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Effect of recycled glass powder on asphalt concrete modification

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Abstract. During recent years researchers performed large effort to increase the service life and asphalt stability of the roads against traffic loads and weather conditions. Investigations carried out in various aspects such as changes in gradation, addition of various additives, changes in asphalt textures and etc. The objective of this research is to evaluate the advantages of adding recycled glass powder (RGP), Crumb Rubber (CR), styrene-butadiene rubber (SBR) and styrene butadiene styrene (SBS) to base bitumen with grade of 60/70 for modification of asphalt concrete. Initial studies conducted for determining the physical properties of bitumen and modifiers. A series of asphalt concrete samples made using various combinations of RGP, CR, SBR, SBS and base bitumen. All samples tested using Indirect Tensile Strength (ITS), Indirect Tensile Strength Modulus (ITSM) and Marshall Stability Tests. The new data compared with the results of control samples. The results showed that replacing RGP with known polymers improved ITS and ITSM results considerably. Also the Marshall Stability of modified mixtures using RGP is more than what is found for the base blend. Ultimately, the new RGP modifier had a huge impact on pavement performance and results in high flexibility which can be concluded as high service life for the new modified asphalt concrete.

Keywords: asphalt concrete; ITS; SBS; SBR; CR; RGP

1. Introduction

Petroleum bitumen widely applied in paving industry. Some bitumen properties, such as viscosity and impermeability as well as its low cost that make it the most suitable material of binding in road paving, airfield and construction (Morales *et al*. 2007).

Bitumen is usually regarded as a colloidal suspension of asphaltene particles surrounded by resins in an oily continuous matrix (Sun and Lu 2006, Cong *et al*. 2006). Petroleum bitumen is a residue of crude oil obtained from refining process and can be divided into four generic groups (SARAs): saturates (S), aromatics (A), Resins (R), and asphaltenes (As). Each one of SARAs fraction is a mixture with different complexity, aromaticity and molecular weight which increased in this order: $S<A<R<As$ (Morales *et al.* 2007, Sadeghpour Galooyak *et al.* 2010).

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Due to the severe temperature susceptibility, bitumen has the characteristics of high temperature rutting and low temperature cracking. Moreover, fatigue and aging of bitumen limiting its industrial application. On the other hand, bituminous pavements are mostly under many distresses caused by temperature variations and traffic heavy loads. Therefore, modification of bitumen is inescapable (Airey 2003). In addition, due to major impact of low temperatures on asphalt cracks, some experimental studies performed on the temperature effects on brittle fracture in cracked asphalt concretes (Ayatollahi and Pirmohammad 2013). Continuous variations of weather and temperature effects on asphalt concrete significantly. In this regard, Pirmohammd and Kiani (2016) conducted a research about the impact of temperature variations on breaking and cracking of asphalt concrete.

Sun and Lu (2006) reported that many modifiers such as carbon black, sulfur, fly ash, amine and polymers applied to improve physical and rheological properties of bitumen.

During recent three decades, modification of bitumen by polymers increased significantly. The pavement with polymer modified bitumen (PMB) shows higher resistance to rutting, thermal cracking, lower fatigue damage, stripping, aging and temperature susceptibility (Hossain *et al*. 1999, Airey *et al*. 2002, Mul *et al.* 2002, Lu and Isacsson 1997).

Generally, common polymers are very useful for road pavements, waterproofing and roofing membranes in order to improve the main distresses associated with bitumen: brittleness at low temperatures which causes thermal cracking; low elastic and viscous properties at high in-service temperature which cause permanent deformation (Navarro *et al*. 2004, Huang *et al*. 2003, Shu and Huang 2008). Consequently, replacing common polymers by recycled ones in bituminous blends is a promising alternative which is environmentally favorable, offering a sustainable life-cycle for some petroleum-derivative polymers. In this case, two major groups of recycled polymers may be considered: crumb tire rubber and waste thermo-plastic polymers.

Using crumb tire rubber in bitumen modification contributes to achieve some environmental EU objectives. According to the directive (2000/53/EC), at least 85% of end-of-life vehicles weight must be re-used or recycled by 2015, and the landfill of scrap tires and other waste plastics prohibited since 2006 (Directive 2000/53/EC, Navarro *et al*. 2005, Colom *et al.* 2007).

Lu and Isacsson's (1997) studies show that Styrene-Butadiene-Styrene (SBS) tri-block co-polymer presented the best results in improving the bitumen properties among the polymer modifiers of bitumen. SBS is a block co-polymer of polystyrene (PS) and polybutadiene (PB). Transition temperature of the glass in the hard block of PS and soft block of PB are about +100°C and -90°C respectively. The SBS has a flat modulus in this temperature range, so it could decrease temperature susceptibility of bitumen in a wide range of temperature. Usually, Styrene is the dispersed phase and provides the strength of material, while the butadiene is the continuous phase and contributes to the elasticity of SBS (Wen *et al*. 2002). Because of the poor compatibility between SBS and bitumen, they are immiscible and unfortunately SBS tends to separate from bitumen at high storage temperatures. Furthermore, since there are unsaturated bonds in SBS, it destines to degrade when it is exposed to heat, UV light and oxygen (Ouyang *et al*. 2006, Cortizo *et al*. 2004, Lu and Isacsson 1998). Another study conducted by Qadir and Qadir (2014) on the impact of polypropylene fibers on the Marshall stability. The results indicated that the fibers increase the ITS at different temperatures.

Recently, due to the increasing importance of environmental issues, many researchers conducted about issues which are common between environments and asphalt (e.g., Ma *et al.* 2016). Considering the application of recycled materials such as glass powder (e.g., Liang *et al.* 2015) and rubber powder, this research also considered the environmental issues too.

Table 1 Engineering properties of aggregates

Property	Method of Testing	Quantity
Percentage of abrasion	ASTM C-131	25
Weight Loss using sodium sulphate	ASTM C-88	3.5%
Percentage of water absorption	ASTM C-127	0.89
Plasticity	ASTM D-4318	Non-plastic

Table 2 Properties of base bitumen with penetration grade of 60/70

Test	Method	Quantity
Physical condition		Solid at room temperature
Ductility	ASTM D-113	More than 100 cm at 25℃
Specific Gravity	ASTM D-70	1.017 at 25℃
Softening point	ASTM D-36	48℃
Penetration	ASTM D-5	64 dmm at 25℃
Flash point	ASTM D-92	More than 230℃
Storage Temperature		Up to 170℃

In this paper, we used SBS, CR, SBR and RGP to improve properties of asphalt concrete. First we added CR, SBR and SBS to asphalt and then RGP added to this mixture.

2. Test materials

Main materials used in this study are as follow:

2.1 Stone aggregates

Stone materials used for preparation of stone matrix asphalt specimens produced from mines located around Kerman city, Iran. Engineering properties of coarse and fine aggregates shown in Table 1.

2.2 Base bitumen

Bitumen of penetration grade 60/70 supplied from Esfahan refinery and all modifications carried out through a series of samples. Properties of the base bitumen determined in laboratory and presented in Table 2.

2.3 SBS and SBR

SBS and SBR are the most common modifiers used for asphalt concrete added to the base bitumen for 3% to 7% of base bitumen weight previously while the average added in this research is 5% of them.

2.4 Waste rubber powder

CR produced from waste rubber. The CR passed through sieve No. 30 for greater uniformity. Both dry and wet process can be used to add CR to base bitumen. Wet process used to add CR to the base bitumen for 10% of base bitumen weight in this research.

2.5 Glass powder

RGP obtained from the waste glass by grinding. The wet process used for adding RGP to the base bitumen.

3. Preparation of polymer bitumen

The modified bitumen generated in a laboratory scale mixer at 180°C for 60 minutes and at a 2000 r/min rotational speed in order to obtain a homogeneous binder.

To produce modified bitumen, primarily modifiers (CR, SBS and SBR) added to the base bitumen for 10%, 5%, and 5% of the base bitumen weight respectively and then some part of CR and SBS/SBR weight replaced by RGP as shown in Tables 3, 4, and 5.

4. Sample preparation

Various combinations of modified bitumen used to make a series of samples. Three samples made for each test and 1200 grams of material prepared for each sample based on the grain size distribution shown in Table 6. The sample materials placed in the oven for 24 hours at a

Table 3 Sample prepared with CR-RGP modified asphalt binders

Sample No.	1	2	3	4	5	6	7	8
Mixture type	Base bitumen	10% CR	9% CR + 1% RGP	7% CR + 3% RGP	5% CR + 5% RGP	3% CR + 7% RGP	1% CR + 9% RGP	10% RGP

Table 4 Sample prepared with SBS-RGP modified asphalt binders

Sample No.	1	2	3	4	5	6	7	8
Mixture type	Base bitumen	5% SBS	4.5% SBS + 0.5% RGP	3.5% SBS + 1.5% RGP	2.5% SBS + 2.5% RGP	1.5% SBS + 3.5% RGP	0.5% SBS + 4.5% RGP	5% RGP

Table 5 Sample prepared with CR-RGP modified asphalt binders

Sample No.	1	2	3	4	5	6	7	8
Mixture type	Base bitumen	5% SBR	4.5% SBR + 0.5% RGP	3.5% SBR + 1.5% RGP	2.5% SBR + 2.5% RGP	1.5% SBR + 3.5% RGP	0.5% SBR + 4.5% RGP	5% RGP

Table 6 Grain size distribution of the material

Sieve size, mm	Lower and upper limits	Average percentage passing
19.00	100	100
12.50	85-95	90
9.50	70-75	72.5
4.75	20-28	24
2.36	16-24	20
0.60	12-16	14
0.30	12-15	13.5
0.075	8-10	9

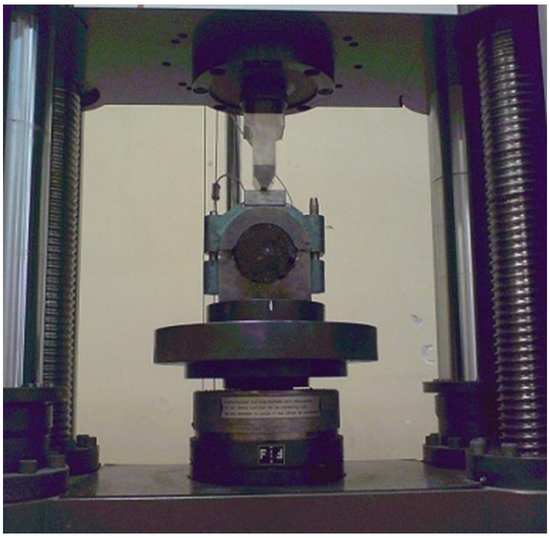


Fig. 1 The Marshall test rig set up

Fig. 2 UTM device used for loading

temperature of 160-170°C, the polymer bitumen heated to 137°C and then the aggregates and polymer bitumen mixed together till the whole grains became quite greasy (i.e., Fully covered with bitumen). The mixture poured into the Marshall mold and compacted using 50 blows of hammer impact (ASTM D1559). About 6% optimum bitumen derived from Marshall Test results.

5. Experimental pogram

5.1 Marshal stability tests

The asphalt Marshal Stability is the maximum load that a sample can hold without fracturing. After producing eight series of asphalt concrete samples, they were kept in an equipped thermostat hot water bath with 60°C for at least 30 minutes and then all samples taken out and put between two maxillofacial Marshall Devices (see Fig. 1). Marshall Tests conducted using UTM Device (see Fig. 2).

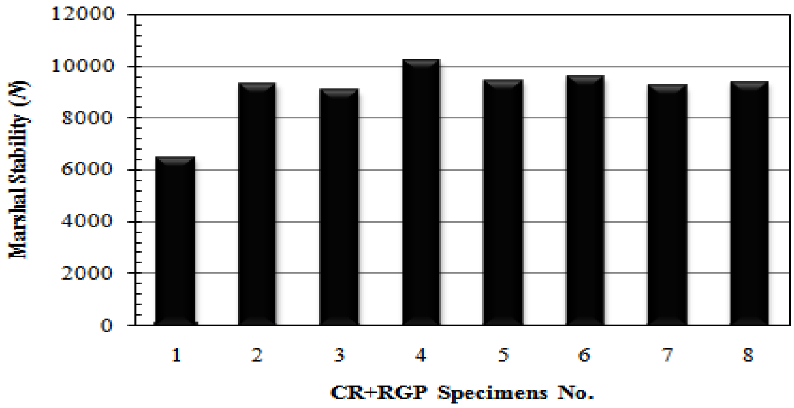


Fig. 3 Marshal stability of samples modified with CR and RGP

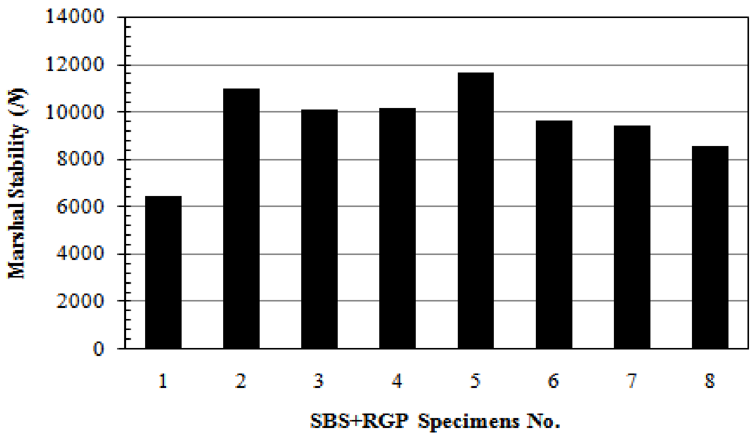


Fig. 4 Marshal stability of samples modified with SBS and RGP

The optimum bitumen content selected as 6% after studying and analyzing Marshal Test results of control samples. Three separately series of Marshall Test conducted for prototype (base) and effects of various polymer samples on prepared samples shown in Tables 3, 4, and 5 with descriptions. The Marshal Stability versus CR+RGP, SBS+RGP, and SBR+RGP samples shown in Figs. 3, 4 and 5 respectively. In all series of tests, the results indicate that the polymer materials have considerable effect on increasing Marshal Stability. Fig. 3 shows that combination of 7% CR +3% RGP for average specimens of series No. 4 results in the Marshal Stability of 10214.4N which is the highest stability in comparison to other combinations of CR and RGP.

Fig. 4 shows that the maximum average of Marshal Stability is 11675.5 N, belongs to sample series No. 5 which is the combination of 2.5% SBS+2.5% RGP. The results show that the maximum stability is 14.3% and it is more than what was found for combination of 7% CR+3% RGP.

Fig. 5 shows that the combination of 3.5% SBR+1.5% RGP for average specimens of series No.4 result in Marshal Stability of 9767.9N which is the highest stability in comparison to other combinations of SBR and RGP. This result shows a decrease of 4.4% in stability in comparison to

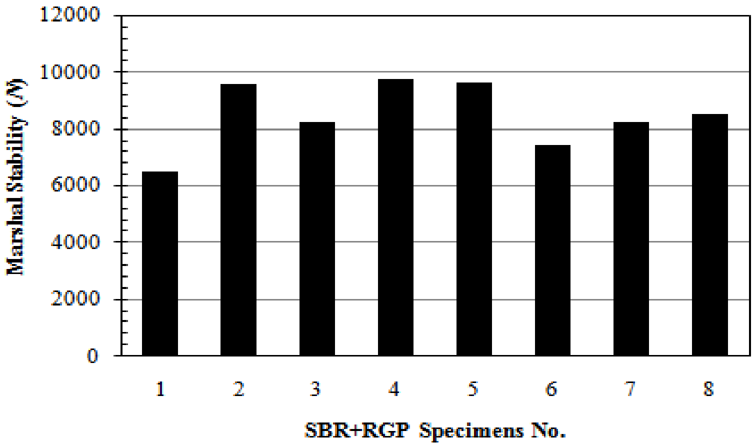


Fig. 5 Marshal stability of samples modified with SBR and RGP

combination of 7% CR +3% RGP.

Comparing Marshall Test results for modified samples using CR+RGP, SBS+RGP, and SBR+RGP shows that all additives have considerable effect on Marshal Stability. However, the combination of 2.5% SBS+2.5% RGP has the maximum effect on Marshal Stability in which it increased from 6481N to 11676N. The results also showed that the additives CR+RGP and SBR+RGP are in second and third order in comparison to SBS+RGP. It is important to note that, using additives CR+RGP for bitumen modification is more economical due to availability of waste tire rubber and waste glass.

5.2 Indirect Tensile Strength test (ITS)

Indirect tensile strength test (ITS) used to measure resistance against mechanical fatigue. Moreover, by ITS and measuring latitudinal deformations of cross section in under pressure samples in addition to assumptions of the Poisson’s ratio, the E-module can be calculated.

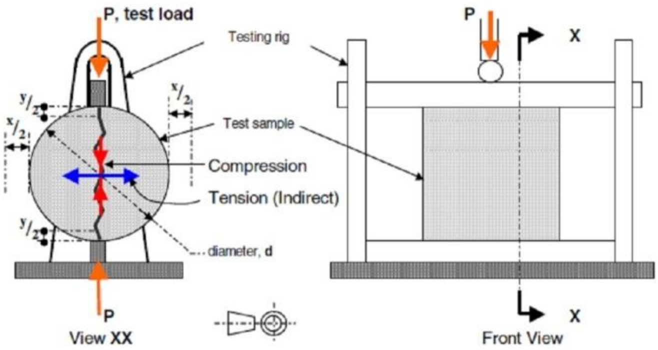
In order to determine the ITS according to AASHTO T283(2007), test samples (Marshall sample or core sample) compressed at 25°C with 50.8 mm/min deformation rate by two opposite beams until it fractures (see Fig. 6(a)-(b)). Both radial deformation and vertical deformation forces monitored. Such loading results in a kind of unified tensile stress which acts vertically along the loading process and therefore the sample always fractured into two parts. The ITS and E-module can be calculated from Eqs. (1) and (2) as follows

$$ITS = \frac{2 \times P}{(\pi \times h \times d)} \tag{1}$$

Where;

ITS = Indirect tensile test (N/mm^2)
P = Maximum test force (N)
h = Height of test sample (mm)
d = Diameter of test sample (mm)

(a) Real picture



(b) Schematic picture

Fig. 6 Indirect tensile strength test

$$E = \frac{8 \times ITS}{(3 \times \varepsilon_2 + \varepsilon_1)} \tag{2}$$

Where;

ITS = indirect tensile test (N/mm2)

ε_1= vertical strain = vertical deformation/*d*, *y/d*

ε_2= horizontal strain = horizontal deformation/*d*, *x/d*

Irregular cross sectional surface doesn't have a major impact on results and therefore the variation coefficient of the test results is insignificant. All samples tested at a temperature and Poisson's ratio of 25°C and 0.35 respectively in all calculations.

Many researchers expressed the relationship between ITS and performance of asphalt concrete (Rogue *et al*. 1998, Zhang *et al*. 2001, Pradyumna *et al*. 2013, Baskandi 2015). They showed that the more tensile strength, the more resistance against low temperature cracking (Huang *et al*. 2003). The ITS versus CR+RGP, SBS+RGP and SBR+RGP samples shown in Figs. 7, 8 and 9 respectively.

The results indicate that the polymer materials have considerable effect on increasing ITS in all series of tests. Fig. 7 shows that the combination of 3% CR+7% RGP for average specimens of series No.6results in the ITS of 14253.8 kPa which is the highest ITS in comparison to the other combinations of CR and RGP.

Fig. 8 represents that the maximum average of ITS is 12150.5 kPa, belongs to sample series No. 7 which is the combination of 0.5% SBS+4.5% RGP. The results show that the maximum ITS is 14.75% less than what was found for combination of 3% CR +7% RGP.

Fig. 9 indicates that the combination of 0% SBR+5% RGP for average specimens of series No.8results in the ITS of 11211.9 kPa which is the highest ITS in comparison to the combinations of SBR and RGP. Such results show 21.34% decrease in ITS in comparison to combination of 3% CR+7% RGP.

Comparing ITS test results for modified samples using CR+RGP, SBS+RGP, and SBR+RGP show that all additives have considerable effect on ITS. However, the combination of CR+RGP has the maximum effect on ITS and changed it from 8945.2 kPa to 14253.8 kPa. The results also show that the additives SBS+RGP and SBR+RGP are in second and third order in comparison to CR+RGP.

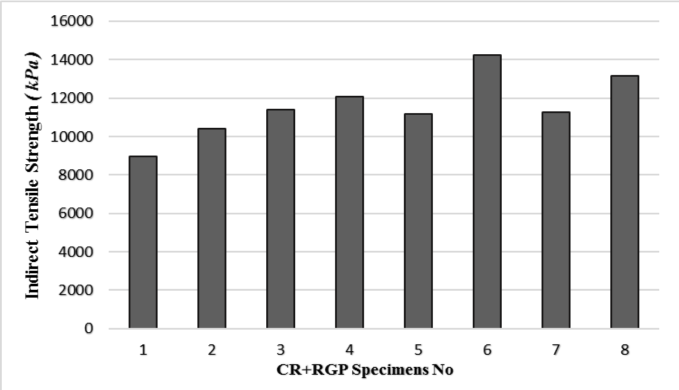


Fig. 7 Indirect tensile strength of samples modified with CR and RGP

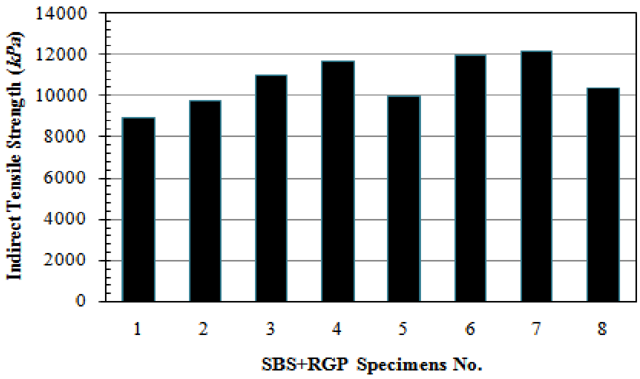


Fig. 8 Indirect tensile strength of samples modified with SBS and RGP

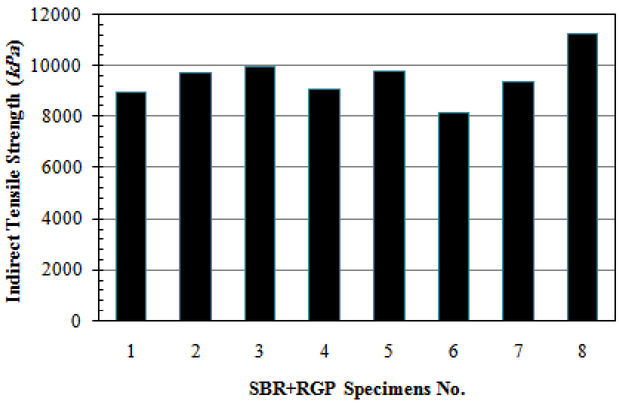


Fig. 9 Indirect tensile strength of samples modified with SBR and RGP

5.3 Determining Indirect Tensile Stiffness Modulus test (ITSM)

Indirect Tensile Stiffness Modulus test (ITSM) conducted based on the BS DD 213 standard.

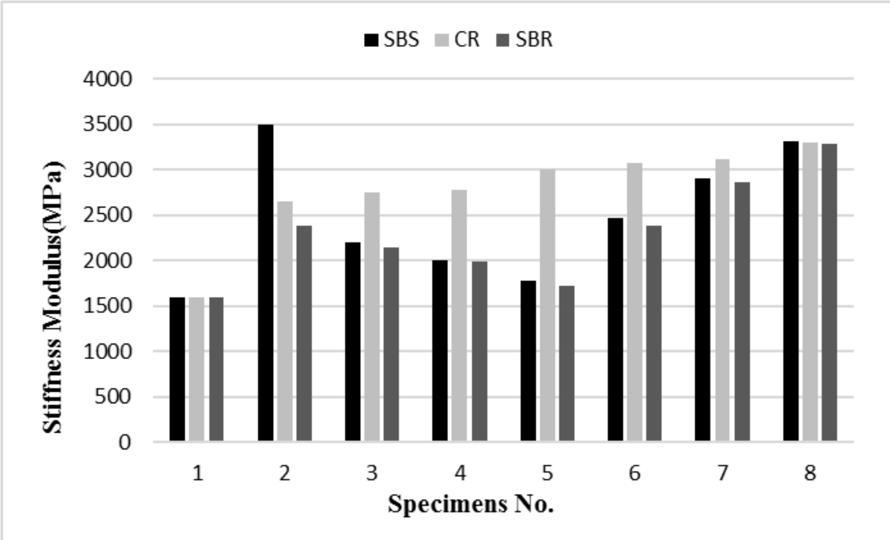


Fig. 10 Stiffness modulus of unmodified and modified samples

According to this standard, ITSM's amount of the samples determined using Eq. (3)

$$S_M = \frac{F(R + 0.27)}{LH} \tag{3}$$

In which, F, R, L, H, and S_M are the maximum dynamic load in Newton (N), Poisson's ratio, thickness (mm), reversible horizontal deformation (mm), and Indirect tensile stiffness modulus of the samples (MPa) respectively. The test conducted using the device UTM under strain controlled conditions. In the test, the Poisson's ratio and the operating temperature are 0.35 and 25℃ respectively. The three seconds loading pulse used and the rise time which is the time applied load increased from zero to a max value was 124 ms. Three samples tested for each test and their average used to present the results (66 samples tested totally). The results of ITSM for all samples are shown in Fig. 10.

6. Analysis and discussion

The results of the present research show that the ITS improved by CR and RGP. In addition, Figs. 7, 8 and 9 show that increase in polymer materials and RGP results in increase in tensile strength. Increase in tensile strength of specimens containing CR and SBS is more than specimens containing SBR. So using these two polymers is more effective. The use of RGP indicate better results in which the most improved results obtained from samples containing 5% CR and 5% RGP. The tensile strength in these samples is 1.6 times more than the control sample. Higher tensile strength shows greater resistance of the mixture against cracking at low temperature. That is, if the polymer materials and RGP added to the mixture, leads to increase in tensile strength following by an increase in bitumen viscosity. Therefore, cracking in asphalt postponed and number of cracks reduced which results in increase in the efficiency and lifespan of asphalt.

As indicated in Figs. 4, 5 and 6, adding CR and SBS, SBR polymers to the bitumen results in an increase in the Marshall Stability of the SMA Asphalt. Moreover, adding such additives results in increase in the average smoothness of asphalt which means these additives increase the strength and elasticity of asphalt; Marshal stability of samples including 2.5%SBS and 2.5%RGP is about 1.8 times more than the control sample.

The results show that the optimum ratio of CR and RGP combination is 7% and 3% respectively and the Marshall resistance of these samples is about 1.6 times more than the control sample.

Using 3.5% SBR and 1.5% RGP results in 1.5 times more Marshall resistance than control samples. Comparing the results of Marshall Resistance test showed that the effect of applying SBS polymer on increasing Marshall Resistance of optimum samples is more than CR and SBR.

Studying the results indicated that all modified samples have more stiffness modulus in comparison to the control samples. Moreover, using RGP and increasing it had positive effects on stiffness modulus. Considering appropriate results of stiffness modulus in addition to glass and rubber powders which are recycled, it seems that using CR+RGP combination is the most appropriate mixture for reformation of the samples.

7. Conclusions

Results of the present study are as follows:

• ITS of the mixture of the samples modified by polymers and RGP is more than control samples. The most increase in ITS observed in the mixtures modified by 5% RGP and 5%CR. Such increase in ITS of modified mixtures shows an improvement in tensile behavior of asphalt at the failure moment under static load. In addition, it can be concluded that modified mixtures are capable of resisting more strains before cracking.

• Due to glass and rubber powders which are recycled, it seems that replacing waste glass powder with a part of common polymers and CR leads to decrease in using polymer and production cost of modified asphalt on one hand in addition to have positive effects environmentally on the other hand.

• Using appropriate combination of RGP and CR resulted in remarkable increase in ITS of samples which lead to decrease in number of cracks and delay in their formation. Therefore, efficiency and lifespan of asphalt increased. Moreover, using them have many positive environmental effects.

• Increase in viscosity of modified samples leads to decrease in sensitivity of such asphalts toward temperature variations. Thus, using this type of asphalt is very useful in areas with high temperature variations daily or annually.

• Marshall Stability of mixtures modified by polymers and RGP is more than base mixtures. Increase in Marshall Stability results in decrease in the asphalt thickness and therefore, decrease in pavement cost. The most increase in Marshall Strength observed in those mixtures modified by 5% SBS and 5% RGP.

• Percentage of mixture and type of modifier play an important role in asphalt efficiency and behavior.

• The results show that the effect of SBR polymer is less than SBS and CR in improving asphalt behavior.

• Results of ITSM test indicate that the highest stiffness modulus obtained for the samples modified by SBS polymer but due to glass and rubber powders which are recycled and obtaining appropriate stiffness modulus for the samples modified by CR and RGP (less than 10% differs from the highest modulus), applying this combination is the most appropriate and recommended.

• Generally, it seems if technical, environmental and economic attitudes considered, using CR and RGP is more appropriate combination to modify asphalt than other mentioned mixtures in the research.

References

AASHTO T283 (2007), Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-induced Damage, American Association of State and Highway Transportation Officials.

Airey, G.D. (2003), "Rheological properties of styrene butadiene styrene polymer modified road bitumens", *Fuel*, **82**(14), 1709-19.

Airey, G.D., Singleton T.M. and Collop J. (2002), "Properties of polymer modified bitumen after rubber-bitumen interaction", *J. Mater. Civil Eng*., **14**(4), 344-354.

Ayatollahi, M.R. and Pirmohammad, S. (2013), "Temperature effects on brittle fracture in cracked asphalt concrete", *Struct. Eng. Mech.*, **45**(1), 19-32.

Baskandi, B. (2015), "Influence of construction parameters on performance of dense graded bituminous mixes", *IOSR J. Mech. Civil Eng.*, **12**(1), 64-78.

Chunfa, O., Qun, G., Yutao, S. and Xiaoqian. S. (2012), "Compatibilizer in waste tire powder and low-density polyethylene blends and the blends modified asphalt", *Appl. Polym.*, **123**(1), 485-492.

Colom, X., Carrillo, F. and Cañavate, J. (2007), "Composites reinforced with reused tyres: surface oxidant treatment to improve the interfacial compatibility", *Compos. Part A*, **38**(1), 44-50.

Cong, Y., Liao, K., Huang, W. and Zhai, Y. (2006), "Study on technical parameters of SBS modified asphalt", *Petrol Sci. Technol*., **24**(5), 507-12.

Cortizo, M.S., Larsen, D.O. and Bianchetto, H. (2004), "Effect of the thermal degradation of SBS copolymers during the ageing of modified asphalts", *Polym. Degrad. Stab*., **86**(2), 275-282.

Hossain, M., Swartz, S. and Hoque, E. (1999), "Fracture and tensile characteristics of asphalt-rubber concrete", *J. Mater. Civil Eng*., **11**(4), 287-294.

Huang B., Li, G. and Shu, X. (2003), "Analytical modeling and experimental study of tensile strength of asphalt concrete composite at low temperatures", *Compos. Part B.*, **34**(8), 705-714.

Liang, J.F., Yang, Z.P., Yi, P.H. and Wang, J.B. (2015), "Mechanical properties of Recycled Fine Glass aggregate concrete under uniaxial loading", *Comput. Concrete*, **16**(2), 275-285.

Lu, X.H. and Isacsson, U. (1997), "rheological characterization of styrene-butadiene-styrene copolymer modified bitumens", *Constr. Build Mater*., **11**(1), 23-32.

Lu, X.H. and Isacsson, U. (1998), "Chemical and rheological evaluation of aging properties of SBS polymer modified bitumens", *Fuel*, **77**(9-10), 961-972.

Ma, F., Sha, A., Lin, R., Huang, Y. and Wang, C. (2016), "Greenhouse gas emissions from asphalt pavement construction: a case study in China", *Int. J. Environ. Res. Public Hlth.*, **13**(3), 351.

Morales, M.G., Partal, P., Navarro, F.J., Boza, M. and Gallegos, C. (2007), "Processing, rheology, and storage stability of recycled EVA/LDPE modified bitumen", *Polym. Eng. Sci*., **47**(2), 181-91.

Mull, M.A., Stuart, K. and Yehia, A. (2002), "Fracture resistance characterization of chemically modified crumb Rubber asphalt pavement", *J. Mater. Sci*., **37**(3), 557-566.

Navarro, F.J., Partal, P., Martínez-Boza, F.J. and Gallegos, C. (2010), "Novel recycled polyethylene/ground tire rubber /bitumen blends for use in roofing applications: thermo-mechanical properties", *Polym. Test.*, **29**(5), 588-595.

Navarro, F.J., Partal, P., Martínez-Boza, F. and Gallegos, C. (2004), "Thermo-rheo-logical behavior and

storage stability of ground tire rubber-modified bitumens", *Fuel.*, **83**, 2041-2049.
Navarro, F.J., Partal, P., Martínez-Boza, F. and Gallegos, C. (2005), "Influence of crumb rubber concentration on the rheological behavior of a crumb rubber modified bitumen", *Energy Fuel.*, **19**(5), 1984-1990.
Ouyang, C., Wang, S.F. and Zhang, Y. (2006), "Thermo-rheological properties and storage stability of SEBS/kaolinite clay compound modified asphalts", *Eur. Polym. J.*, **42**(2), 446-57.
Pirmohammad, S. and Kiani, A. (2016), "Impact of temperature cycling on fracture resistance of asphalt concretes", *Comput. Concrete*, **17**(4), 541-552.
Pradyumna, T.A., Mittal, A. and Jain, P.K. (2013), "Characterization of Reclaimed Asphalt Pavement (RAP) for use in bituminous road construction", *Procedia-Soc. Behav. Sci.*, **104**, 1149-1157.
Qadir, A. and Qadir, A. (2014), "Rutting performance of polypropylene modified asphalt concrete", *IJCE*, **12**(3), 304-312.
Rogue, R., Zhang, Z. and Sankar, B. (1998), "Determination of crack growth rate parameters of asphalt mixtures using the superpave indirect tension test", *IDT. J Asphalt Paving Technol.*, **68**, 404-33.
Sadeghpour Galooyak, S., Dabir, B., Nazarbeygi, A.E. and Moeini, A. (2010), "Rheological properties and storage stability of bitumen / SBS / montmorillonite composites", *Constr. Build. Mater.*, **24**(3), 300-307.
Shu, X. and Huang, B. (2008), "Micromechanics-based dynamic modulus prediction of polymeric asphalt concrete mixtures", *Compos. Part B.*, **398**(4), 704-713.
Sun, D. and Lu, W. (2006), "Phase morphology of polymer modified road asphalt", *Petrol Sci. Technol.*, **24**(7), 839-49.
Wen, G., Zhang, Y. and Zhang, Y.X. (2002), "Rheological characterization of storage-stable SBS-modified asphalt", *Polym Test.*, **21**(3), 295-302.
Zhang, Z., Rogue, R., Birgisson, B. and Sangpetngam, B. (2001), "Identification and verification of a suitable crack growth law", *J. Asphalt Pav. Technol.*, **70**, 206-41.

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