Performance Improvement of Porous Asphalt Mixtures using Crumb Rubber and Steel Slag Powder

Ali Nazarinasab[1], Mojtaba Ghasemi[2], Seyed Morteza Marandi[3]

Received: 13. 06. 2017   Accepted: 14. 11. 2017

Abstract

In recent decades, porous asphalt has been extended for surface drainage in various regions throughout the world. The permeability of porous asphalt has an important role in the performance of asphalt pavements in the rainy weather. The most remarkable problem related to the porous asphalt is its short service time. Considerable efforts have been made to enhance the mechanical properties of porous asphalt. Steel slag produced from manufacturing processes is a by-product commonly deposited in landfills and thus results in many serious environmental problems. Very high amounts of steel slag is produced in Iran and if these waste materials could be well put into practical uses, it would decrease the burden on the environment. This paper presents a series of tests on modified bitumen and porous asphalt with steel slag powder (SSP) and crumb rubber (CR). Reference tests were also conducted on control bitumen and porous asphalt. The material properties for different types of bitumen and porous asphalt were evaluated by penetration degree, softening point, ductility, Marshall stability, indirect tensile strength (ITS), porosity, and permeability. The results of current research demonstrated that it was feasible to replace partial CR with SSP. SSP can not only increase the softening point and ductility, but also reduce the penetration degree. Compared with the control porous asphalt, the modified porous asphalt with SSP/CR had higher Marshall stability, Marshall quotient (MQ), ITS and porosity. When 90% of CR was replaced by SSP in porous asphalt, highest permeability was observed. From these results, it was concluded that SSP can potentially be used as modifier replacement in the production of modified porous asphalt.

Keywords: Bitumen Modification, Crumb Rubber, Steel Slag Powder, Porous Asphalt

Corresponding author E-mail: m.ghasemi@kgut.ac.ir

[1] M.Sc. Student, Department of Civil Engineering, Graduate University of Advanced Technology, Kerman, Iran

[2] Assistant Professor, Department of Civil Engineering, Graduate University of Advanced Technology, Kerman, Iran

[3] Professor, Department of Civil Engineering, Shahid Bahonar University, Kerman, Iran

1. Introduction

Over the past decades, porous asphalt mixtures are extensively used as motorway surface layer in several nations due to their merits. The particularities of porous asphalt mixtures cover a vast range of advantages such as benefits in friction, smoothness, permeability, safety during wet conditions (enhanced skid resistance and reduced spray and splash), good visibility of markings at night and during raining, water drainage, economy, environment and tire/pavement noise. The most remarkable problem related to the porous asphalt is its short service time compared with the dense-graded asphalt concrete [Qian and Lu, 2015; Luo, Lu and Qian, 2015; Frigio et al. 2013; Poulikakos and Partl, 2012; Liu et al. 2009, Mo et al. 2011].

Considerable efforts have been made to enhance the lifespan and mechanical properties of porous asphalt, such as improving the mixtures with polymers. Bitumen plays a major role in the road construction industry. The efficiency and durability of asphalt increase by modifying bitumen [Sadeghpour Galooyak et al. 2015; Taherkhani et al. 2017]. The net result of asphalt pavement problems such as thermal cracking, rutting, bleeding, and loss of flexibility along with uncomfortable driving conditions on roads and shorter pavement life is directly caused by the use of unmodified bitumen [Lan et al. 2015; González et al. 2012]. Polymers are used to improve the bitumen quality and reduce its temperature susceptibility [Baumgardner et al. 2014]. By adding polymer to bitumen, many bitumen deficiencies were removed and also viscoelastic behavior and bitumen properties were improved [Ameri, Hesami and Goli, 2013].The effect of polymer modification on the linear rheology depends on polymer nature, concentration, and testing temperature [Moghadasnejad et al. 2012; Bolden, Abu-Lebdeh and Fini, 2013].

In addition to traditional polymers, CR used as a bitumen modifier, resulting in stiffer bitumen have increased viscosity at high temperatures. The stiffening effect of CR on bitumen can help to minimize drain down while increasing the durability of the mix. Many benefits are obtained by using the CR modified bitumen in road pavement applications. Moreover, asphalt mixture, which is made from the modified bitumen, has long-lasting function and improved temperature susceptibility [Lyons and Putnam, 2013; Subhy, Lo Presti and Airey, 2015; Ghasemi and Marandi, 2014; Goli, Ziari and Amini, 2016].

One of the main threats to the environment is the accumulation of waste materials such as rubber, glass, metal, plastic, etc. Fast-growing increase of population leads to huge amount of waste with rapidity. The disposal of waste should be proportional to its increasing which falls in three main categories: burying, incineration, and recycling. Recycling and reusing waste materials are effective solutions toward increasing consumption of natural resources and mitigating environmental pollution [Shahiri and Ghasemi, 2017; Du et al. 2016; Mohammadzadeh Moghaddam et al. 2014; Ziari et al. 2016; Taherkhani, Firoozei and Bolouri Bazaz, 2016]. Steel slag is a by-product of iron and steel making, marketed primarily to the construction industry [Ruth et al. 1997; Ziaee et al. 2014]. By using SSP in road construction, the amounts of natural materials applied in the road construction industry can be reduced and fewer areas would be required for storing SSP, and thus has a lower environmental impact [Ameri, Hesami and Goli, 2013].

The main purpose of this study is to experimentally investigate a new compound of waste disposal materials (combination of CR and SSP) to modify bitumen and asphalt. From an environmental and economic viewpoint, the use of CR and SSP as bitumen modifying agents contributes to solving a waste disposal problem. Furthermore, in the case of impact of SSP on bitumen, review of prior studies has also shown a lack of research that focuses on the subject.

2. Materials

2.1 Aggregate

The aggregate was obtained from an asphalt plant in Kerman, located in the south east of Iran. Table 1 shows aggregation used for the production of porous asphalt in this study. The aggregate was first sampled from the quarry and transported to the lab where it was dried in an oven at 110 ºC and then, mechanically sieved into the individual size fractions needed to produce the mix gradation. Properties of aggregate are presented in Table 2.

2.2 Bitumen

In this investigation, 60–70 penetration bitumen, obtained from Pasargad Mineral Oil Refinery in Shiraz, was used. Engineering properties of the bitumen are presented in Table 3.

2.3 CR

The rubber powder used for the purpose of this study is the one prepared through ambient procedure from cutting, scraping and powdering waste tires and then adding it to the traditional bitumen to produce rubber modified bitumen. The rubber powder sifts through a No. 30 sieve (fiber and metals have been removed from the rubber) and its density is 1320 kg/m3. Granulated crumb rubber used is shown in Table 4.

2.4 SSP

Steel slag used in this study was produced in a steel factory in Kerman, Iran. Steel slag was produced in pieces with an approximate dimension of 10cm*10cm. Then, the slag was taken into the laboratory and changed into the powder by a hammer, milling machine, and ball mill in three stages. The milling machine and SSP passing #200 sieve are shown in Figures 1 and 2. The chemical properties of SSP are indicated in Table 5.

Table 1. Aggregate gradation used in this study

Sieve No.	Sieve size(mm)	Lower Limits (%)	Upper Limits (%)	%Passing
¾ “	19	100	100	100
½ “	12.5	88	100	94
3/8 “	9.5	59	79	69
# 4	4.75	9	29	19
# 8	2.36	1	7	4
# 30	0.6	1	7	4
# 100	0.15	1	3.6	2.3
# 200	0.075	0	2	1

Table 2. Physical and mechanical properties of aggregates

Sample	Bulk specific gravity	Apparent specific gravity	Water absorption (%)	Toughness (%)
Coarse aggregate	2.72	2.77	0.32	22.87
Fine aggregate	2.65	2.69	1.44	-
Filler	2.48	2.53	-	-
ASTM standard	C-127 & C-128	-	-	C-131

Figure 1. The milling machine

Figure 2. SSP passing #200 sieve

Table 3. Conventional rheological properties of the unmodified bitumen used in this study

Test	Standard ASTM	Value
Penetration (100g, 5 s, 25◦C), 0.1 mm	ASTM D5-73	70
Softening point (◦C)	ASTM D36-76	43
Ductility (25◦C, 5 cm/min) (cm)	ASTM D113-79	>100
Flashing point (◦C)	ASTM D92-78	>302

Table 4. Crumb rubber gradation used in this study

Sieve No.	Sieve size(mm)	%Passing
# 30	0.6	100
# 50	0.3	65
# 100	0.15	24
# 200	0.075	3

Table 5. Chemical composition of used SSP

Chemical composition	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3
Values	39.4%	32.1%	16.9%	7.1%	3.75%

Table 6. Specification of CR-SSP modified bitumen

Sample No.	CR (%, by bitumen weight)	SSP (%, by bitumen weight)
1	10	0
2	9	1
3	7	3
4	5	5
5	3	7
6	1	9
7	0	10

3. Experimental Study

3.1 Preparation of Mixtures

All the modified bitumen samples were prepared using a high shear mixer with shearing speed of 3000 rpm. To modify bitumen, at first, 1000 g of bitumen was heated in an iron container to turn it into fluid, then the modifiers (CR, SSP) with specific ratio were put in bitumen with mixing for 60 min at the temperature of 160 °C. To study the effects of SSP and CR on the specification of the modified bitumen, seven bitumen mixtures were studied. The percentage of additives used are shown in Table 6. The research program being selected is similar to previous studies [Ghasemi and Marandi, 2013].

3.2 Preparation of Samples

Marshall Test has been inserted in Standard No. ASTM-D1559, entitled ‘‘Standard Testing Method for determination of asphalt mixtures resistance against plastic deformation with Marshall Method’’. Manufacturing and preparing methods of specimens of asphalt mixture for asphalt mix design is performed based on Standard Method (ASTMD1559). According to the Marshall Test results, in the asphalt specimens ,optimum percentage of bitumen is 6%. To produce asphalt samples, at first, weight ratio of necessary aggregate for each sample was carefully measured (specified gradation and Marshall density mold); then it was heated for 24 hours at 160 ºC in a heater. Finally, aggregate was brought out and well mixed with optimum bitumen ratio and thrown in mold. According to AASHTO T245, to compact the sample, 75 blows imposed on both sides of samples using an automatic Marshall hammer. In this research, about 120 samples of asphalt mixture made of additive SSP and CR were studied. These samples are shown in Figure 3.

3.3 Testing Program

3.3.1 Bitumen Conventional Tests

To evaluate the effects of CR and SSP on the specifications of bitumen, experimental tests of penetration degree, softening point, ductility and flash point were carried out on the modified bitumen. Thermal sensitivity of the modified bitumen samples, which is the change of consistency parameter as a function of temperature, was evaluated by a penetration index (PI) as well as the results of the degree of penetration and softening point tests. The PI is calculated by

$$PI = \frac{1952 - 500\log Pen_{25} - 20SP}{50\log Pen_{25} - SP - 120} \qquad (1)$$

where Pen_{25} is the penetration grade of bitumen at 25 °C, and SP is the bitumen’s softening point temperature.

3.3.2 Marshall Strength

Marshall stability and flow tests were performed on the modified and unmodified compacted specimens according to ASTM D1559. In the Marshall test, as an empirical test, the cylindrical compacted specimens (100 mm in diameter by approximately 63.5 mm in height) were immersed in water at 60 ˚C for 25–30 min.

Figure 3. Compacted asphalt mixture samples

Then, the samples were brought out from the water and their outer surface were dried with cloth napkins; then, they were loaded to failure using curved steel loading plates along the diameter at constant compression rate of 51 mm/min. The MQ, which 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.

3.3.3 ITS

The indirect tensile test can be used to predict the fatigue potential, moisture sensitivity, and determination of tensile properties of asphalt mixtures.

The ITS of each mixture was measured in accordance with AASHTO T283 method and at a temperature of 25 °C and loading rate of 51 mm per minute. Three compacted specimens from each mixture were conditioned in air at 25 °C for 24-h prior to testing the ITS. ITS was calculated according to Equation (2):

$$ITS = \frac{2P_{\max}}{\pi d} \qquad (2)$$

where P_{max} is the failure load (N) of the samples under diametric compressive loading, d and h are the mean values of the diameter (mm) and height (mm) of the Marshall samples, respectively.

3.3.4 Porosity

In this study, the effective porosity calculated using Eq. (3) was used for the basis of comparison.

$$\text{Porosity}(\%) = 1 - \frac{\left(\frac{M_{dry} - M_{sub}}{\rho_w}\right)}{V_T} \qquad (3)$$

The effective porosity only accounts for the water accessible air voids while the total porosity (or air void content) accounts for all the air voids within a specimen. However, the effective porosity was used because only the accessible voids contribute to the permeability of the specimens. In this procedure, the volume of the specimen is determined by measuring the diameter and height in at least three different locations to determine the average diameter and height. These dimensions were then used to calculate the total volume (V_T) of the cylindrical specimen. Next, the dry mass of the specimen was recorded (M_{dry}) and the specimen was then submerged in a 25 °C water bath for 30 min. After 30 min, the specimen was inverted 180 degree and tapped five times on the bottom of the water bath to release air entrapped in the specimen. Tapping was done in such a manner that the entrapped air was made sure to be released while being careful not to damage the specimen. After tapping, the specimen was again inverted 180 degree and the submerged mass was recorded (M_{sub}). The porosity of each specimen was calculated using Eq. (4), where ρ_w is the density of water.

3.3.5 Permeability

Permeability of all the samples was measured using constant-head procedure. According to Equation (4), permeability of the compacted porous asphalt mixtures was calculated:

$$K = \frac{QL}{Aht} \qquad (4)$$

where Q is the volume of accumulated water, A the cross-section of the compacted asphalt mixture, t the time collecting water, L the length of asphalt sample, and h the height of the water inlet to the water outlet (Figure 4).

4. Results and Discussions

4.1 Effects of SSP and CR on the Bitumen Strength Parameters

As shown in Figure 5, unmodified bitumen has the highest penetrating ratio. According to the results, the penetration values of CR modified bitumen decrease on increase of the SSP content.

Figure 4. Permeability testing device

Figure 5 also shows that 10% SSP ratio has the most effect on reducing the bitumen penetration value. These modified samples prevent asphalt mixture from rutting at high temperature and reduce its temperature susceptibility. The results also show that the addition of SSP makes the modified bitumen harder and more consistent than control bitumen.

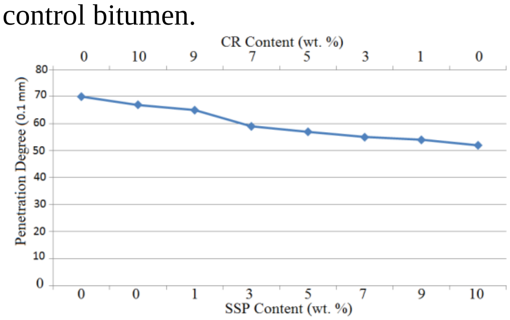

Figure 5. Penetration degree test results

Bitumen softening point with various additives is shown in Figure 6. Results show that SSP increased the bitumen softening point more than CR. As a result, the softening point of the modified samples was observed to be higher than that of the unmodified samples. This leads to increasing bitumen efficiency at high temperature. The highest softening point belongs to the bitumen sample with 10% SSP. It has also been observed that the increase in the softening point of control bitumen was significant when SSP was added in percentages from 9 to 10%. Greater softening point causes less temperature susceptibility and low degree of changes in its viscosity. Thus, with the addition of SSP the modified bitumen will become less susceptible to temperature changes.

Ductility test method provides one measure of tensile properties of bituminous materials. Ductility of bitumen to various additives is shown in Figure 7. Results show that ductility is decreased with increase of SSP and decrease of CR content. The highest ductility belonged to the unmodified bitumen and the lowest ductility belonged to the bitumen sample with 9% SSP and 1% of CR content. The results also show that with increase of SSP content to 10%, and decrease in CR to 0%, a huge drop in ductility occurred. It seems that the decrease in the ductility value may be due to omitting the CR content, and therefore decrease interlocking of polymer molecules with bitumen.

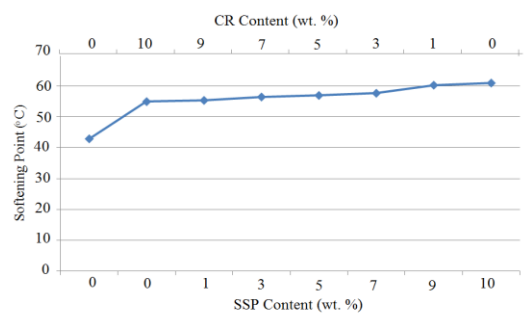

Figure 6. Softening point test Results

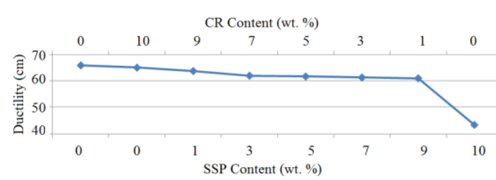

Figure 7. Ductility test Results

According to the results shown in Table 7, it can be seen that increase in SSP content led to increase in PI. Generally, a higher PI implies a lower thermal sensitivity. Therefore, PI values increase with increasing amounts of SSP and decreasing amounts of CR. Then the thermal sensitivity of modified bitumen decreases with the addition of SSP to the mix and the resistance to low temperature increases.

4.2 Effects of SSP and CR on the Marshall Stability Parameters

Results of Marshall tests are shown in Figures 8 and 9. According to the results, the modified asphalt mixtures are more stable than the unmodified asphalt mixtures (except the asphalt mixture with 100% CR). The highest Marshall stability belongs to the asphalt mixture with 100% SSP. And one more, Marshall stability increased due to replacing SSP with CR. Figure 8 shows that the Marshall stability was reduced due to adding CR to bitumen. Suspension and indissolubility of a large amount of CR in bitumen may be the reason of this reduction.

Figure 9 shows Marshall flow test results. This figure indicates that the Marshall flow value in all the modified mixtures is less than that of the unmodified asphalt mixtures and the lowest flow value belongs to the modified mixture with 100% SSP.

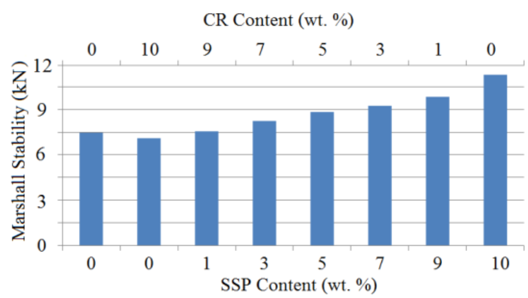

Figure 8. Marshall stability test results

Figure 10 shows the MQ valuethat is equal to the ratio of Marshall stability to Marshall flow. The figure also shows the ratio of stability to shear stress, permanent deformation, and cracking. Moreover, it is indicated in this figure that all the modified asphalt mixtures have higher MQ than the unmodified asphalt mixtures, which may be due to high viscosity of the modified bitumen to unmodified bitumen. The highest MQ belongs to the asphalt mixture with 100% SSP, showing this sample to have the greatest hardness than the other asphalt samples.

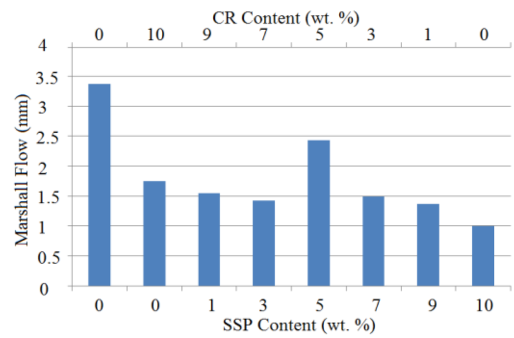

Figure 9. Marshall flow test results

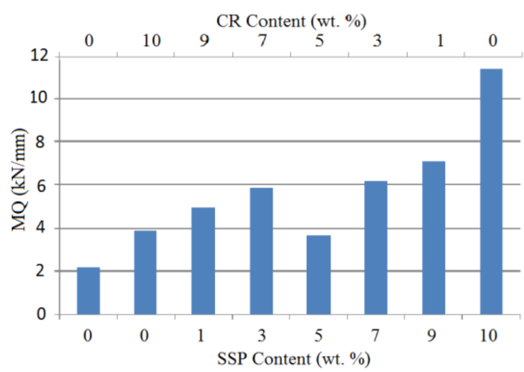

Figure 10. MQ results

4.3 Effects of SSP and CR on the Tensile Strength Parameters

Figure 11 shows the results of ITS test. This figure indicates that the ITS of the modified samples is higher than that of the unmodified samples.

Table 7. PI of unmodified and modified specimens

SSP(CR) content (wt.%)	0(0)	0(10)	1(9)	3(7)	5(5)	7(3)	9(1)	10(0)
PI	-2.395	0.73	0.74	0.74	0.75	0.81	1.29	1.32

Moreover, the ITS increased due to increasing SSP ratio. The highest ITS belongs to modified asphalt samples with 100% SSP. It can be clearly seen that the addition of the additives seems to have a positive effect on the strength of the samples.

4.4 Effects of SSP and CR on the Porosity Parameters

Figure 12 shows the changing porosity of the modified and unmodified asphalt mixtures. As seen in this figure, porosity of the modified asphalt mixtures is higher than that of the unmodified asphalt mixtures. Statistically, porosities of 10% CR, 9% SSP+1% CR and 10% SSP mixtures are nearly the same. The addition of CR and SSP to porous asphalt increased the effective porosity. It seems that this reaction may be caused by decreases in ductility values.

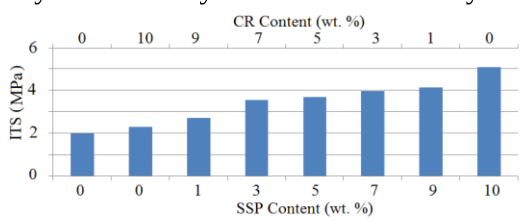

Figure 11. ITS test results

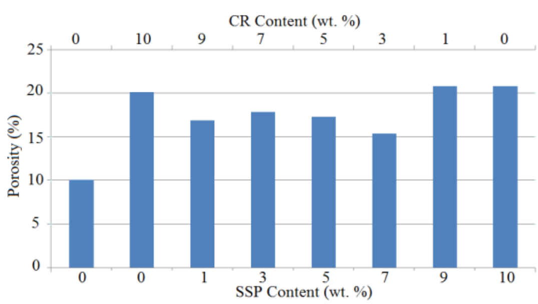

Figure 12. Porosity of porous asphalt mixtures

4.5 Effects of SSP and CR on the Permeability Parameters

Figure 13 shows the changing permeability of the asphalt mixture. According to the results, permeability of the modified asphalt mixture is higher than the unmodified asphalt mixture and the highest permeability belongs to the asphalt mixture with 100% SSP. Increasing permeability of the modified asphalt mixture may occur due to reducing thickness of bitumen layers between aggregate pieces, increasing bitumen viscosity (for adding modifier), or having suspended particles and filler (SSP,CR) that lead to increasing flow channels within the mix. On the other hand, the modified asphalt mixtures, compared to the unmodified asphalt mixtures, have greater No. of pores within the mix due to higher viscosity and stability of the modified bitumen against draindown. However, the unmodified asphalt mixture, due to having great draindown of pure bitumen, has sealed cavities and fewer No. of pores.

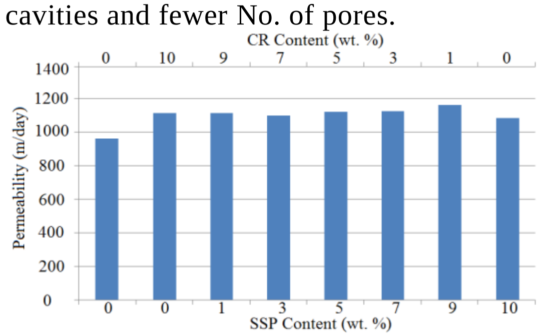

Figure 13. Permeability of porous asphalt mixtures

5. Comparisons of the Results of This Study and Previous Study

Ghasemi and Marandi (2013) measured the effectiveness of modified bitumen and asphalt mixtures with CR and recycled glass powder (RGP). In their study, 60/70 bitumen of Isfahan Refinery was used. Seven bitumen samples with the combination of CR-RGP were produced and tested. The best results belong to the modified asphalt mixture samples with 5% RGP and 5% CR. Table 8 shows the improvement of the results of modified samples compared to unmodified samples in the present and pervious researches. Moreover, Table 8 indicates that in both the studies, different parameters experienced an increase in all the modified samples to base bitumen. This comparison revealed that the combination of SSP and CR functioned better than the combination of RGP and CR.

Table 8. Comparison between the improvement of results of current studies and previous ones

	Optimum Modifier	Marshall stability (% increase)	MQ (% increase)	ITS (% increase)
Pervious study	RGP 5% +CR 5%	+53%	+122%	+56%
Current study	SSP 9% + CR 1%	+31%	+222%	+106%

6. Conclusions

The following conclusions can be drawn based on this study:

(1) SSP can increase the softening point and ductility of CR modified bitumen and reduce the penetration degree. Moreover, viscosity is reduced due to increasing SSP.

(2) The use of SSP as modifier increases the Marshall stability, MQ, ITS and porosity of the modified porous asphalt with CR.

(3) When CR was replaced by SSP, comparable even higher permeability was observed.

(4) The use of SSP can increase the mechanical properties of modified porous asphalt with CR. The replacement ratio of up to 90% by weight for SSP as modifier has relatively major influence on the mechanical properties of porous asphalt.

(5) SSP has the potential to improve the specification of CR modified bitumen and porous asphalt.

(6) The replacement of SSP with a portion of CR has positive environmental effects by returning a quantity of SSP abundant in nature.

(7) Partial substitution of CR with SSP in the modification of porous asphalt improved PI, the Marshall strength, ITS, porosity, and permeability by 19%, 67%, 117%, 5% and 5% respectively.

8. References

-Ameri, M., Hesami, S. and Goli, H. (2013) “Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag”, Construction and Building Materials, Vol. 49, No. 1, pp.611-617. [doi:10.1016/j.conbuildmat.2013.08.034]

-Baumgardner, G. L., Hardee, J. R., Negulescu, I. I., Williams, E. R., Howard, I. L. and John, R. (2014) “Quantitative analysis of functional polymer in recycled tyre rubber used in modified asphalt binders”, , Road Materials and Pavement Design, Vol. 15, No. 1, pp. 263–278. [doi:10.1080/14680629.2014.927413]

-Bolden, J., Abu-Lebdeh, T. and Fini, E. (2013) “Utilization of recycled and waste materials in various construction applications”, American Journal off Environmental Sciences, Vol. 9, No. 1, pp. 14-24.

[doi : 10.3844/ajessp.2013.14.24]

-Du, Y., Bo, Y., Jin, F. and Liu, C. (2016) “Durability of reactive magnesia-activated slag-stabilized low plasticity clay subjected to drying–wetting cycle”, European Journal of Environmental and Civil Engineering, Vol. 20, No. 2, pp. 215-230. [doi:10.1080/19648189.2015.1030088]

-Frigio, F., Pasquini, E., Ferrotti, G. and Canestrari, F. (2013) “Improved durability of recycled porous asphalt”, Construction and Building Materials, Vol. 48, No. 1, pp. 755-763. [doi:10.1016/j.conbuildmat.2013.07.044]

-Ghasemi, M. and Marandi, S.M. (2014) “Engineering Properties of SMA Mixtures/Polymer/RGP Blends”, International Journal of Transportation Engineering (IJTE), Vol. 2, No. 2, pp. 97-106.

-Ghasemi, M. and Marandi, S.M. (2013) “performance improvement of a crumb rubber modified bitumen using recycled glass powder”, journal of Zhejiang university-science A, Vol. 14, No. 11, pp. 805–814. [doi:10.1631/jzus.A1300053]

-Goli, A., Ziari, H. and Amini, A. (2016) “Evaluating the performance of crumb rubber modified binders used in Isfahan Province”, International Journal of Transportation Engineering (IJTE), Vol. 4, No. 2, pp. 97-107.

-González, V., Martínez-Boza, F.J., Gallegos, C., PérezLepe, A., and Páez, A. (2012) "A study into the processing of bitumen modified with tire crumb rubber and polymeric additives", Fuel Process, Vol. 95, No. 1, pp. 137-143. [doi:10.1016/j.fuproc.2011.11.018]

-Lan, W., Ghani, R., Yongming, X. and Gang, C. (2015) "Microstructure and rheological properties of aged and unaged polymer-modified asphalt binders", Road Materials and Pavement Design, Vol. 16, No. 3, pp. 592-607. doi:10.1080/14680629.2015.1021368]

-Liu, Q., Schlangen, E., García, Á., and Ven, M. (2009) "Induction heating of electrically conductive porous asphalt concrete", Construction and Building Materials, Vol. 24, No. 1, pp. 1207–1213. [doi:10.1016/j.conbuildmat.2009.12.019]

-Luo, S., Lu, Q. and Qian, Z. (2015) "Performance evaluation of epoxy modified open-graded porous asphalt concrete", Construction and Building Materials, Vol. 76, No. 1, pp. 97-102. [doi:10.1016/j.conbuildmat.2014.11.057]

-Lyons, K.R. and Putnam, B.J. (2013) "Laboratory evaluation of stabilizing methods for porous asphalt mixtures", Construction and Building Materials, Vol. 49, No. 1, pp. 772–780. [doi:10.1016/j.conbuildmat.2013.08.076]

-Mo, L.T., Huurman, M., Wu, S.P. and Molenaar, A.A.A. (2011) "Bitumen–stone adhesive zone damage model for the meso-mechanical mixture design of raveling resistant porous asphalt concrete", International Journal of Fatigue, Vol. 33, No. 1, pp. 1490-1503. [doi:10.1016/j.ijfatigue.2011.06.003]

-Moghadasnejad, F., Aghajani, P., Modarres, A. and Firoozifar, H. (2012) "Investigating the properties of crumb rubber modified bitumen using classic and SHRP testing methods", Construction and Building Materials, Vol. 26, No. 1, pp. 481-489. [doi:dx.doi.org/10.1016/j.conbuildmat.2011.06.048]

-Mohammadzadeh Moghaddam A., Ziaee, S.A., Farhad Mollashahi, H. and Jalili Qazizadeh, M. (2014) "Effects of waste fibers stabilizers on the draindown and moisture damage sensitivity properties of SMA mixtures", International Journal of Transportation Engineering (IJTE), Vol. 2, No. 2, pp 155-165.

-Poulikakos, L. and Partl, M.N. (2012) "A multi-scale fundamental investigation of moisture induced deterioration of porous asphalt concrete", Construction and Building Materials, Vol. 36, No. 1, pp.1025-1035. [doi:10.1016/j.conbuildmat.2012.04.071]

-Qian, Z. and Lu, Q. (2015) "Design and laboratory evaluation of small particle porous epoxy asphalt surface mixture for roadway pavements", Construction and Building Materials, Vol. 77, No. 1, pp. 110-116. [doi:10.1016/j.conbuildmat.2014.12.056]

-Ruth, B.E., Tia, M., Jonsson, G. and Setze, J.C. (1997) "Recycling of asphalt mixtures containing crumb rubber", Final Report. FL/DOT/MO D510717. University of Florida. Florida Department of Transportation, 221p.

-Sadeghpour Galooyak, S., Palassi, M., Goli, A. and Zanjirani Farahani, H. (2015) "Performance Evaluation of Nano-silica Modified Bitumen", International Journal of Transportation Engineering (IJTE), Vol. 3, No. 1, pp. 55-66.

-Shahiri, J. and Ghasemi, M. (2017) "Utilization of Soil Stabilization with Cement and Copper Slag as Subgrade Materials in Road Embankment Construction", International Journal of Transportation Engineering (IJTE), Vol. 5, No. 1, pp. 45-58.

-Subhy, A., Lo Presti, D. and Airey, G. (2015) "An investigation on using pre-treated tyre rubber as a replacement of synthetic polymers for bitumen modification", Road Materials and Pavement Design, Vol. 16, No. 1, pp. 245-264. [doi:10.1080/14680629.2015.1030826]

-Taherkhani, H., Firoozei, F. and Bolouri Bazaz, J. (2016) "Evaluation of the mechanical properties of the cement treated cold-in-place recycled asphalt mixtures", International Journal of

Transportation Engineering (IJTE), Vol. 3, No. 4, pp. 301-312.

-Taherkhani, H., Moghadas Nejad, F., Khodaii, A. and Saleh Ahari, A. (2017) "Investigating the effects of temperature and loading frequency on the resilient modulus of SBS polymer modified asphalt concrete in dry and saturated conditions", International Journal of Transportation Engineering (IJTE), Vol. 5, No. 1, pp. 1-16.

-Ziaee, S.A., Kavussi, A., Jalili Ghazizadeh, M. and Mohammadzadeh Moghadam, A. (2014) "Evaluation of long term ageing of asphalt mixtures containing EAF and BOF steel slags", International Journal of Transportation Engineering (IJTE), Vol. 2, No. 3, pp. 245-265.

-Ziari, H., Moniri, A., Ayazi, M. and Nakhaei, M. (2016) "Investigation of rutting performance of wma mixtures containing copper slag", International Journal of Transportation Engineering (IJTE), Vol. 3, No. 3, pp. 227-235.