\cos\delta$, respectively) of the asphalt binder. In conclusion, the rubber additive improved the rutting resistance as well as the fatigue resistance of the asphalt binder by increasing the complex shear modulus value and the storage modulus, and decreasing the phase angle.

Keywords: *superpave, DSR, rubber, shear properties, asphalt binder*

1. Introduction

Many researchers studied the effect of rubber and polymer materials as additives and modifiers on the performance and evaluation of asphalt binders as well as hot-mix asphalt used for construction of road pavements.

McQuillen and Hicks (1987) evaluated construction projects of rubber-modified asphalt pavements in the USA. The projects used reclaimed rubber from ground automotive and light truck tires to reduce reflective and thermal cracking, reduce traffic noise, increase resistance to tire wear, and reduce the environmental impact of tire disposal. They used two systems: PlusRide® and Arm-R-Shield®. One important finding was the high cost of rubber-modified asphalt mixes due to the fact that the financial risk perceived by contractors is increased, the unusual aggregate gradation required by the process and the particularly with the PlusRide® system, and the increased mixing temperatures and times required. For Arm-R-Shield® system, the high cost of the mix was primarily a result of the cost of the asphalt-rubber asphalt binder supplied by the manufacturer. These costs could be reduced by development of specifications which limit the contractor's risk, such as the use of conventional aggregate gradations, requiring minimum increases in mixing temperature and time, and allowing competition between rubber-modified asphalt suppliers.

Papagiannakis and Lougheed (1995) conducted a review of crumb-rubber modified asphalt concrete technology. In their study, they presented an analysis of the characteristics of Crumb-Rubber Modified (CRM) asphalt pavements. The analysis included a literature review of asphalt pavement materials with CRM in the asphalt binder (wet process) or in the aggregate (dry process). In addition, the analysis covered testing using Brookfield viscometer to determine the curing properties of the CRM and asphalt mixes using different percentages of CRM and several grades of asphalt binders. Belding of CRM rubber and asphalt binder has been practices for years. The reaction that normally takes place between rubber particles and asphalt binder is not chemical in nature but rather a diffusion process that includes a physical absorption of the aromatic oils of the asphalt binder into the polymer chains. Findings from their literature review revealed that the presence of CRM in asphalt produced a thicker binder that increased aging resistance. In addition, the presence of carbon black in CRM improved binder durability. The CRM had reduced temperature susceptibility resulting in more uniform fatigue characteristics, improved rutting resistance at higher temperatures, and increased thermal cracking resistance at lower temperatures. The analysis showed that applications of CRM paving materials were met with various degrees of success.

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However, failures of these applications normally was a result of inexperience with CRM technology in project selection, design engineering, and construction decisions, and the existing Quality Control and Quality Assurance (QC/QA) methods, which have not been developed enough to ensure desired asphalt binder properties in field. Brookfield viscosity testing showed that the viscosity of the modified asphalt binder increased as the amount of aromatic oils decreased. The results also showed that as the percentage of rubber increased, the Brookfield viscosity increased significantly. For example, an asphalt binder with 18% rubber had a viscosity approximately 12 times that of the unmodified asphalt binder. When maintaining blending temperatures, there was a non-linear increase in the viscosity with time for mixes with large quantities of CRM (such as 18%). Therefore, this indicated that minimizing blending times was desirable to control the viscosity increase of the mix to obtain a workable mix at the end.

Carlson and Zhu (1999) provided historical perspective on the Asphalt Rubber (AR) paving material including its development and obstacles to its development in the USA particularly in the areas of Arizona, California, and Florida. AR has been used because of its engineering benefits and contribution to the reduction of waste tires. In these three states, government programs for waste tire have been required to control the flow and disposal of waste tires. A fee structure has been required to handle waste tire piles and to add value to waste tires for processors. Fees have been used to provide equipment to processors and motivate the production of beneficial end uses of waste tires. As markets develop and piles are eliminated, fees can be reduced. Environmentally economical options should be included as well. Crumb rubber markets always encourage the development of new technologies that utilize this material. A promising technology is a spray application that is crumb rubber based to existing highway sound barriers since crumb rubber has a notable sound energy-absorbing characteristic and relatively is inexpensive. These spray materials tested to date have been synthetic stucco mud with crumb as the aggregate and a paint like polymer liquid. Waste tires due to their beneficial engineering properties such as durability, flexibility, strength, and resistance to cracking can be utilized by agencies not only for asphalt technology but also for other manufacturing technologies.

Waheed Uddin (2003) studies the viscoelastic characterization of polymer-modified asphalt binders of pavement applications. In his study, virgin asphalt and modified asphalt binders and mixes used on several test sections of the I-55 highway rehabilitation project in Northern Mississippi were compared. The creep compliance data for these asphalt binders were measured at low temperatures using a modified test procedure adapted for the Bending Beam Rheometer (BBR) equipment. The Dynamic Shear Rheometer (DSR) was also used at high service temperatures. The creep compliance data of the asphalt binder was used as an input to simulate creep compliance behavior of the mix using a micromechanical model. The field evaluation confirmed the relatively poor performance of the virgin asphalt sections with respect to rutting compared to the modified asphalt binder sections.

Newman (2004) demonstrated the differences in fatigue performance for several Polymer-Modified Asphalt (PMA) mixtures used for heavy-duty pavements. The fatigue performance was measured using the flexural beam testing described in the AASHTO TP-8. The polymer additives studied were: A chemically Modified experimental Crumb Rubber product (MCR), a linear random Styrene-Butadiene latex polymer (SBR), an in-situ crosslinked block copolymer (reactive SB), a linear Styrene-Butadiene-Styrene block copolymer (SBS), and a Modified SBS (MSBS). The percentages of polymer were 3 and 5% except for MCR that was tested at 5% only and the MSBS for which the polymer amount was considered proprietary. Findings of his study showed that the fatigue properties of the asphalt mixtures were affected by the choice of a modifier. Although fatigue is not a widely observed distress for military airfields, fatigue damage should be minimized for airfields especially those critical to mobilization. The choice of polymer modifier for a particular project could depend on several factors including: cost, construction ability, availability, and expected performance. The expected performance is normally difficult to quantify and needs to be done on a case-by-case basis. In this study, SB, SBR at higher loadings, and MSBS significantly affected the number of cycles to failure and would be expected an increased level of resistance against cracking due to repetitive loadings.

Vacin (2004) investigated polymer-modified asphalts by shear and tensile compliances. The Polymer-Modified Asphalt (PMA) binders were tested using the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR). Two commercially available asphalt binders of Different Performance Grades (PGs) were used. Asphalt binder results were compared with the results of mastic (asphalt binder and mineral filler) and Hot-Mix Asphalt (HMA). This was investigated using the dynamic mode (oscillation) and the creep test mode in the DSR. The Time-Temperature Superposition (TTS) principle was applied to the master curves of the three tested materials (PMA, mastic, and HMA). Preliminary results of the study showed that the performance of shear compliance of the HMA was similar to that of the asphalt binder and mastic at short loading (and / or low temperatures) but exhibited different behavior at long time loading (and / or high temperatures). The study also discussed the relation between the shear and tensile compliances (J(t) and D(t)). The shear and tensile compliances were obtained for PMA, mastic, and HMA by the relaxation of the spectra from master curves. Results of the tested asphalt binders showed a relationship between these fundamental parameters, which is important for proper asphalt binder evaluation. This is in accordance with the AASHTO 2002 design guide, where materials tend to be described by still the empirical method but based on mechanical principles.

Yildirim (2007) presented a review of research that has been conducted on polymer-modified asphalt binder over the last three decades. It was shown in his study that polymer modification of asphalt binders had increasingly become the norm in designing optimally performing pavements, particularly in the United States, Canada, Europe and Australia. Specific polymers that have been used included rubber, SBR, SBS, and Elvaloy®. The review also showed that new specifications have been designed and existing ones have been modified to capture the rheological properties of polymer-modified asphalt binders. In addition, it was found that the elastic recovery test was good at determining the presence of polymers in an asphalt binder, but was less successful at predicting field performance of the pavement.

Fernandes *et al.* (2008) evaluated polymer-modified asphalt binders through rheology. Their study proposed the use of oil shale from sedimentary rock as a compatibilizer for Polymer-Modified asphalt Binders (PMB). PMBs were produced by mixing the asphalt binder with a linear SBS copolymer (3.5% by weight) using two oil shale contents (2 and 4%) and petroleum aromatic oil to evaluate the effect of the compatibilizer agent on the SBS PMB properties. The rheological properties of the SBS PMB were obtained using the Dynamic Shear Rheometer (DSR) and the morphology was accessed by the fluorescence optical microscopy. The results of the study showed that the aromatic and shale oils had similar effects on the microstructure, storage stability, and viscoelastic behavior of the PMBs. Thus, shale oil could be successfully used as a compatibilizer agent without loss of properties and could also replace the aromatic oil. In addition, it was observed that the linear and radial SBS PMBs and linear SBS PMB with 2% shale oil could be used up to 70ºC, and the linear SBS PMBs with 4% shale oil or 2% of aromatic oil could be used only up to 64ºC according to the Superpave procedures.

Mohamed *et al.* (2009) characterized the rheological properties of crumb rubber-modified bitumen containing antioxidant. Viscoelastic properties of crumb rubber-modified bitumen with antioxidants (CR30) were determined using the Dynamic Shear Rheometer (DSR). The DSR was used to test the asphalt binders before and after oven aging. The asphalt binders were aged for 3 and 9 days. Results of a compatibility test showed that the CR30-modified asphalt binder was compatible with the base asphalt binder. The results of the unaged asphalt binder revealed that the 1% CR30- and 5% CR30-modified asphalt binders caused an increase in the complex shear modulus (G*) value as a result of the rheological changes. Results of the study also showed that aging had significance influence on asphalt binder rheology by increasing the complex shear modulus values and decreasing the phase angle.

Jeong *et al.* (2010) investigated the interaction effects of Crumb Rubber-Modified (CRM) asphalt binders as a function of various blending treatments in the laboratory. CRM asphalt binders were produced using seven blending times (5, 30, 60, 90, 120, 240, and 480 min), three blending temperatures (177, 200, and 223ºC), and four rubber contents (5%, 10%, 15%, and 20% by weight of asphalt binder). The results of the study revealed several findings: (1) The interaction time and interaction temperature for CRM asphalt binders were observed to have significant effect on the asphalt binder properties; (2) The longer time and higher temperature for interaction of CRM asphalt binders resulted in an increase in the high failure temperature and the viscosity. This was due to the increase in the rubber mass through asphalt binder absorption. However, this study found that the control asphalt binder with PG 64-22 had little change of the asphalt binder properties as a function of interaction conditions; (3) The effect of CRM percentage was statistically significant on the viscosity and G*/sin δ values. Also, the asphalt binder with higher CRM percentage showed a higher Large Molecular Size (LMS) value, and the increase in CRM percentage was considered to result in the additional loss of the low molecular weight in the asphalt binder to the CRM.

Yu *et al.* (2011) investigated the effects of microwave treatment on the crumb rubber-modified asphalt. The pretreatment by microwave irradiation before blending with an asphalt matrix improved the properties of rubber-asphalt blends. This treatment cleft the surface vulcanization network, resulting in higher surface activity of the crumb rubber and improved compatibility with asphalt. This new rubber blend exhibited minor temperature susceptibility behaviors and high ductility at 5°C and an improved viscoelastic nature and storage stability. Characterization was performed to elucidate the mechanism for this improvement using a microwave treatment technique.

Mashaan *et al*. (2012) presented an overview of crumb rubber-modified asphalt. This study aimed at presenting and discussing the findings from some studies on the use of crumb rubber in asphalt pavements. The findings of the review conducted in this study showed that the crumb rubber modifier was used in HMA to improve its rutting resistance and produce pavements with better durability minimizing the distress caused in HMA pavements. Hence road users would be ensured of safer and smoother roads. In addition, the use of crumb rubber modifier as an additive in asphalt binders would reduce pollution problems and protect the environment as well.

2. Materials and Testing

2.1 Asphalt Binder

The asphalt binder used was obtained from Jordan Petroleum Refinery (JPR). The specific gravity of the used asphalt binder is 1.03 and the consistency properties are as: penetration value of 60/70, softening point of 52ºC, and ductility of 88 cm.

2.2 Crumb Rubber

The untreated crumb rubber used in this research was obtained from a small local recycling factory located near Al Zarka city. The factory produces in addition to different sizes of crumb rubber many other by products such as tiny steel wires obtained from vehicle tires. The Crumb Rubber (CR) used was originally

Table 1. Crumb Rubber Gradation

Sieve size	% Passing
0.60 mm (No.30)	100
0.30 mm (No.50)	42.0
0.15 mm (No.100)	17.5

taken from recycled vehicle tires. The gradation of the used (CR) is shown in Table 1, and it has a specific gravity of 1.05.

2.3 Binder Modification

The wet process was followed to modify 60/70 penetration grade asphalt binder by adding and mixing Crump Rubber (CR) at 2, 4, 6, and 8 percent by weight of asphalt binder (Ramadan *et al.*, 2012). For this purpose, a setup for a high speed mixer was set to keep the mixture at the desired temperature (180ºC) through a total mixing time of about 15 minutes. During mixing, the asphalt binder was first heated to 150ºC, and then the CR was added gradually while the mixer is rotating at lower speed. The mixture was kept in the mixing cup, the temperature was gradually raised to 180ºC, and the mixer was set at its maximum rotating speed for the remaining mixing time (around 10 minutes). A homogeneous mixture of CR and asphalt binder for all different percentages of added CR was obtained.

2.4 Preparation of DSR Samples

The DSR samples of rubber-modified asphalt binders were prepared as described in the following procedure. The rubber-modified asphalt binder was heated in an oven at approximately 150°C for enough period of time to ensure fluidity. The heated asphalt was poured into a silicone mold (25 mm in diameter) as shown in Fig. 1(a) and allowed to cool down for enough period of time until it became solid enough to be removed from the mold. Afterwards, the asphalt disk was placed between the two plates (the fixed plate and the oscillating spindle) of the DSR prior to testing as shown in Fig. 1(b).

2.5 Dynamic Shear Rheometer (DSR) Tests

The Dynamic Shear Rheometer (DSR) that is shown in Fig. 2 was used to measure the dynamic shear properties of the fresh asphalt binder and the rubber-modified asphalt binders at test temperatures of: 58, 64, 70, 76, and 82°C and one loading frequency of 10 rad/sec (1.59 Hz).

Fig. 2. Dynamic Shear Rheometer (DSR)

The DSR tests were conducted using a strain-controlled testing mode in which a 12 percent dynamic shear strain (sinusoidal) was applied to the sample using the upper oscillating plate as described in the AASHTO T 315 test method (AASHTO Standard Test Methods, 2008). A sample thickness of either 1 mm for high temperatures or 2 mm for low temperatures is used in the DSR tests. A spindle of 25 mm in diameter is used for high temperatures and a small spindle of 8 mm in diameter is used for low temperatures. In this study, a thickness of 1 mm and a spindle of 25 mm were used.

During the DSR test, the resulting shear stress, the complex shear modulus value, and the phase angle were recorded by Bohlin® software (Bohlin® DSR-II User Manual, 2005).

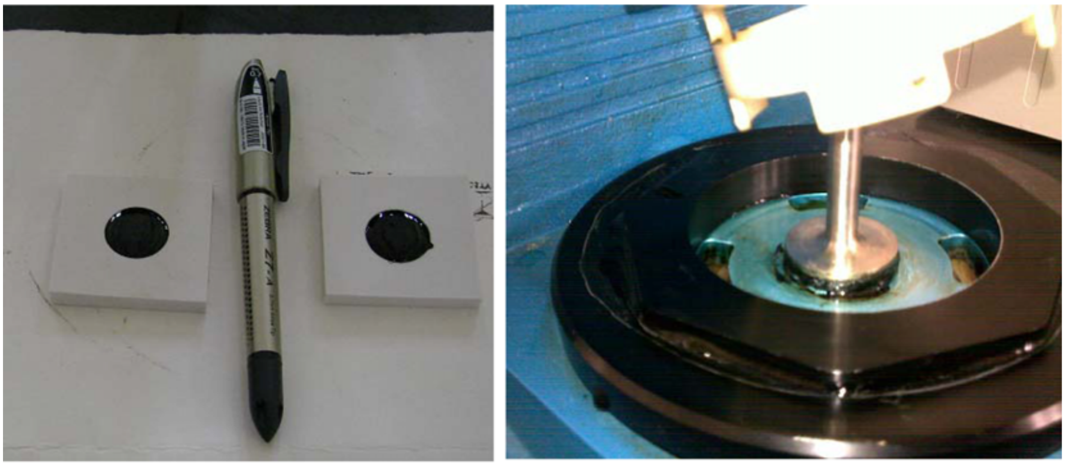
The complex shear modulus value (|G*|) and the phase angle (δ) are calculated using the following equations:

$$|G^*| = \frac{\tau_{\max}}{\gamma_{\max}} \tag{1}$$

where,

|G*| = Complex shear modulus value

$\tau_{\max}$ = Amplitude of the resulting sinusoidal shear stress



(a) (b)

Fig. 1. DSR Samples: (a) DSR Samples in Silicone Molds, (b) Sample Placed between the Two Plates

Table 2. DSR Testing Matrix

Percentage of Rubber (By Volume of Asphalt)	6	0.0, 2.5, 5.0, 7.25, 10, and 15
Asphalt Binder	1	PG 64-10
Additive	1	Rubber
Loading Frequency (rad/sec)	1	10
Temperature (°C)	5	58, 64, 70, 76, and 82°C
Replicates	2	Two DSR Samples
Total No. of DSR Tests	6 × 1 × 1 × 1 × 5 × 2 = 60 Tests	

$\gamma_{\max}$ = Amplitude of the applied sinusoidal shear strain

$$\tau_{\max} = \frac{2T}{\pi r^3} \tag{2}$$

$$\gamma_{\max} = \frac{\theta r}{h} \tag{3}$$

where,

T = Maximum applied torque

r = Radius of asphalt binder sample (either 12.5 mm or 4 mm)

θ = Rotation angle

h = Sample height or thickness (either 1 mm or 2 mm)

$$\delta = (time\ \ lag)(360^{o})f \tag{4}$$

where,

d = Phase angle (in degrees)

f = Loading frequency (Hz)

The DSR testing matrix used in this study is shown in Table 2.

3. Analysis and Discussion

The DSR test data obtained for the asphalt binder and the rubber-modified asphalt binders at 6 different rubber percentages, 1 loading frequency, and 5 test temperatures were analyzed. The test results were presented in the following subsections.

3.1 Complex Shear Modulus

The complex shear modulus value (|G*|) was plotted versus temperature for the rubber-modified asphalt binders at different rubber percentages as shown in Fig. 3. In this figure, the |G*| value decreased with the increase in temperature with higher values at higher rubber percentages and lower values at lower rubber percentages. The rate of decrease in the |G*| value with the increase in temperature was higher at lower temperatures and higher rubber percentages than the rate at higher temperatures and lower rubber percentages as shown in the same figure. In addition, the difference in the |G*| values between rubber percentages was higher at lower temperatures than that at higher temperatures.

The |G*| value was also plotted versus rubber percentage for the rubber-modified asphalt binders at different temperatures as shown in Fig. 4. In this figure, the |G*| value increased with the increase in rubber percentage with higher values at lower temperatures and lower values at higher temperatures. The rate of increase in the |G*| value with the increase in rubber percentage was higher at higher rubber percentages and lower temperatures than the rate at lower rubber percentages and higher temperatures as shown in this figure. In addition, the difference in the |G*| values between temperatures was higher at higher rubber percentages than that at lower percentages.

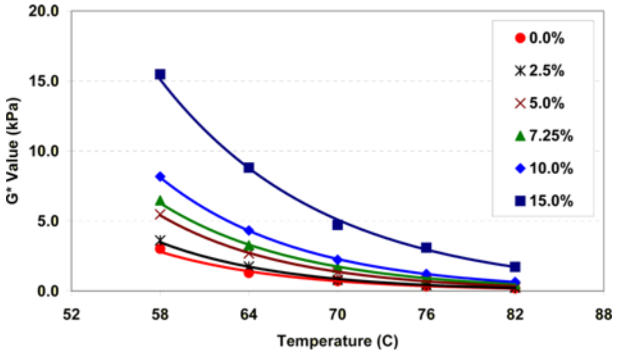


Fig. 3. |G*| Value versus Temperature for Rubber-modified Asphalt Binder

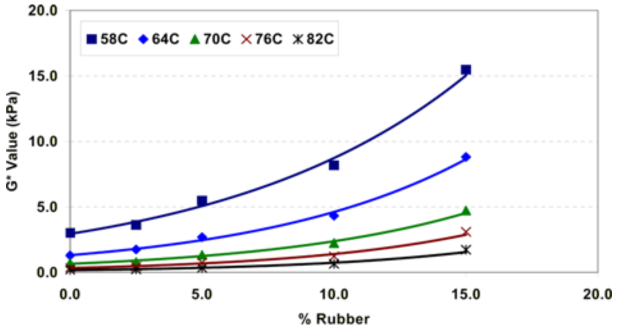


Fig. 4. Percentage of Rubber versus |G*| Value

3.2 Phase Angle

The phase angle (δ) value was plotted versus temperature for the rubber-modified asphalt binders at different rubber percentages as shown in Fig. 5. In this figure, the phase angle (δ) increased with the increase in temperature with higher values at lower

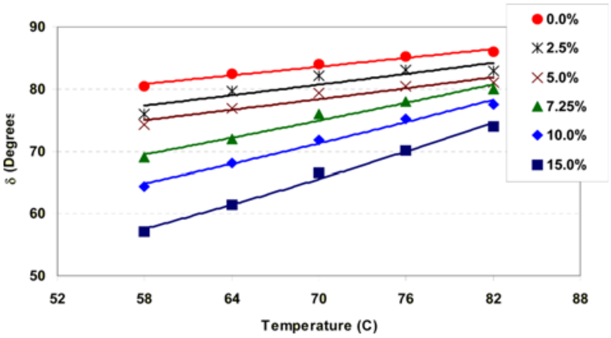


Fig. 5. Phase Angle (δ) versus Temperature for Rubber-modified Asphalt Binder

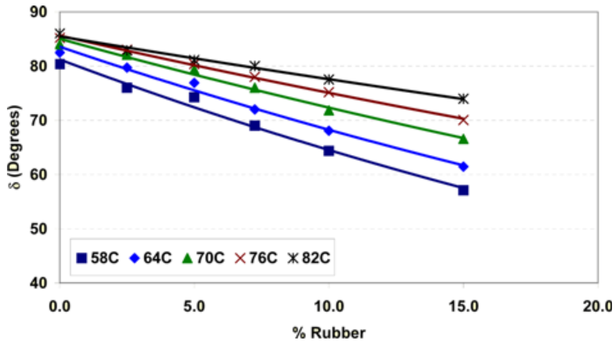


Fig. 6. Percentage of Rubber versus Phase Angle (δ)

rubber percentages and lower values at higher rubber percentages. The rate of increase in the phase angle (δ) with the increase in temperature was higher at higher temperatures and higher rubber percentages than the rate at lower temperatures and lower rubber percentages as shown in the same figure. In addition, the difference in the phase angle (δ) between rubber percentages was higher at lower temperatures than that at higher temperatures.

The phase angle (δ) was also plotted versus rubber percentage for the rubber-modified asphalt binders at different temperatures as shown in Fig. 6. The phase angle (δ) decreased with the increase in rubber percentage with higher values at higher temperatures and lower values at lower temperatures as shown in the same figure. The rate of decrease in the phase angle (δ) with the increase in rubber percentage was higher at lower temperatures and lower rubber percentages than that at higher temperatures and higher rubber percentages as shown in this figure. In addition, the difference in the phase angle (δ) between temperatures was higher at higher rubber percentages than that at lower rubber percentages.

3.3 Superpave Rutting Parameter

|G*|/sin δ is considered the Superpave rutting parameter. This parameter is used to measure the rutting resistance of asphalt binders and to classify asphalt binders for their high temperature performance grade. The Superpave specifies for the rutting parameter a minimum limit of 1.0 kPa for fresh asphalt binders and 2.2 kPa for asphalt binders aged using the Rolling Thin-Film Oven (RTFO) test.

Superpave specifies a lower limit for the rutting parameter to ensure that the asphalt binder has enough stiffness to resist rutting at high temperatures. The increase in the |G*| value and / or the decrease in the phase angle (δ) are desirable to produce an asphalt binder with high rutting resistance. A higher |G*| value indicates that the asphalt binder has higher stiffness to resist rutting, and lower phase angle (δ) value ensures that the asphalt binder becomes more elastic to recover part of the deformation.

In asphalt pavements subjected to traffic loading, rutting is controlled by controlling the total dissipated energy per each traffic loading cycle. The elastic part (or what is called storage modulus) of the asphalt material is responsible for recovering some of its deformation. The energy is dissipated in damping and plastic flow (permanent flow). The damping energy is recovered if given enough time through rest periods, but the energy related to permanent flow is lost.

Mathematically, the work dissipated per loading cycle at a constant stress can be expressed as follows (Roberts, 1996):

$$W_i = \pi\tau_i(\gamma_i \sin\delta) = \pi\tau_i\left(\frac{\tau_i}{G^*}\right)\sin\delta = \pi\tau_i^2\left[\frac{1}{\dfrac{G^*}{\sin\delta}}\right] \qquad (5)$$

where,

W_i = Energy (work) dissipated per load cycle i per unit volume (N/m^2)
t_i = Shear stress applied during the load cycle (Pa)
|G*| = Complex shear modulus value (Pa)
g_i = Shear strain during the load cycle i (%)
d = Phase angle (degree or radian)

This equation indicates that the work (energy) dissipated per loading cycle is inversely proportional to |G*|/sin δ (rutting parameter), and also shows that the work dissipated per loading cycle can be decreased by either increasing the value of the complex shear modulus value (|G*|) and / or decreasing the value of the phase angle (δ).

The |G*|/sin δ was plotted against temperature as shown in Fig. 7. The |G*|/sin δ value decreased with the increase in temperature with higher values at higher rubber percentages and lower values at lower rubber percentages. The rate of decrease in the |G*|/sin δ value with the increase in temperature was higher at lower temperatures and higher rubber percentages than the rate at higher temperatures and lower rubber percentages as shown in the same figure. In addition, the difference in the |G*|/sin δ values between rubber percentages was higher at lower temperatures than that at higher temperatures.

The |G*|/sin δ value increased with the increase in rubber percentage with higher values at lower temperatures and lower values at higher temperatures as shown in Fig. 8. The rate of

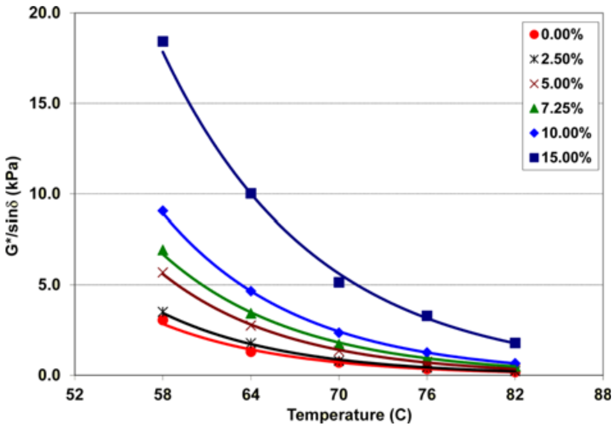


Fig. 7. |G*|/sinδ Value versus Temperature for Rubber-modified Asphalt Binder

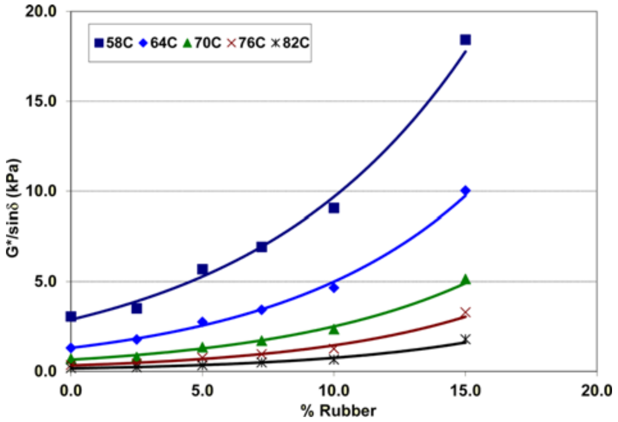


Fig. 8. Percentage of Rubber versus |G*|/sinδ Value

Table 3. Continuous Performance Grade (cPG) of Rubber-modified Asphalt Binders

% Rubber	cPG	PG
0.0	67	PG 64
2.5	69	PG 64
5.0	73	PG 70
7.25	75	PG 70
10.0	78	PG 76
15.0	86	PG 82

increase in the |G*|/sin δ value with the increase in rubber percentage was higher at higher rubber percentages and lower temperatures than the rate at lower rubber percentages and higher temperatures as shown in this figure. In addition, the difference in the |G*|/sin δ values between temperatures was higher at higher rubber percentages than that at lower percentages.

The effect of rubber on the Performance Grade (PG) of the asphalt binder was also investigated. Table 3 below shows the continuous Performance Grade (cPG) as well as the Performance Grade (PG) of the asphalt binder. The addition of rubber resulted in an increase in the high continuous performance grade from cPG 67 for unmodified asphalt binder to cPG 86 for 15-percent rubber-modified asphalt binder. Taking Jordan as an example, areas with extreme conditions require a high performance grade of PG 70. Therefore, the results shown in Table 3 indicate that a 5-percent rubber-modified asphalt binder satisfy this need. The use of recycled Crumb Rubber (CR) from vehicle tires as shown in this study will be useful and effective in asphalt pavements technology in Jordan and elsewhere and will reduce the impact of this waste material on environment.

3.4 Superpave Fatigue Parameter

The Superpave fatigue parameter for asphalt binders is |G*|sin δ. This parameter indicates the asphalt binder's resistance to fatigue under traffic loading at intermediate temperatures. The Superpave specifies a higher limit for the fatigue parameter of 5,000 kPa for asphalt binders aged using the Pressure Aging Vessel (PAV) after they have been aged also in the RTFO test.

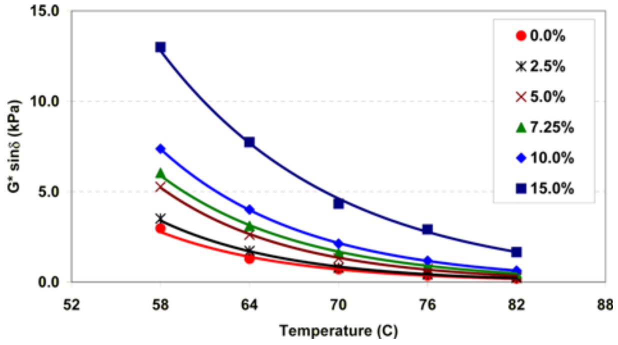


Fig. 9. |G*|sinδ Value versus Temperature for Rubber-modified Asphalt Binder

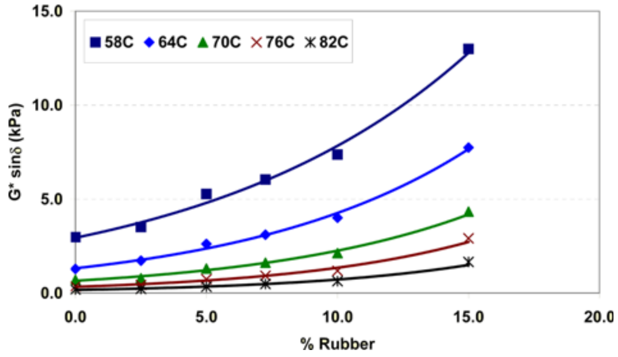


Fig. 10. Percentage of Rubber versus |G*|sinδ Value

A lower value for |G*| and / or a lower value for phase angle (δ) are desirable to control fatigue cracking of asphalt binders. As the |G*| value gets higher, the asphalt binder becomes stiffer and more susceptible to fatigue cracking. On the other hand, as the phase angle (δ) gets lower, the asphalt binder becomes more elastic and thus more resistant to fatigue cracking.

The |G*|sin δ value decreased with the increase in temperature with higher values at higher rubber percentages and lower values at lower rubber percentages. This is clear in Fig. 9. The rate of decrease in the |G*|sin δ value with the increase in temperature was higher at lower temperatures and higher rubber percentages than the rate at higher temperatures and lower rubber percentages as shown in the same figure. In addition, the difference in the |G*|sin δ values between rubber percentages was higher at lower temperatures than that at higher temperatures.

The |G*|sin δ value increased with the increase in rubber percentage with higher values at lower temperatures and lower values at higher temperatures as shown in Fig. 10. The rate of increase in the |G*|sin δ value with the increase in rubber percentage was higher at higher rubber percentages and lower temperatures than the rate at lower rubber percentages and higher temperatures as shown in this figure. In addition, the difference in the |G*|sin δ values between temperatures was higher at higher rubber percentages than that at lower percentages.

3.5 Storage Modulus

The storage modulus or the elastic portion of the complex

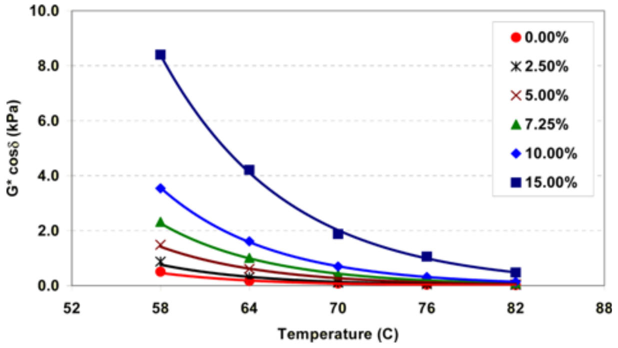


Fig. 11. |G*|cosδ Value versus Temperature for Rubber-modified Asphalt Binder

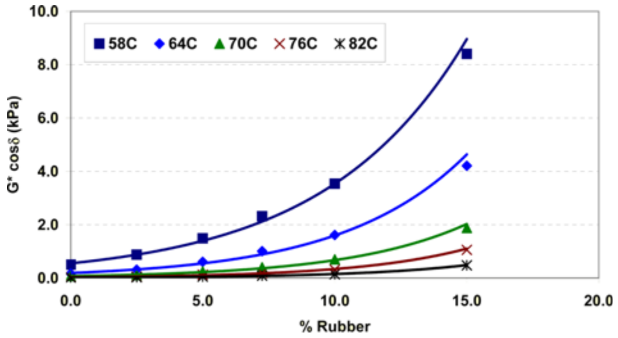


Fig. 12. Percentage of Rubber versus |G*|cosδ Value

shear modulus of the material is represented by |G*|cos δ. This part of the complex shear modulus (storage modulus) helps the material to resist deformation due to traffic loading frequency especially at lower temperatures.

The |G*|cos δ value decreased with the increase in temperature with higher values at higher rubber percentages and lower values at lower rubber percentages as shown in Fig. 11. The rate of decrease in the |G*|cos δ value with the increase in temperature was higher at lower temperatures and higher rubber percentages than the rate at higher temperatures and lower rubber percentages as shown in the same figure. In addition, the difference in the |G*|cos δ values between rubber percentages was higher at lower temperatures than that at higher temperatures.

The |G*|cos δ value was also plotted versus rubber percentage for the rubber-modified asphalt binders at different temperatures as shown in Fig. 12. In this figure, the |G*|cos δ value increased with the increase in rubber percentage with higher values at lower temperatures and lower values at higher temperatures. The rate of increase in the |G*|cos δ value with the increase in rubber percentage was higher at higher rubber percentages and lower temperatures than the rate at lower rubber percentages and higher temperatures as shown in this figure. In addition, the difference in the |G*|cos δ values between temperatures was higher at higher rubber percentages than that at lower percentages.

4. Conclusions

Based upon the analysis and results of this study, the following conclusions can be drawn:

1. The rate of decrease in each of the complex shear modulus value (|G*|), the rutting parameter (|G*|/sin δ), the fatigue parameter (|G*|sin δ), and the storage modulus (|G*|cos δ) with temperature was higher at lower temperatures and higher rubber percentages than the rate at higher temperatures and lower rubber percentages. In addition, the difference in the value of each of these parameters between rubber percentages was higher at lower temperatures than that at higher temperatures.
2. The rate of increase in each of the complex shear modulus value (|G*|), the rutting parameter (|G*|/sin δ), the fatigue parameter (|G*|sin δ), and the storage modulus (|G*|cos δ) with rubber percentage was higher at higher rubber percentages and lower temperatures than the rate at lower rubber percentages and higher temperatures. In addition, the difference in the |G*| values between temperatures was higher at higher rubber percentages than that at lower percentages.
3. The rate of increase in the phase angle (δ) with temperature was higher at higher temperatures and higher rubber percentages than the rate at lower temperatures and lower rubber percentages. In addition, the difference in the phase angle (δ) between rubber percentages was higher at lower temperatures than that at higher temperatures.
4. The rate of decrease in the phase angle (δ) with rubber percentage was higher at lower temperatures and lower rubber percentages than that at higher temperatures and higher rubber percentages. In addition, the difference in the phase angle (δ) between temperatures was higher at higher rubber percentages than that at lower rubber percentages.
5. With the increase in the rubber percentage in the asphalt binder, the value of each of the |G*|, |G*|/sin δ, |G*|sin δ, and |G*|cos δ increased, and the value of the phase angle (δ) decreased at different temperatures.
6. The Superpave high temperature Performance Grade (PG) value of asphalt binders can be improved by the increase in the complex shear modulus value (|G*|) and the decrease in the phase angle (δ) as a result of the addition of the rubber.

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