Engineering Properties of SMA Mixtures/Polymer/RGP Blends

Mojtaba Ghasemi[1], Seyed Morteza Marandi[2]

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Abstract:

In this research, the efficiency of Recycled Glass Powder (RGP) is evaluated for improvement of polymer-modified bitumen and asphalt mixture performance. An extensive laboratory programm was undertaken for polymer-modified bitumen including Crumb Rubber (CR), Styrene Butadiene Styrene (SBS) and Styrene Butadiene Rubber (SBR). Rheological and mechanical properties of modified bitumen samples such as penetration index (PI), and also asphalt mixture performance indices including Marshall stability, indirect tensile strength (ITS), compressive strength and indirect tensile stiffness modulus (ITSM) were investigated. The results showed that application of RGP-CR modifier had not only positive impact on the efficiency of bitumen and asphalt, but also made more improvement in their engineering properties. Moreover, modification using 5% CR and 5% RGP in asphalt mixtures resulted in the best overall performance. Moreover, from environmental point of view, application of RGP in asphalt mixtures is considered to be beneficial since it prevents accumulation of waste glass in the natural environment.

Keywords: Crumb rubber, styrene butadiene styrene, styrene butadiene rubber, recycled glass powder, stone matrix asphalt

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Corresponding author Email:marandi@uk.ac.ir

1- Ph. D. Student, Department of Civil Engineering, Shahid Bahonar University, Kerman, Iran

2-Associate Professor, Department of Civil Engineering, Shahid Bahonar University, Kerman, Iran

1. Introduction

Refined bitumen materials have been successfully used in many highways and airports for decades. In recent years, increase in traffic loads in terms of numbers and weights of heavier trucks and vehicles with higher tire pressure has increased pavement damages. As a result, materials with better properties are required to decrease pavement distresses. Polymer modification is able to overcome the weakness of bitumen and improving the performance of asphalt mixtures. There are various modifier additives that are currently applied in bitumen modifications such as crumb rubber (CR), styrene butadiene styrene (SBS) and styrene butadiene rubber (SBR) [Ahmedzade, Tigdemir, and Kalyoncuoglu, 2007].CR (which is obtained from grinding scrap tires) has been widely used in construction industry, particularly in asphalt industry for more than four decades [Xiao and Amirkhanian, 2009, Xiao, et al., 2009a, Xiao, Amirkhanian and Shen, 2009b]. For instance, CR can be used as bitumen modifier to reduce construction costs and energy consumption. This technique may also help to reduce environmental pollution using recycling waste tires [Chiu and Lu, 2007, Lee, Akisetty and Amirkhanian, 2008]. In addition, combination of CR and bitumen can improve the performance and engineering properties of asphalt pavements [Chiu and Lu, 2007, Partl, Pasquini and Canestrari, 2010]. Due to all advantages, nowadays, bitumen modification using CR has become a common practice in construction industry. However, it was intended to use the combination of CR and another recycled material to improve the performance of modified bitumen and asphalt mixture.

SBS is in group of elastomers, which improves elastic properties of bitumen and is probably the best polymer for modifying bitumen. Although bitumen flexibility increases at low temperatures, some researchers have referred to the decrease of resistance and endurance against penetration at higher temperatures [Gorkem and Sengoz, 2009]. Additionally, it seems that modifying asphalt mixtures using polymers has the maximum potential for successful application in designing flexible pavements. These advantages result in increasing pavements' useful lifetime and decreasing thickness of the base or asphalt concrete layer [Al-Hadidy and Tan, 2009a and 2009b]. Awanti et al. (2008) found that Marshall flow, stability, and indirect tensile strength of polymered asphalt was more than that of conventional asphalt at different temperatures. Also, they showed that the sensitivity of polymered asphalt against moisture was lower than that of conventional asphalt. Xiao and Amirkhanian (2007) conducted an experimental research and showed that modifying bitumen using SBS leads to the resistance improvement against initial cracking. However, it did not affect the aging of the asphalt mixture. Using SBR modified bitumen results in more flexibility and resistance to cracking of pavement at lower temperatures [Lu, and Isacsson, 2001, Becker, Meondez and Rodriguez, 2001]. Application of SBR modified bitumen has other advantages like improving adhesion and cohesion of pavement and increasing its elasticity [Roque, 2004]; also, it has higher ductility compared to base bitumen [King, 1999]. Despite these advantages, SBR is an expensive polymer and its application is not beneficial for the environment.

One of the most important threats to the environment is accumulation of waste materials such as rubber, glass, metal, plastic, etc… As the population increases, the amount of waste rapidly grows and waste disposal has to be proportionally increased [Batayneh, Marie and Asi, 2007, Shayan and Xu, 2004, Yazoghli Marzouk, Dheilly and Queneudec, 2007]. There are three major ways to deal with waste materials: burying, incineration and recycling. Recycling and reusing waste materials can be effective to reduce consumption of natural resources and mitigate environmental pollution [Pierce and Blackwell, 2003, Segre and Joekes, 2000].Glass, as a waste material, is produced millions of tons annually in the world. However, it can be recycled frequently without changing its properties. In road construction, glass pieces have been used only as aggregates so far [Wu, Yang and Xue, 2004]. An experimental research on the influence of recycled glass powder (RGP) on physical and mechanical properties of SBS modified asphalt binders and mixtures was carried out by Ghasemi and Marandi (2011). They showed that using RGP has improved the performance of modified pavement considerably in comparison with conventional asphalt-mix pavements.In order to have aforementioned benefits of polymer modifiers and decrease disadvantages, simultaneous effects of CR-RGP, SBS-RGP and SBR-RGP on engineering properties of bitumen and asphalt mixtures was investigated and new contributions are presented.

2. Materials and Methods

2.1 Experimental Program

The experimental program flowchart for this study is shown in Figure (1).

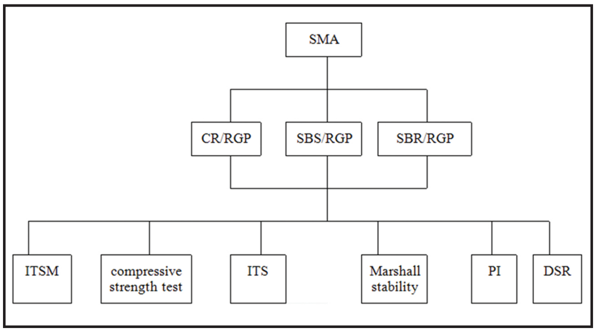

Figure 1. Experimental program flowchart

2.1.1 Preparation of Laboratory Samples

Pure bitumen with penetration grade of 60-70 delivered from Isfahan Oil Refinery was used to make laboratory specimens. Engineering properties of pure bitumen are determined at University pavement laboratory and presented in Table 1.The required crumb rubber (*CR*) was prepared from cutting, scraping and powdering waste tires and then adding to the pure bitumen. Powdering scrap tire and making *CR* can be done by ambient grinding or cryogenic grinding methods. If the process of making rubber powder is done at room temperature or higher, it is called ambient grinding**.** If the process of making rubber powder is done at a temperature of $-120^{\circ}C$ using liquid nitrogen to freeze off the rubber and thereby reducing its size, it is called cryogenic grinding**.** In present research, *CR* is obtained from ambient method. The bitumen modified by ambient *CR* has more viscosity and less sensitivity to rutting and cracking [Lee, Akisetty and Amirkhanian, 2008]**.***SBS*, containing 30% by weight styrene, produced by Yueyang Petrochemical Co. Ltd. China. *SBR*, containing 27.3% by weight styrene, 0.64% by weight water soluble and 0.37% by weight volatile fraction, produced by Lanzhou Petrochemical Co. Ltd. China. Recycled glass powder (*RGP*) was obtained by following a two-steps procedure: first the waste glass was crushed by hammer in a big metal container and then turned into powder in a ball mill for 10 minutes**.** The produced powder then passed through a sieves No. 200 (diameter less than 0.074*mm*)**.** The density of obtained *RGP* was 2.47 g/cm^3**.** Grain size distribution of *RGP* derived using a Laser Particle Analyzer is shown in Table 2**.**Microscopic morphology of *RGP* measured using Scanning Electron Microscopy (*SEM*) and is illustrated in Figure (2)**.** *SEM* examination shows that the glass powder particles are coarse, angular and flaky with a wide range of particle sizes**.** In order to determine degree of absorption, the specific surface area test performed on *RGP* material according to ASTM C204 standard. The measured *RGP* specific surface area measured was 467 m^2/kg, which indicates a high absorption**.**

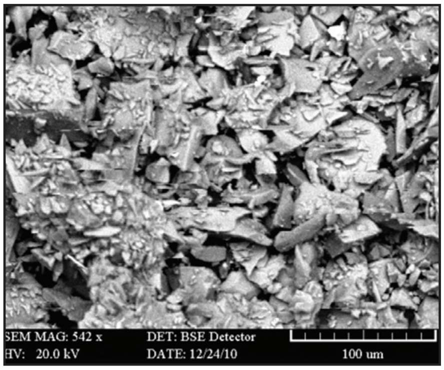

Figure 2. SEM morphology of RGP (measured by authors)

Table 1. Conventional rheological properties of pure bitumen (measured by authors)

Test	Standard ASTM	AC 60-70
Penetration (100g, 5 sec., 25°C), 0.1 mm	D5-73	64
Ductility (25°C, 5 cm/min), cm	D113-79	100+
Ductility after loss of heating test, cm	D113-79	100+
Solubility in trichloroethylene, %	D2042-76	98.8
Softening point, °C	D36-76	47.4
Flash point, °C	D92-78	285
Loss of heating, %	D1754-78	0.03
Specific Gravity	D70	1.01

Table 2. Particle size distribution of RGP (performed by authors)

Size (*nm*)	458.7	396.1	342.0	295.3	255.0	220.2	190.1
Percent Passing (%)	100	99.6	88	52.4	14.3	0.6	0

Twenty modified bitumen samples were produced using *CR-RGP*, *SBS-RGP* and *SBR-RGP*. Refered to previous researches, optimum percent of *CR*, *SBS* and *SBR* for bitumen modification were 10%, 5% and 5% respectively [Xiao et al., 2009a, Awanti et al., 2008, Rogge et al., 1989]. In present work, 10, 30, 50, 70, 90 and 100 percent of modifiers were replaced with *RGP*. Modified bitumen generated with a laboratory scale mixer at a temperature of 180°C for 1 *hr* and 3000 *rpm* rotational speed. The aggregate used in asphalt concrete mixtures, was obtained from an asphalt plant located in Kerman, south east of Iran. The specifications of Aggregates are presented in Table 3. Coarse and fine crushed aggregates with a maximum size of 19 *mm* were selected for *SMA* mixtures. Aggregate gradation of the mixture is shown in Figure (3).

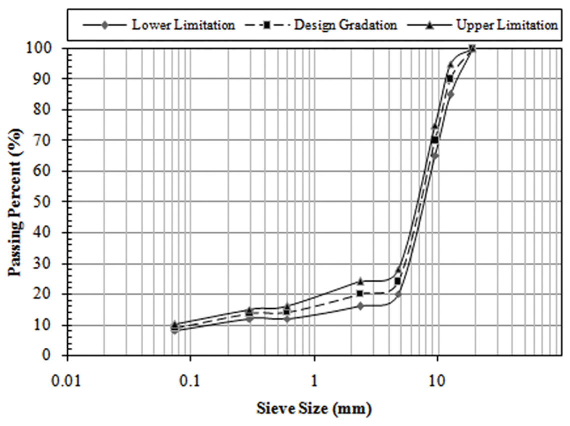

Figure 3. Grain size distribution curves of *SMA* (measured by authors)

2.2 Dynamic Shear Rheometer (*DSR*) Test

The best way to evaluate the fundamental rheological properties of bitumen is usually performed by mechanical-dynamical methods based on oscillatory tests. These tests can be conducted with DSR. In present study, DSR test carried out on modified and unmodified bitumen using CR-RGP, SBS-RGP and SBR-RGP. The main results of DSR include complex shear modulus (G*) and phase angle (δ). G* is defined as the ratio of maximum stress to maximum strain and represents overall resistance against deformation of the asphalt specimen under shear load. This experiment conducted under conditions of controlled stress under frequency of 10 rad/sec (1.59 Hz) and at a temperature of 64°C in accordance with ASTM D7175. Based on this standard for high temperature tests (46-82°C), the samples should be of 1mm thickness and 25 mm in diameter.

2.3 Conventional Tests

The base and modified bitumen tested for degree of penetration and softening point. Average results were calculated for three similar samples with the same modifier content. Thermal sensitivity of modified bitumen samples, which is the change of consistency parameter as a function of temperature, was evaluated by penetration index (*PI*) as well as the results of degree of penetration and softening point tests [Read and Whiteoak, 2003].

2.4 Marshall Properties

Stone Matrix Asphalt (*SMA*) mix design conducted in accordance with National Cooperative Highway Research Program (*NCHRP*) No. 425. Existing materials in the site that had acceptable specification, i.e. 60-70 penetration grade base bitumen, were used to prepare the reference mixture. Marshall Specimens constructed in pavement laboratory using 50 blows of Marshall Hammer on each side. Optimum bitumen content was selected for the *SMA* mixture to achieve 4% air void and less than 0.3% drain down.

The optimum bitumen content found through Marshal tests using the stability and the flow, air voids, and VMA. In this research, the optimum bitumen content for control samples was 6.1% for preparation of all modified and unmodified *SMA* mixtures. Moreover, in order to eliminate the influence of bitumen content on analysis of experimental results, three samples of each mixture were made with identical bitumen content and the mean results used as the outcome.

The Marshall quotient (*MQ*, calculated as the ratio of

Table 3. Specifications of aggregates (measured by authors)

Property	Coarse aggregate	Fine aggregate	Filler	ASTM Standard
Bulk specific gravity	2.73	2.66	2.48	C-127 & C-128
Apparent specific gravity	2.77	2.70	2.64	
Water absorption (%)	0.28	1.49	-	
Toughness (%)	23.09	-	-	C-131
Soundness (%, Na_2SO_4)	1.87	1.21	-	C-88

stability (*kN*) to flow (*mm*)) represents an approximation of the ratio of load to deformation under particular conditions of the test may be used as a measure of the material's resistance to permanent deformation in service [Zoorob and Suparma, 2000].

2.5. Tensile Strength Test

The purpose of tensile strength test is to evaluate moisture sensitivity of asphalt mixtures**.** It has been shown that the tensile strength of hot mix asphalt (*HMA*) is related to fatigue cracking [Goh, 2011]. When the mixture has higher tensile strength, the asphalt pavement can withstand higher strain before failure or cracking**.** Furthermore, the moisture susceptibility of asphalt mixture can be determined by comparing the tensile strength of asphalt mixture under dry and wet conditions**.** In this study, the tensile strength of all samples is measured in accordance with AASHTO T283**.** Indirect tensile strength was performed using a universal testing machine (UTM, Zwick 1498) at the temperature of 25°C and the deformation rate of 50.8 *mm*/*min*.

Moisture Sensitivity of mixtures can be calculated using the tensile strength ratio (*TSR*) according to the following equation**:**

$$TSR = ITS_1 / ITS_2$$

Where ITS_1 is the average indirect tensile strength of the conditioned sample, and ITS_2 is equal to the average indirect tensile strength of unconditioned sample (both measured in *MPa*)**.**

2.6. Compressive Strength Test

Compressive strength test performed using a UTM (Zwick 1498)**.** In order to apply compressive loads to the sample accurately, the two sides of the sample were made perfectly smooth and parallel to each other**.** Compressive strength tests were conducted in load-controlled mode using loading rate of 10 *kN*/*min* and the maximum load recorded during the test**.** 288 Marshall samples used in this testing programm in four groups**.** The first group of samples kept in air at normal temperature for 24 hours (R_{25})**.** The second group kept in water at 25°*C* temperature for 24 hr. (R_w). The third group underwent 25 cycles of freezing and thawing as described in the following. These samples were first put in plastic bags with about 10*ml* of water; subsequently, they were placed in the freezer for 4 hours at a temperature of -20°*C* and eventually let to thaw for 4 *hr* at 25°*C* (R_f). The fourth group was placed in oven for 4 hours at 50°*C* (R_{50}). The first three and the fourth groups were tested at 25°*C* and 50°*C* respectively**.**

2.7. Indirect Tensile Stiffness Modulus Test

Stiffness modulus of asphalt mixtures is measured under indirect tension condition, which is the most common method of measuring stress-strain relationship and evaluating elastic properties as an important performance characteristic in pavement design. In order to determine the indirect tensile strength, a test sample (Marshall sample or core sample) is compressed at a rate of 50.8 mm/min by two opposite beams until it fractures. The force, radial deformation and vertical deformation are monitored. Compressive forces will occur in the load direction, as well as tensile forces tangentially to the load direction according to the laws of plasticity. Indirect tensile stiffness modulus test (ITSM) conducted according to BS DD 213. ITSM (measured in MPa) is defined by the following equation:

$$S_m = F\left(R + 0.27\right) / L H$$

Where S_m is the indirect tensile stiffness modulus, F is the peak value of the applied vertical repeated load (N), H is the mean amplitude of the horizontal deformation obtained from five applications of the load pulse (mm), L is the mean thickness of the test specimen (mm), and R is the Poisson's ratio (assumed to be 0.35). The test performed in controlled deformation conditions using a UTM. The target value of deformation selected was 6 µm. The rise time (defined as the time that applied load is increased from zero to a maximum value) was 124 ms. Application of the load pulse set to 3 seconds. Tests were carried out at a temperature of 25°C.

3. Results and discussion

3.1 DSR Test Results

*G** and *δ* of modified and unmodified bitumen were measured at 64°*C*. The ratio *G**/*sin* (*δ*), known as rutting parameter, was calculated for all of the samples. Rutting parameters of the modified samples with different *CR-RGP*, *SBS-RGP* and *SBR-RGP* content are presented in Figure (4). The results showed that the rutting parameter values of the modified samples were more than those of base bitumen. Also, adding *RGP* to *SBR* and *SBS* modified bitumen decreased their rutting parameter while, for *CR* modified bitumen, an increase in rutting parameter was observed. This can be interpreted as the result of various factors such as higher *G** level, lower *δ*, etc. The maximum rutting parameter obtained was for the modified sample using 5% *SBS*. In other words, the test results demonstrated that *SBS* modified bitumen is the best binder for rutting resistance. On the other hand, both *CR* and *RGP* were recycled materials with very low cost and showed more than 181% increase in rutting parameter compared with the base bitumen.

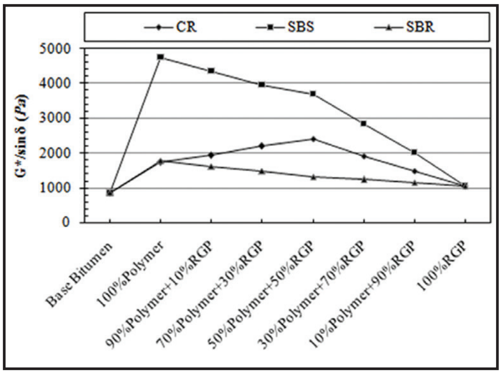

Figure 4. Rutting parameter at 64°*C* for base and modified bitumen

3.2 Results of Conventional Bitumen Test

Generally, lower penetration index (*PI*) implies higher thermal sensitivity. According to Figure (5), *PI* values are increased by the modification. *SBS* and *CR* modified bitumen show the best results in the current experiment. Difference in the results of *SBS* modified bitumen and *CR* modified bitumen is negligible. The results demonstrate that polymer substitution using *RGP* does not increase the thermal sensitivity, and furthermore, for *SBR* modified bitumen, *RGP* addition decreases the thermal sensitivity of the binder. Therefore, thermal sensitivity of polymer modified bitumen is decreased by adding *RGP* to the mix.

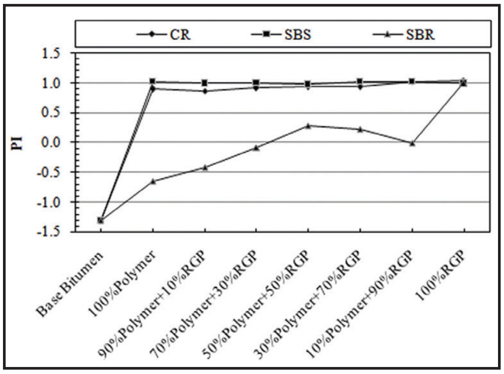

Figure 5. Penetration Index for base and modified bitumen

3.3 Results of Marshall Test

Marshall stability test results carried out on specimens with constant bitumen content of 6.1% and different amounts of modifiers are presented in Figure (6). It can be generally inferred from the test results that *MQ* for all modified mixtures is higher than the control mixture and its maximum value is measured to be over two times higher than that of the control mixture. Also, *CR* modified bitumen shows the best results in this experiment. No significant negative impact is found after *RGP* addition. For asphalt mixtures, the maximum *MQ* is obtained with 5% *CR* and 5% *RGP*. Consequently, it can be concluded that improvement is occurred in Marshall properties of asphalt concrete mixtures using *RGP* modifier.

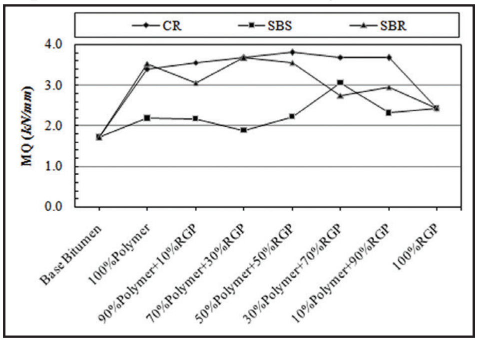

Figure 6. Marshall quotient for base and modified bitumen

3.4 Results of Indirect Tensile Strength (*ITS*) Test

Figure (7) depicts *ITS* test results for unconditioned asphalt samples with different percentages of modifiers. The results show that *CR* modified bitumen has more resistance to indirect tension. For asphalt mixtures, the maximum tensile strength is obtained with 5% *CR* and 5% *RGP*. The tensile strength of more modified samples is higher than that of the control sample. Moreover, tensile strength of *CR-RGP* samples is about 25% higher than that of *CR* samples and about 50% more than that of the unmodified samples. Then, positive influence is found for *RGP* addition.

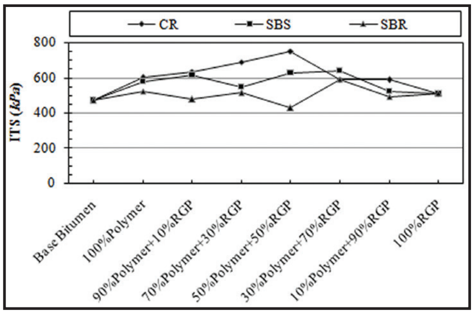

Figure 7. Indirect tensile strength of unmodified and modified mixtures

Figure (8) shows results of *TSR* test for asphalt mixes. The results indicate that *CR* modified bitumen has more TSR and less sensitivity to moisture in comparison with other modifiers. The maximum *TSR* is observed for the sample containing 5% *CR* and 5% *RGP*. Also, no negative impact is found after *RGP* addition. Strength of all the mixes is higher than the minimum required (75%).

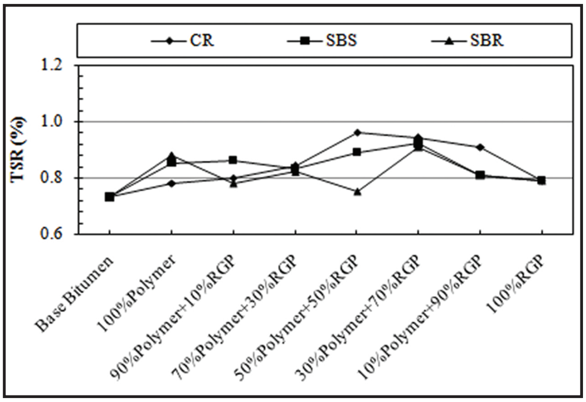

Figure 8. Comparison of tensile strength ratio for modified and unmodified mixtures

3.5 Results of Compressive Strength Test

Compressive strength values for different mixtures are presented in Figures (9-12). The results indicate that, the mixture modified using *SBS* has the greatest strength under different testing conditions compared with other modifiers. On the other hand, the presence of *RGP* has significant effect on *SBS* modified bitumen for different conditions and improved compressive strength at high, normal and low temperatures and saturated condition compared with *SBS* modified bitumen by 16%, 32%, 41% and 35%, respectively. Overall, it can be seen that *RGP* has improved compressive strength of *SMA* mixtures.

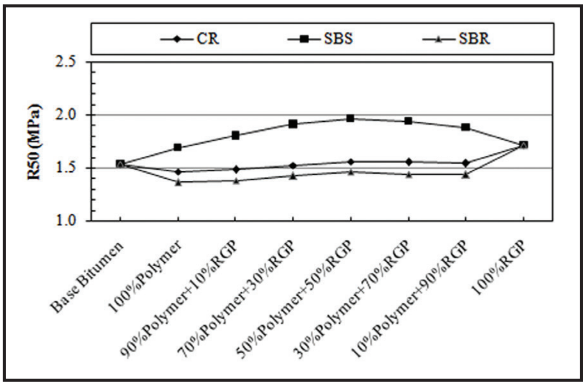

Figure 9. R_{50} for Modified and Unmodified Mixtures

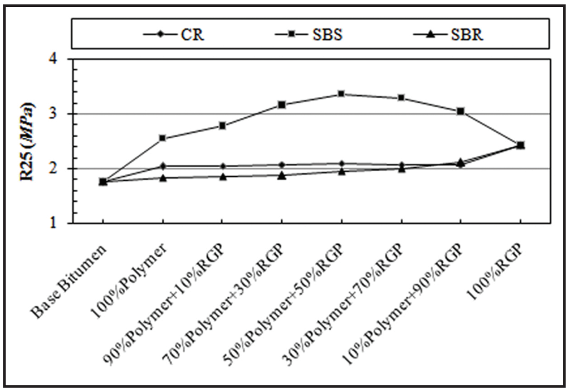

Figure. 10. R_{25} for Modified and unmodified mixtures

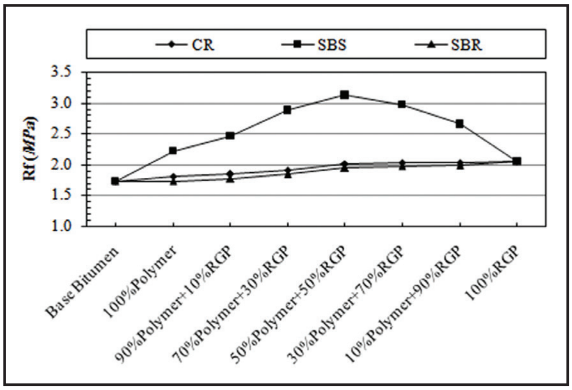

Figure 11. R_f for Modified and unmodified mixtures

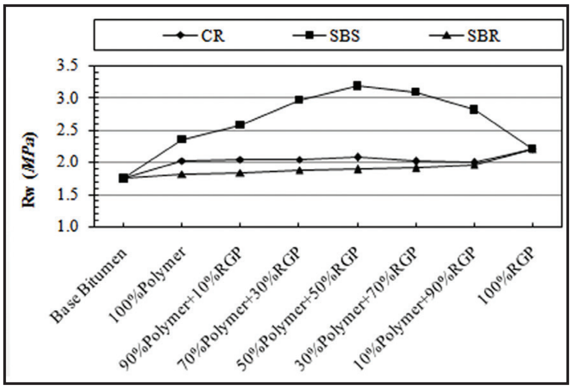

Figure 12. R_w for Modified and unmodified mixtures

3.6 Results of Indirect Tensile Stiffness Modulus Test

Three samples tested for each modified and unmodified mixtures. To obtain a stiffness modulus for a mixture, each sample was tested in three different conditions and the average value was adopted. Stiffness modulus of the mixtures is shown in Figure (13). The results indicate that, although *SBS* modified bitumen shows the highest stiffness modulus, *CR-RGP* modified bitumen that used recycled materials demonstrates very good stiffness modulus and is only 6.9% lower than the top mixture. All modified mixtures have higher stiffness modulus than the control mixture, resulting the pavement to show less strain at lower temperatures. Then, no negative impact was found after *RGP* addition.

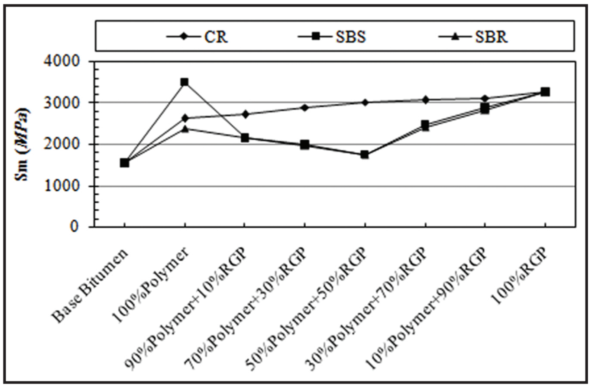

Figure 13. Stiffness modulus of modified and unmodified Mixtures

4. Conclusions

In present work, more than 800 samples of bitumen and asphalt mixtures were examined through extensive laboratory tests. The results are summarized as follows:

1. The maximum rutting parameter was obtained for the sample modified using 5% *SBS*.
2. *PI* values increased by modification. *SBS* and *CR* modified bitumen showed the best results in the current research. The results indicated that not only polymer substitution with *RGP* does not increase the thermal sensitivity but also, for *SBR* modified bitumen, *RGP* addition decreases the binder thermal sensitivity.
3. The value of *MQ* for all modified mixtures was higher than that of the control mixture. In addition, the maximum value of modified mixture *MQ* was two times higher than the control mixture. *CR* modified bitumen showed the best results in this experiment.
4. Tensile strength of more modified samples was higher than that of the control sample. The results showed that CR modified bitumen had more resistance to indirect tension. Also, tensile strength of *CR-RGP* modified samples was about 25% greater than that of *CR* modified samples and about 50% higher than that of unmodified samples.
5. The average compressive strength of modified mixtures was higher than that of the control mixture. In addition, for all conditions including high temperatures, cycles of freezing and thawing and saturating, *SBS* modified samples showed higher levels of strength compared with other samples. Meanwhile, high temperatures, cycles of freezing and thawing and saturating reduced compressive strength of modified mixtures by 41%, 7% and 5%, respectively.
6. The results of stiffness modulus test indicated that, although *SBS* modified bitumen showed the highest stiffness modulus, *CR-RGP* modified bitumen that used recycled materials and had very low cost demonstrated very good stiffness modulus and was only 6.9 % lower than top mixture.

Overall, assessment of mechanical properties of asphalt mixtures showed that, when *RGP* was applied, improvement was observed in Marshall and mechanical properties. It is also inferred that rutting parameters, stiffness and thermal sensitivity are improved with *RGP* entrance. Moreover, Marshall quotient, tensile strength, compressive strength and stiffness modulus of asphalt mixture increased in the presence of *RGP* content. The only foible in modification with *RGP* was rutting parameter and stiffness modulus reduction for *SBS* modified bitumen and mixture. Optimal modification was attained with 5% *CR* and 5% *RGP*. So, *RGP* can be substituted partly for the polymer in the bitumen modification.

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