Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 625.85

DOI: 10.34910/MCE.113.9

Effect of temperature on permanent deformation of polymer-modified asphalt mixture

N. Lotfi Omran[a] ✉, ***K. Rajaee***[b], ***S.M. Marandi***[a]

[a] *Shahid Bahonar University of Kerman, Kerman, Iran*

[b] *Graduate University of Advanced Technology, Kerman, Iran*

✉ *navid.lotfii.omran@gmail.com*

Keywords: asphalt mixtures, polymers, temperature, dynamic creep test, permanent deformation

Abstract. This study aims to evaluate the permanent deformation of unmodified and styrene-butadiene-rubber (SBR) modified asphalt mixtures using dynamic creep test. The purpose was to assess the effect of SBR as one of the most plentiful and low-cost polymers in Iran on rutting resistance of asphalt mixtures in the regions with hot climate, such as the areas around the “Persian Gulf”, and the central deserts of the “Iran Plateau”. First, the critical gradation of aggregates with higher permanent deformation was determined. Then, the aggregates with critical gradation were mixed with the optimum amount of bitumen modified by different amounts of SBR, and tested to obtain an optimum SBR content with lower permanent deformation. Finally, the unmodified and SBR-modified asphalt mixtures with optimum SBR content (6%wt) were tested at 40 and 50 ˚C as the simulated ambient temperatures in order to evaluate the effect of SBR and rising temperature on rutting resistance of the asphalt mixtures. In addition, the flow number (FN) of asphalt mixtures is calculated according to Goh and You method. Results showed that with addition of 6% SBR, the permanent strains of asphalt mixtures decreased by 39 and 60%, and the creep modulus increased by 64 and 133% at 40 and 50 ˚C, respectively. Furthermore, with the temperature rising from 40 to 50 ˚C, the permanent strains of asphalt mixtures containing 0 and 6% SBR increased by 61 and 5%, and their creep modulus decreased by 34 and 6%, respectively. The FNs of unmodified samples were obtained 8416 and 9728 loading cycles at 40 and 50 ˚C, respectively. In contrast, up to the last loading cycle, the SBR-modified samples did not experience the tertiary flow at both ambient temperatures. These results let us conclude that the SBR-modified bitumen is able to significantly reduce the permanent deformations, and enhance the resilience and creep modulus of asphalt mixtures; moreover, it can minimize the negative effects of rising temperature on their engineering properties.

Citation: Lotfi Omran, N., Rajaee, K., Marandi, S.M. Effect of temperature on permanent deformation of polymer-modified asphalt mixture. Magazine of Civil Engineering. 2022. 113(5). Article No. 11309. DOI: 10.34910/MCE.113.9

1. Introduction

In recent decades, with progress in all fields of science, road construction was also included in this scientific development. The mixture of stone materials with bitumen provided a novel product called asphalt mixture. This material has a limited service life like other construction materials. However, two main factors, traffic loads and climate condition, cause more decrease in service life of asphalt mixtures than other construction materials. On the other hand, in recent years the costs of roads construction and their maintenance have increased. Thus, damages of asphalt layer of flexible pavements such as rutting, reflective cracking, fatigue cracking, etc., impose immense annual costs on the contractors and organizations responsible for road maintenance and operation. Rutting (permanent deformation) is one of the most common flexible pavements damages that occurs under heavy traffic loads particularly in hot climates [1, 2]. The pavement structure undergoes accumulated permanent deformations under repetitive traffic loads [3]. Permanent deformation of pavements includes two different modes: first, the compactive deformation (consolidation of layers), and secondly, the plastic deformation (asphalt shear flow) [4, 5]. In the first mode, the deformed surface is lower than the initial pavement surface and is occurs in the wheel path; and in the second mode, the deformed surface is higher than the initial pavement surface and is occurs in form of “heave” between and outside of wheel paths due to shear flow of asphalt materials [5]. Presence of depressions and heaves on the pavement surface may cause serious hazards for vehicles. The resistance of different types of asphalt mixtures with the ordinary bitumen against high temperatures depends on the type and content of bitumen, shape and gradation of aggregates, as well as climate condition. Therefore, in view of high economical and time costs of annual repair of road surface, studying and introducing economically and technically optimized methods to improve the thermal stability and overcome the rutting of road surface is inevitable.

Binder modification using petrochemical products such as polymers is an effective method for improving the resistance of asphalt mixtures against the common damages [6] including fatigue cracking [7, 8], moisture susceptibility [7, 9], rutting in high temperature [5, 7, 8, 10–12], cracking in low temperature [10–13], etc. The styrene-butadiene rubber (SBR) is one of the polymers used for bituminous binder modification [13, 14] which is produced by copolymerization of styrene and butadiene [7]. SBR is a member of elastomers family which can improve the rheological properties, flexibility, thermal and fatigue cracking, and moisture susceptibility of asphalt mixtures [7]. The butadiene soft monomer makes the binder more flexible, while the styrene hardener monomer increases the binder softening point [7]. In addition, SBR has higher cracking resistance and lower cost in comparison to another binder modifier, styrene-butadiene-styrene (SBS) [11]. Several researchers investigated the performance of polymer-modified asphalt mixtures [5, 7, 8, 10, 13, 15–20] Khodaii and Mehrara [5] investigated the permanent deformation of unmodified and SBS-modified asphalt mixtures using dynamic creep test. They used 4, 5 and 6% of SBS as a binder modifier and concluded that the SBS-modified asphalt mixtures had lower permanent deformation and higher compactibility than unmodified asphalt mixture. Hao et al. [17] used the mixture of SBR and polyphosphoric acid (PPA) to improve different properties of asphalt and asphalt mixtures. They demonstrated that the combination of 0.75% PPA/2.5% SBR shows excellent anti-deformation property and cracking behavior. Zhai et al. [10] used the combination of SBR and nano-$CaCO_3$ to evaluating the performance of asphalt mixtures. Their results showed that 5% nano-$CaCO_3$/4% SBR significantly improved deformation resistance performance and provided superior rutting resistance of asphalt mixture compared to SBS-modified asphalt mixture. Vamegh et al. [7] assessed the moisture susceptibility and permanent deformation of modified asphalt mixtures by using the blends of SBR and polypropylene as inexpensive asphalt modifiers. Their experimental results indicated that the moisture resistance and retained Marshall stability of polymer blends-modified samples were approximately identical to SBS-modified samples. Moreover, with the increase in the SBR content, the indirect tensile strength, moisture resistance, ductility under repetitive loads and rutting resistance of asphalt mixtures increased as well. Ameri et al. [8] studied the fatigue life of asphalt mixture modified by styrene-butadiene rubber (SBR), poly butadiene rubber (PBR) and their residual wastes. They concluded that all used polymers and their residual wastes enhanced the fatigue resistance of asphalt mixtures, while the residual waste polymers with lower costs had an effect similar to that of the SBR and PBR. Liu and Liang [20] investigated the influence of SBR and SBS on properties of cement emulsified asphalt mortar (CEAM). Their results indicated that the flow time and air content of fresh CEAM decreased and increased with the SBR and SBS contents, respectively. In addition, the type and content of modifiers had less effect on compressive strength of CEAM at early age. Nevertheless, at later age, the compressive strength of SBS-modified CEAM reduced obviously, which was related to the non-uniformity and larger air content of this mixture. The flexural strength of modified CEAM had similar trend for both modifiers. The authors also said that after 100 freeze-thaw cycles, the quality of SBR-modified CEAM increased obviously.

There are technical and economical considerations of using appropriate binder modifiers and aggregate gradations for each special condition of the roads such as traffic loads and climate conditions. In addition, little attention is paid to the temperature effect on permanent deformation of SBR-modified asphalt mixtures as a common economical mixture in the literatures. Thus, this study aimed to investigate the permanent deformation of unmodified (dense and coarse graded asphalt mixtures) and SBR-modified asphalt mixtures under rising temperature using dynamic creep test. The flow number of the asphalt mixtures as a rutting indicator [21, 22] was determined using Goh and You method [23]. In the country of research, two main factors affected the selection of SBR as an asphalt modifier. First, very low price of SBR compared to SBS; and secondly, suitable performance of SBR-modified asphalt mixtures against many common damages of asphalt mixtures at both high [12, 24] and low temperatures [8, 10, 14, 25]. These properties are suitable for regions with hot summers and cold winters, such as central deserts of “Iran plateau”, and the communication roads of commercial ports around the “Persian Gulf” with very hot climate and high volume traffic of heavy vehicles.

2. Materials

2.1. Stone materials

The siliceous filler and crushed aggregates were used as stone materials. To evaluation the effect of aggregate gradation on permanent deformation of asphalt mixtures, two gradations of aggregates known as coarse and dense grades were used. These gradations were in the permitted range (upper and lower limits) of aggregate gradations for asphalt mixtures according to the Journal No. 101 of Plan and Budget Organization of Iran, with the subject of "General Technical Specifications of the Road". The particle size distributions and some engineering properties of the used stone materials (dense and coarse graded) are shown in Figure 1 and Table 1, respectively.

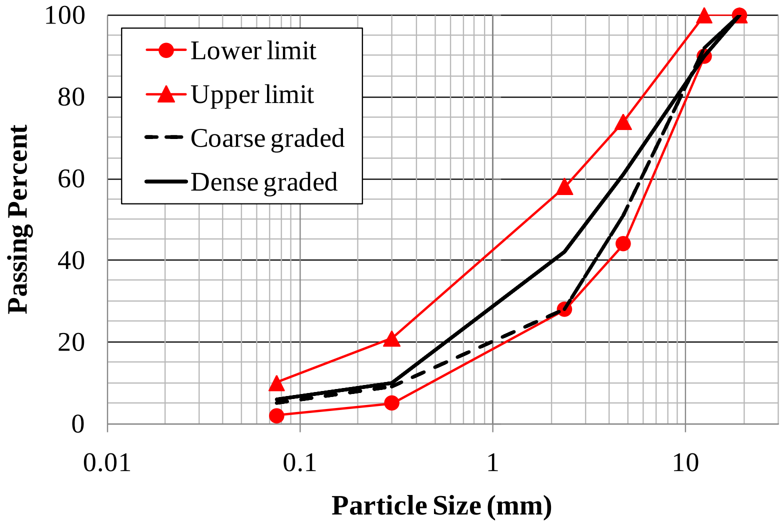

Figure 1. Particle size distribution of used stone materials (dense and coarse graded).

Table 1. Engineering properties of stone materials.

Property	Test method	Value	Standard value
Los Angeles abrasion loss (%)	AASHTO T96	29	≤25[a]
Two fractured faces (%)	ASTM D5821	100	100[a]
Flakiness index (%)	BS 812-105.1	10	≤10[b]
Elongation index (%)	BS 812-105.2	10	≤10[b]
Bulk specific gravity of coarse aggregates	AASHTO T85	2.659	
Absorption of coarse aggregates (%)	AASHTO T85	0.7	≤2.5[a]
Bulk specific gravity of fine aggregates	AASHTO T84	2.592	
Absorption of fine aggregates (%)	AASHTO T84	1.7	≤2.5[a]
Bulk specific gravity of mineral filler	AASHTO T84	2.721	

[a] According to Journal No. 101 of Plan and Budget Organization of Iran, with the subject of "General Technical Specifications of the Road".

[b] According to MS-2.

2.2. Binder

The used bitumen as a binder with penetration grade of 60–70 was produced in Isfahan oil refinery. Some engineering properties of bitumen are presented in Table 2.

Table 2. Engineering properties of bitumen.

Property	Test method	Value	Standard value[a]
Specific gravity at 25 ˚C	AASHTO T228 (ASTM D70)	1.018	
Penetration at 25 ˚C (100g-5s) (0.1mm)	AASHTO T49 (ASTM D5)	66	60-70
Softening point (˚C)	AASHTO T53 (ASTM D36)	50	49-56
Ductility at 25 ˚C (cm)	AASHTO T51 (ASTM D113)	>100	≥100
Solubility in trichloroethylene[b]	AASHTO T44 (ASTM D2042)	99.7	≥99
Flash point (˚C)	AASHTO T48 (ASTM D92)	285	≥232
Kinematic viscosity at 120 ˚C (cSt)	AASHTO T201 (ASTM D2170)	565	
Kinematic viscosity at 135 ˚C (cSt)	AASHTO T201 (ASTM D2170)	321	
Kinematic viscosity at 160 ˚C (cSt)	AASHTO T201 (ASTM D2170)	133	
Thin-Film of bitumen (163 ˚C-5h)	AASHTO T179 (ASTM D1754)	+	≤0.8
Heating loss (%)	–	0.04	
Penetration index (PI)	–	-0.53	

[a] According to the Journal No. 234 of Plan and Budget Organization of Iran, with the subject of "Iran Highway Asphalt Paving Code".

[b] Conducted by CC4.

2.3. Binder modifier

Granular SBR-1712 with linear molecular structure was produced in Bandar-e-Imam Petrochemical Co., and used as a binder modifier with the amounts of 4, 6 and 8%wt of the bitumen. Some engineering properties of SBR-1712 are presented in Table 3.

Table 3. Engineering properties of SBR-1712 (reported by manufacturer).

Property	Test method	Value
Volatile materials (% wt)	ASTM D1416	<0.75
Ash content (% wt)	ASTM D1416	<1.5
Organic acids (% wt)	ASTM D1416	3.9–5.7
Soaps (% wt)	ASTM D1416	<0.5
Bounded styrene (% wt)	ASTM D1416	22.5–24.5
Raw viscosity	ASTM D1646	42–52
Compound viscosity	ASTM D1646	<62
Tensile strength (kg/cm^2)	ASTM D412	>200
Ultimate elongation (35 min cured) (%)	ASTM D412	>530
300% modulus (35 min cured) (kg/cm^2)	ASTM D412	79–109

2.4. Sample preparation

2.4.1. Obtaining the optimum bitumen contents (OBC)

To obtain the optimum bitumen contents (OBC) for unmodified coarse and dense graded mixtures, the Marshall method was used according to ASTM D1559 with 75 blows on two ends of each sample. Some of the base properties of unmodified coarse and dense graded asphalt mixtures are given in Table 4.

Table 4. Base properties of unmodified asphalt mixtures.

Property	Test method	Value		Standard value[a]
		Coarse graded	Dense graded	
Optimum bitumen content (OBC) (%)	ASTM D1559	5	5.5	
Marshall stability (kg)	ASTM D1559	640	610	≥800
Specific gravity	AASHTO T166	2.41	2.407	
Air void (%)	MS-2	1.9	1.5	3-5
Flow (mm)	ASTM D1559	2.7	3	2-3.5

[a] According to AASHTO T245.

2.4.2. SBR-modified bitumen

To obtain a homogeneous SBR-modified bitumen, in premixing process, the bitumen was heated to 150 ˚C and SBR granules in desired percentages (4, 6 and 8% wt of bitumen) were added to the bitumen and mixed by a High-Shear mixer (Silverson 14RT) with the speed of 150 rpm for 5 min. After premixing process, the temperature and rotation speed of mixer were increased to 170˚C and 1000 rpm respectively, until approximate homogeneity was achieved. Then, the mixing process was continued for 75–90 min with the speed of 2000 rpm.

2.4.3. Sample preparation for dynamic creep test

In order to prepare the samples for dynamic creep test, the Marshall method was used with 75 blows on two ends of each sample. The dimensions of cylindrical samples were 101.6 mm in diameter and 63.5±1 mm in height. It is worth noting that to determine the critical aggregate gradation in terms of permanent deformation value, the unmodified asphalt mixtures with coarse and dense graded aggregates were tested using dynamic creep test first. Then, the critical aggregate gradation with higher permanent deformation was selected to prepare the SBR-modified asphalt mixtures and continue the tests. The next section contains more explanations.

3. Results and Discussion

The dynamic creep tests were carried out on the samples using Universal Test Machine (UTM 14P) according to Australian code AS 2891.12.1. The used setup of UTM 14P and testing conditions are shown in Table 5.

Table 5. The used setup of UTM 14P and testing conditions.

Property	Value
Pre-loading stress (KPa)	10
Pre-loading time (s)	50
Confining pressure (KPa)	0
Contact stress (KPa)	2
Deviator stress (KPa)	200
Wave shape	Square pulse
Frequency (Hz)	0.5
Pulse width (ms)	500
Rest period (ms)	1500
One cycle time (ms)	2000
End of loading cycles	10000
Ambient temperatures (˚C)	40 and 50

The repetitive axial stress pulse was applied to the samples and the vertical deformations were measured by the Linear Variable Displacement Transducer (LVDTs). Before the tests, the exact dimensions of each sample were measured and supplied to the device software. The UTM device was equipped with an environmental chamber to change the temperature of samples to desired ambient temperatures (40 and 50 ˚C). The main reason for selecting these ambient temperatures was to simulate the approximate normal range of maximum daily temperatures of the considered areas in the summer (the areas around the “Persian Gulf”, and the central deserts of the “Iran Plateau”). These ambient temperatures were also applied by Khodaii and Mehrara [5] for dynamic creep test on polymer-modified asphalt mixtures. The samples were placed in the testing device 2 hours prior to loading start to achieve the temperature equilibrium. After that, the pre-load compressive stress (10 KPa) was applied onto the samples by loading shaft for 50 s to eliminate any probable roughness of samples surface. This causes a uniform load distribution on the cross section of the samples. Then, the stress was reduced to 2 KPa as contact stress and the deviator stress of 200 KPa was applied to the samples for 500 ms and lifted for 1500 ms as rest period. Each of these loading and lifting is known as one cycle. The dynamic creep tests were continued up to 10000 cycles and the contact stress was applied constantly throughout the tests, even in the rest periods.

In the first stage, the coarse and dense graded mixtures were prepared using unmodified bitumen to determine the critical mix design with more permanent deformation at the highest ambient temperature (50

˚C). As shown in Figure 2, in the initial loading cycles (up to 1500 cycles), the permanent strain of coarse graded mixture was slightly higher than that for dense graded one. This can be due to more compactive deformation of coarse graded mixture because of more air voids. However, in cycles above 1500, there was a dramatic difference between the permanent strains of coarse and dense graded mixtures. So that at the end of 10000 cycles, the permanent strain of dense graded mixture (24623 μs) was about 96% higher than the coarse graded permanent strain. Like SMA mixtures, the skeleton of coarse graded mixture was built with the purpose of stress transition between the coarse aggregates, and the thin film of bitumen that covers the aggregates is more to prevent the aggregates segregation than for the load-bearing purpose. There is more bitumen content in the dense graded mixture than in the coarse graded one, and in consequence, the thermo-mechanical behavior of this mixture depends more on the properties of bitumen than that of the coarse graded mixture. Therefore, the dense graded mixture was selected as a critical mix design with high chance of the occurrence of rutting to be modified by SBR in further research.

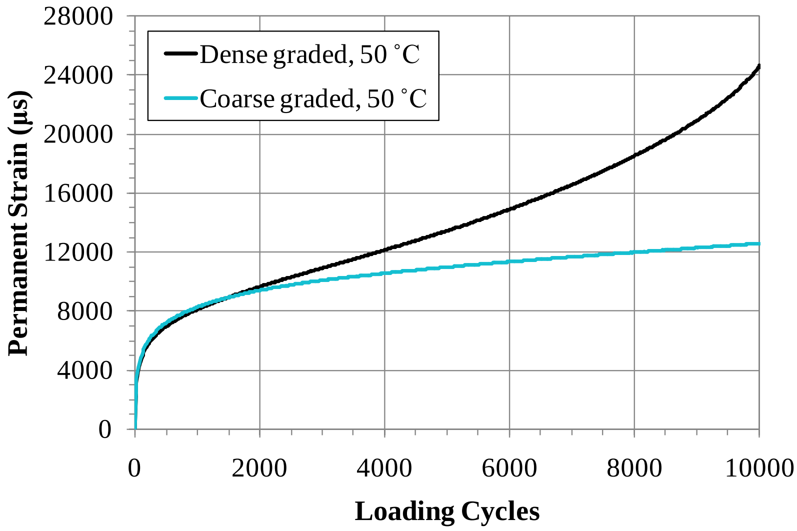

Figure 2. Permanent deformation curves of unmodified coarse and dense graded asphalt mixtures.

In the second stage, to determine the optimum SBR content, the dense graded aggregates as the critical gradation were mixed with modified bitumen by 4, 6 and 8%wt of SBR and tested by UTM device. These assumed SBR contents are close to the optimum polymer contents of some researches [5, 7, 26]. Figures 3 and 4 illustrated the permanent strains and creep modulus of unmodified and SBR-modified dense graded samples containing different SBR contents at ambient temperature of 40 ˚C, respectively. As can be seen in Figure 3, with addition of SBR into the samples, the permanent deformations were significantly decreased. This can be due to the good elastic properties of SBR and better adhesiveness of SBR-modified bitumen to the stone materials to create a stronger tensile connector between the aggregates. Moreover, as can be seen in Figure 4, with addition of SBR to the asphalt mixture, as well as with the increase of its content, the creep modulus of samples increased. The lowest permanent strain (9044 μs) and highest creep modulus (21.9 MPa) at the end loading cycle belonged to the sample containing 8% of SBR. However, the difference between the permanent strain and creep modulus of this sample and those of the 6% SBR sample (9355 μs and 21.3 MPa, respectively) was very slight. Therefore, since using as little polymeric materials as possible is more beneficial, 6% of SBR was considered an optimum content for consequent studies. The decrease in permanent deformation and increase in creep modulus of samples containing different amounts of SBR compared to unmodified sample are presented in Figure 5 (a and b). As can be seen in Figure 5a, with the increase of SBR content, the permanent deformation decreased more and more to the point the decrease in permanent deformations of samples containing 4, 6 and 8% of SBR, were 27, 39 and 41%, respectively. The decrease in permanent deformation value of the sample containing 4% of SBR has a considerable difference from that for the 6% SBR sample. On the other hand, the difference of the decrease of samples with 6 and 8% of SBR was only 2%. According to Figure 5b, the above mentioned relationships in terms of the increase in creep modulus of asphalt mixtures due to addition of SBR and increase in its content, are significant. So that in high SBR contents (6 and 8%), the creep modulus of modified asphalt mixtures increased 64 and 69%, respectively. Thus, as mentioned earlier, due to slight differences between the effectiveness of 6 and 8% of SBR on engineering properties of asphalt mixtures, 6% of SBR was chosen as the optimum content.

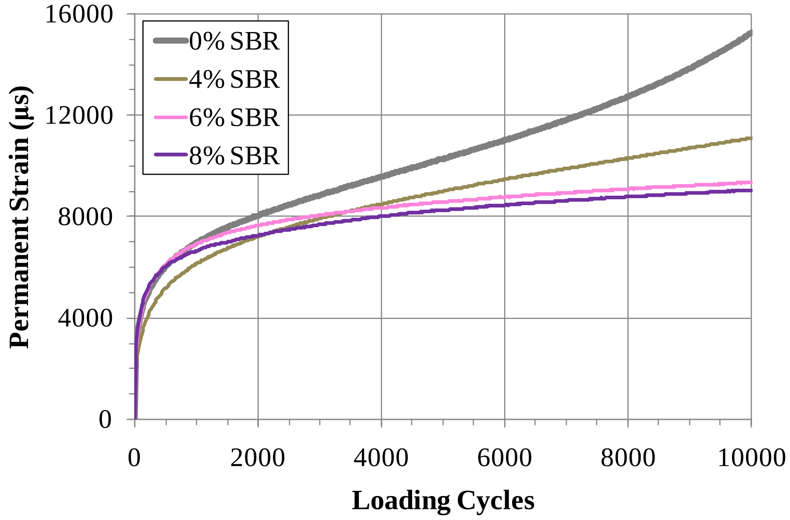

Figure 3. Permanent deformation curves asphalt mixtures containing different SBR contents at 40 ˚C.

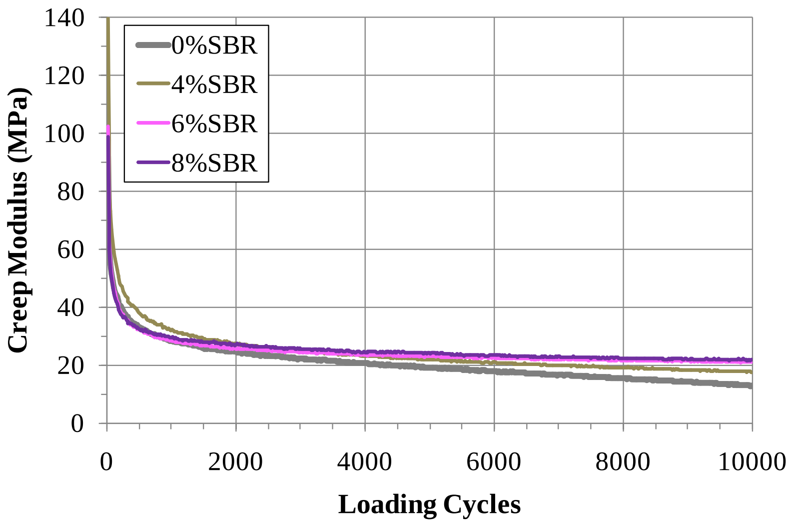

Figure 4. Creep modulus curves of asphalt mixtures containing different SBR contents at 40 ˚C.

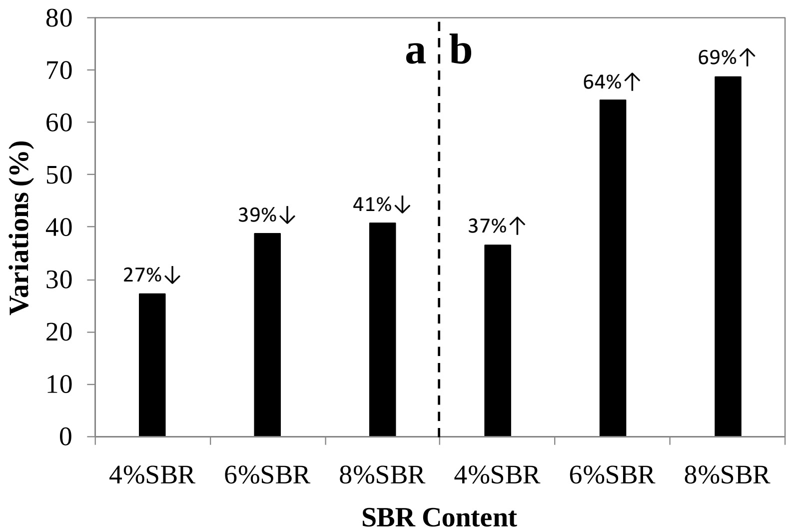

Figure 5. a) Decrease in permanent strain, and b) increase in creep modulus (Mc) of asphalt mixtures with addition of different amounts of SBR at 40 ˚C at the end of 10000 loading cycles.

In the third stage, the unmodified and modified dense graded samples with 6%wt of SBR were tested at 40 and 50 ˚C as ambient temperatures to evaluate the effect of SBR on permanent deformation of asphalt mixtures at high temperatures and in condition of rising temperature. As illustrated in Figure 6, at the last load cycle, the permanent strains of SBR-modified samples (9355 μs at 40 ˚C, and 9825 μs at 50 ˚C) were significantly lower than that for unmodified ones (15264 μs at 40 ˚C, and 24623 μs at 50 ˚C). Figure 7a also indicates that with the temperature rising from 40 to 50 ˚C, the permanent strain of unmodified sample increased by 61%, while this increase was 5% for the SBR-modified sample. This indicate that in contrast to the unmodified sample, rising temperature has a slight negative effect on the rutting resistance of SBR-modified asphalt mixtures. With rising temperature, the viscosity of binder will decrease and the asphalt mixtures undergo more and faster deformations. This decrease in viscosity is significantly more obvious in unmodified samples during rising temperature. While the binder is modified by polymeric additives like SBR, rising temperature had not remarkable effect on decreasing its viscosity due to the good temperature stability of polymer-modified bitumen. This is due to creation of polymeric network in the bitumen structure, which is more temperature-resistant. The confirmation of this is shown in Figure 7b: with 6% SBR addition, the permanent strain of asphalt mixtures decreased by 39 and 60% at 40 and 50 ˚C, respectively. This was due to a very low increase in permanent strain of SBR-modified mixtures (5%) against rising temperature, in comparison to that for unmodified ones (61%).

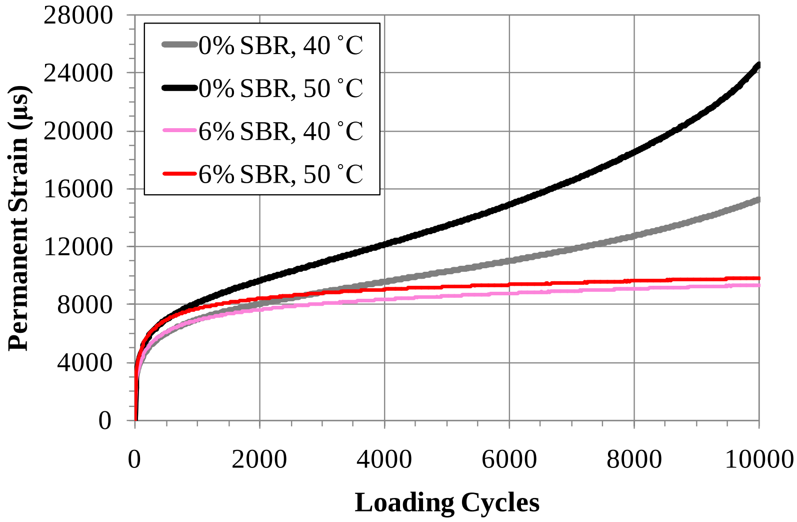

Figure 6. Permanent deformation curves of unmodified and SBR-modified asphalt mixtures at different ambient temperatures.

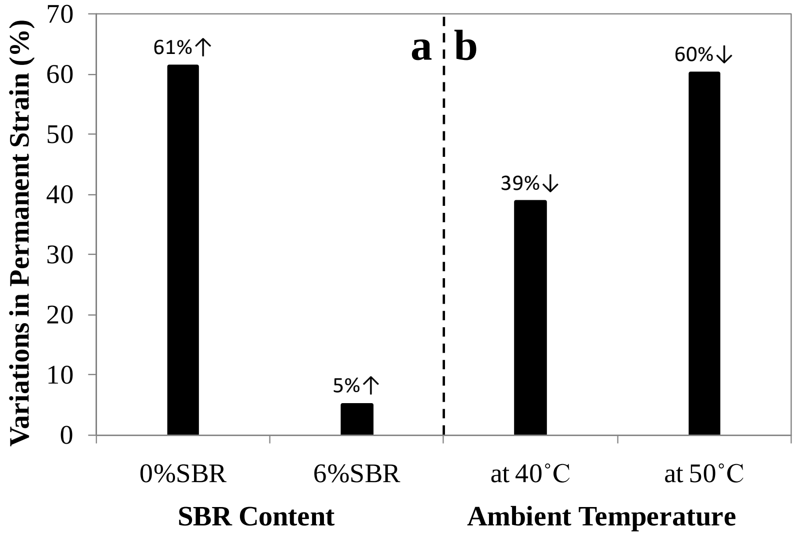

Figure 7. Increase and decrease in permanent strain of a) unmodified and modified asphalt mixture with 6% of SBR due to temperature rising from 40 to 50 ˚C, and b) asphalt mixtures with 6% SBR addition at 40 and 50 ˚C, respectively, at the end of 10000 loading cycles.

Figure 8 showed the resilient modulus of unmodified and modified samples versus the load repetition at both ambient temperatures of 40 and 50 ˚C. As indicated, the resilient modulus of modified samples was higher than that for unmodified ones at both ambient temperatures. The rising temperature caused a decrease in resilient modulus due to a drop the in binder viscosity. In initial time of loading up to around 500 cycles, a sharp rise (about 60–70 MPa) was observed in resilient modulus of all of the tested samples. As reported by Khodaii and Mehrara [5], compactive deformation has a direct relation with resilient modulus, so that the more compactive deformation the more resilient modulus. Therefore, it can be said that all of the unmodified and modified samples experienced compactive deformations in initial cycles of loading. After that, as the loading cycles continued, a slight rising or a drop were observed in their resilient modulus trends. This means that the samples were gently compacted [5]. After 6000 cycles, the unmodified samples showed a downward trend in their resilient modulus curves, while the modified samples remained at a constant level. It can be concluded that in near-to-last cycles, the compactive deformation of unmodified samples seized and the shear flow tended to initiation. On the other hand, the general trends of resilient modulus of modified samples were at approximately the same level, which means the compactive deformation of modified samples was slowly progressing up to the last loading cycle. The main reason of this lies in the elastic properties of the SBR network, which preserved the stone materials and prevented and/or postponed the excessive deformations.

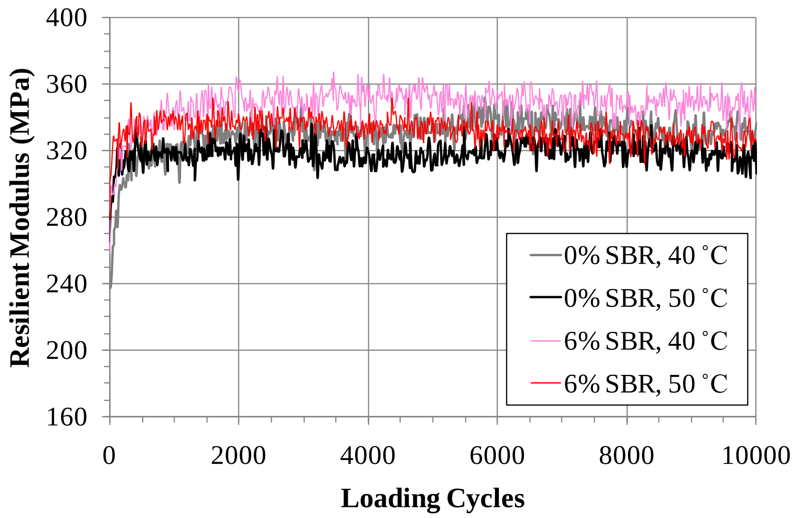

Figure 8. Resilient modulus of unmodified and SBR-modified asphalt mixtures at different ambient temperatures.

Figure 9 illustrates the variations of creep modulus of unmodified and modified samples versus the loading cycles at different ambient temperatures. As it can be seen, the creep modulus of all samples had a sharp drop (from 80–100 to around 30 MPa) in initial loading times up to around 500 cycles. This can be due to the compactive deformation of samples in initial loading cycles. After these drops, the creep modulus of SBR-modified samples reached an approximately constant level, while a 10 ˚C rise in ambient temperature had a negligible effect on their creep modulus. So that after 10000 loading cycles, the creep moduli of the samples modified by 6% of SBR at 40 and 50 ˚C, were about 21.3 and 20 MPa, respectively. On the other hand, the unmodified samples showed a decreasing trend in their creep modulus and a 10 ˚C rise in ambient temperature had a significant effect. So that the creep modulus of the sample tested at 50 ˚C (8.6 MPa) significantly decreased in comparison to the one tested at 40 ˚C (13 MPa). According to researches conducted by Gokhale et al. [4] and Khodaii and Mehrara [5], the dynamic creep test conducted by UTM device could not separate the compactive and shear deformations of asphalt mixtures from each other. But Gokhale et al. [4] reported that the compactive deformation mainly occurs in initial loading cycles while with the continuing load repetition, the compactive deformation tends to decrease and the shear deformation gradually appears. Therefore, in initial loading cycles, the UTM device considered the rising resilient modulus as permanent deformation and indicated a considerable drop in creep modulus curve [5]. As indicated in Figure 10a, with a 10 ˚C rise in temperature, the creep modulus of unmodified sample decreased by 34%. While this decrease was 6% for SBR-modified sample, which was due to the good stability of SBR-modified samples against rising temperature. Figure 10b indicates that with rising temperature, the positive effect of SBR becomes more obvious. So that at 40 ˚C, with the 6% SBR addition, the creep modulus of asphalt mixture increased by 64%. Whereas the same increase at 50 ˚C was 133%. As mentioned earlier, this can be due to the better stability of SBR-modified bitumen against rising temperature in comparison to the unmodified samples.

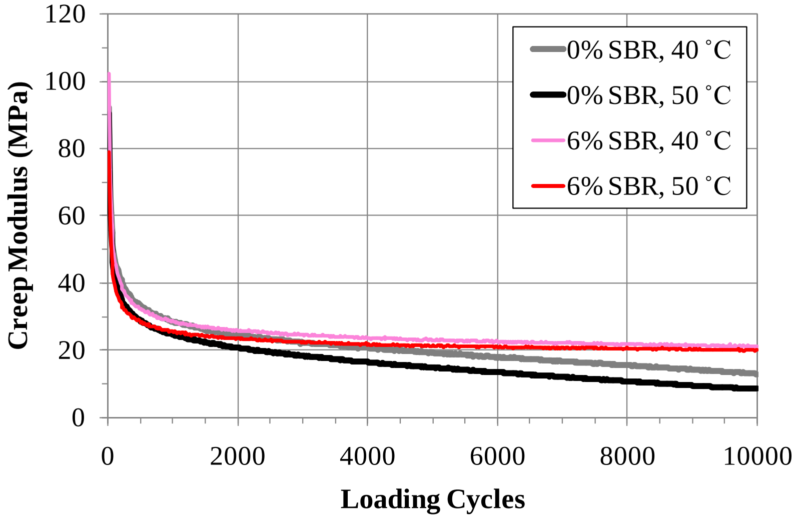

Figure 9. Creep modulus of unmodified and SBR-modified asphalt mixtures at different ambient temperatures.

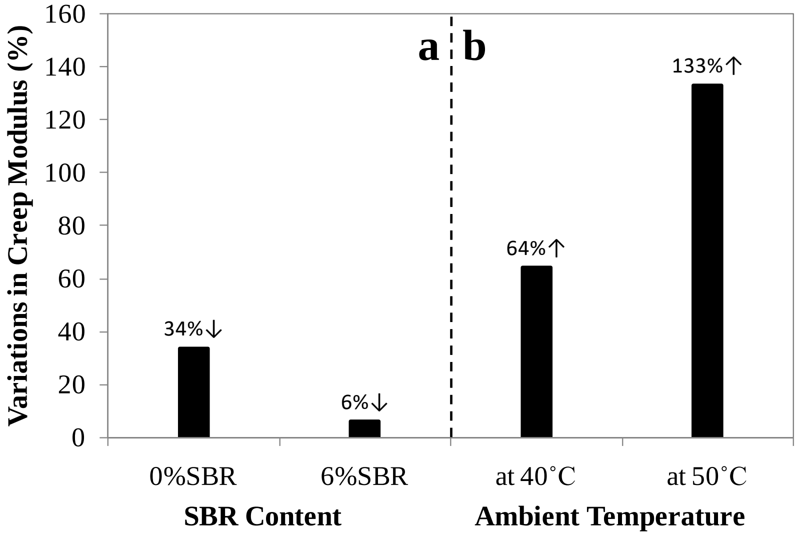

Figure 10. Decrease and increase in creep modulus of a) unmodified and modified asphalt mixture with 6% of SBR due to temperature rising from 40 to 50 ˚C, and b) asphalt mixtures with 6% SBR addition at 40 and 50 ˚C, respectively, at the end of 10000 loading cycles.

Figure 11 illustrated the variations in the ratio of creep modulus (Mc) to resilient modulus (Mr) versus the number of loading cycles. A sharp drop (about 0.18–0.29) is observable in all of the tested samples up to around 500 cycles due to the decrease of creep modulus and increase of resilient modulus (see Figures 8 and 9). This confirms the samples compaction in the initial loading cycles. As the loading cycles continued, the Mc/Mr had an approximately constant value in SBR-modified samples and rising temperature had no effect on this ratio. As shown in Figure 12a, with the temperature rising from 40 to 50 ˚C, the Mc/Mr of the unmodified sample decreased by 27%. Whereas this decrease was only 0.1% for SBR-modified sample. At 40 and 50 ˚C, with the 6% SBR addition, the Mc/Mr of the modified samples increased by 59 and 118%, respectively. The variations of Mc and Mr, as well as shear deformation were negligible and the SBR-modified samples were compacted, considering a slight increase in their resilient modulus [5]. The unmodified samples demonstrated a decreasing trend in Mc/Mr up to the last loading cycle. In view of the downward trend in their resilient modulus, it can be concluded that the proportion of compactive deformation to shear deformation is dropping [4], [5] with the shear deformation occurring in unmodified samples [5].

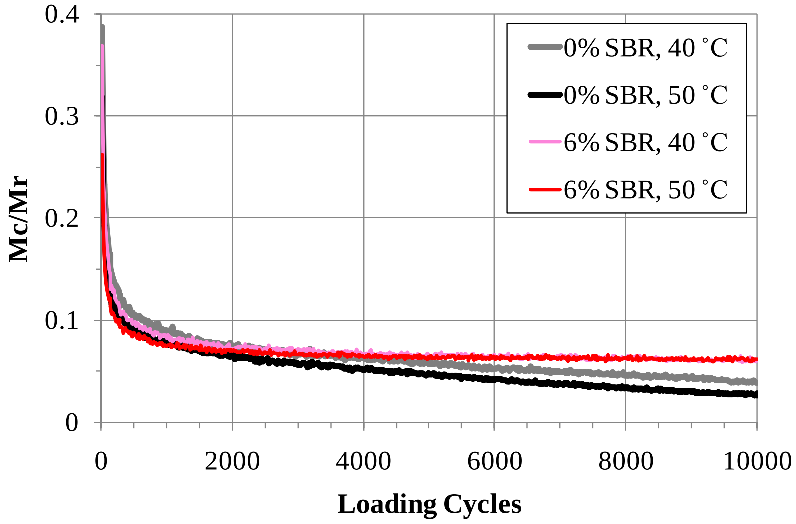

Figure 11. The ratio of creep to resilient modulus (Mc/Mr) of unmodified and SBR-modified asphalt mixtures at different ambient temperatures.

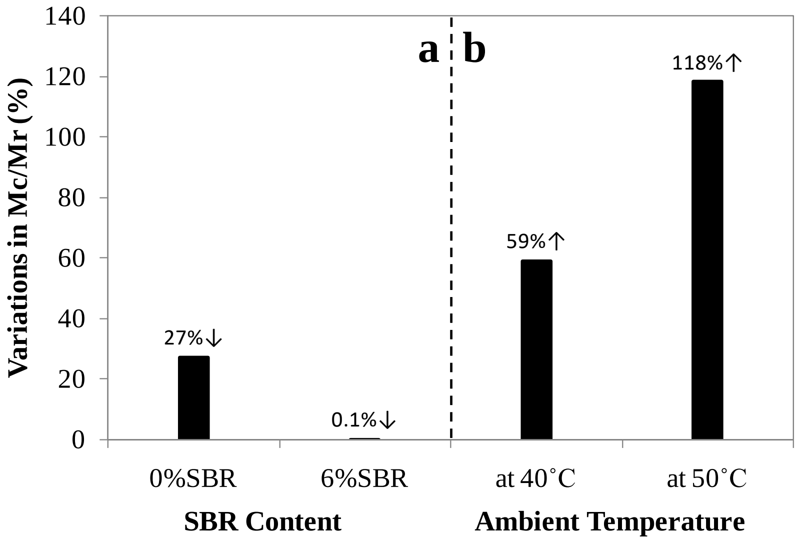

Figure 12. Decrease and increase in Mc/Mr of a) unmodified and modified asphalt mixture with 6% of SBR due to temperature rising from 40 to 50 ˚C, and b) asphalt mixtures with 6% SBR addition at 40 and 50 ˚C, respectively, at the end of 10000 loading cycles.

3.1. Determination of flow number (FN)

The permanent deformation curve of asphalt mixtures can be divided into the following three stages: First, the primary stage or primary flow that initiates from the coordinate origin and can be modeled using Power-law [22] or logarithmic functions [27]. Secondly, the secondary flow that initiates from the end point of the primary stage and continues in the form of a simple linear function; and thirdly, the tertiary stage or tertiary flow that initiates from the end point of the secondary stage which is called flow number (FN). The FN is a critical point in which the linear trend of the secondary stage is substituted with an ascending non-linear trend that indicates that the permanent strain increases dramatically from each cycle to the next one. From FN point, the pure plastic shear deformation begins [23] and the individual aggregates that make up the skeleton of asphalt mixture move past each other [28]. According to literature, the FN has a strong correlation to the Traffic Force Index (TFI) [29] and field rutting performance [21], and is a rutting indicator for asphalt mixtures [21, 22].

In this stage, the Goh and You method [23] was used in order to determine the FN of samples. In this method, the minimum value of strain rate (SR) curve versus the loading cycles is considered as FN. It is worth noting that if the minimum value of SR matches the last loading cycle, the FN is not determined and the sample does not experience the tertiary flow up to the last loading cycle [23]. Equation (1) indicated the SR formula, where ε and N are the permanent strain and the number of loading cycle, respectively.

$$SR = \frac{\varepsilon}{N} \tag{1}$$

Figure 13 shows the SRs of the selected samples versus the number of loading cycles. Based on the calculated SR values for different samples, it must be said that the minimum SRs for unmodified samples were obtained in loading cycles of 9728 and 8416 as FNs at the ambient temperatures of 40 and 50 ˚C, respectively. This indicates that the tertiary flow or pure shear deformation occurred in unmodified samples. Also with rising temperature, the FN value decreased due to decrease in viscosity of the binder. Under this condition, the occurrence of shear deformation was accelerated and the sample experienced a higher permanent deformation. On the other hand, the minimum SRs for samples modified by 6% of SBR under both ambient temperatures were obtained in the last loading cycle. As mentioned recently, this means that the SBR-modified samples had higher rutting resistance than unmodified samples, so that the tertiary flow did not occur up until the last loading cycle.

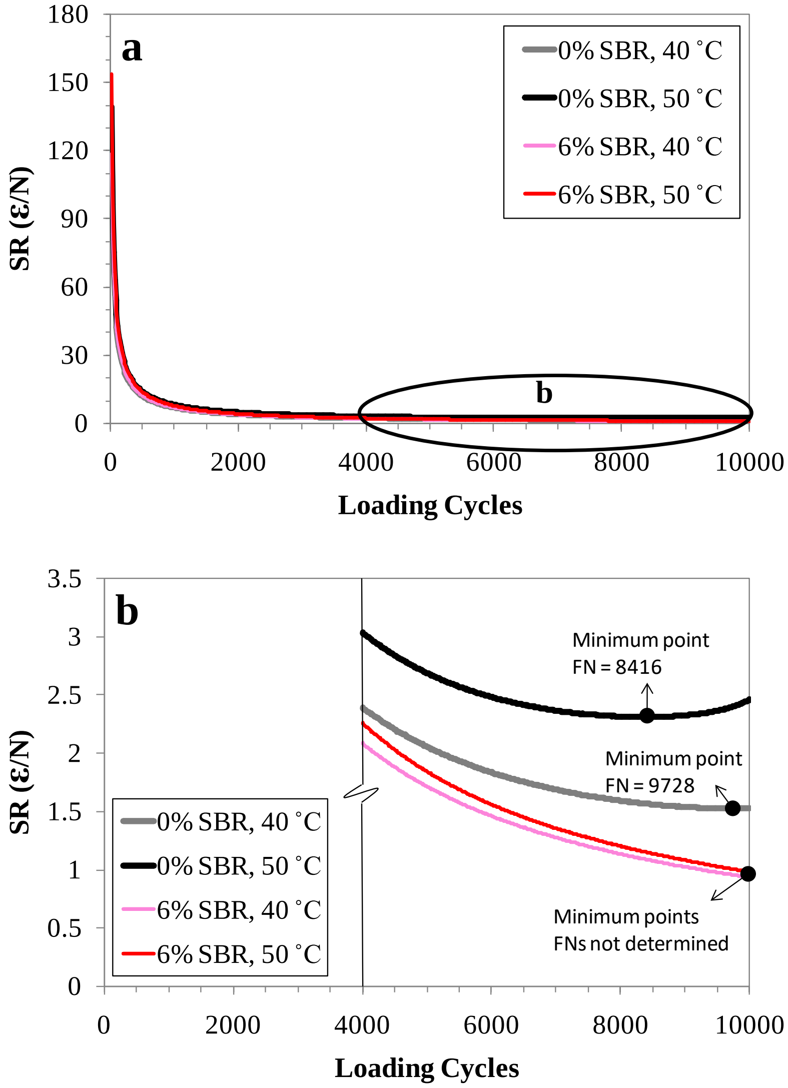

Figure 13. The flow number (FN) of unmodified and SBR-modified asphalt mixtures.

Figure 14 illustrated the triple flows of permanent deformation curves. As it can be seen, the secondary flow of SBR-modified samples continued up to the last loading cycle. Thus, the tertiary flow did not occur at desired loading cycles. While in unmodified samples, the linear trend of secondary flows stopped in their FNs, and the tertiary flows with the origin of FNs started with a dramatic slope increase. It must also be noted that line 1, as a border of primary and secondary flows, was drawn hypothetically to show the approximate location of this border in permanent deformation curves in terms of the changes in their trends.

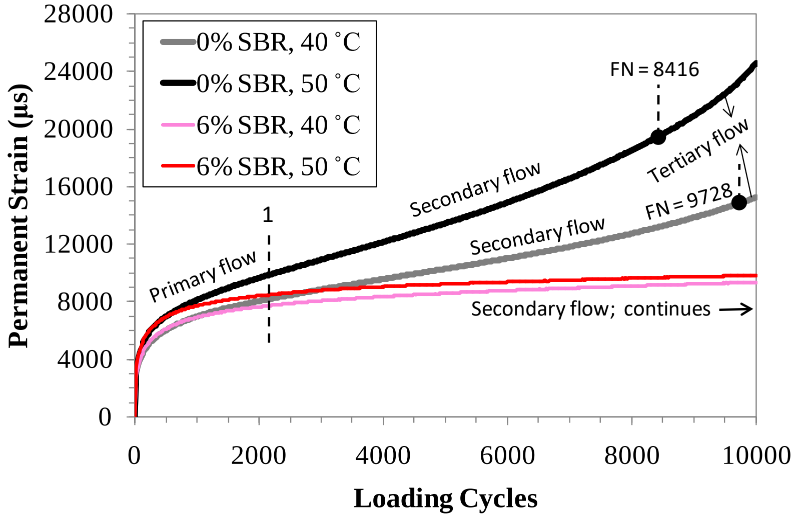

Figure 14. The triple stages of permanent deformation curves of unmodified and SBR-modified asphalt mixtures.

4. Conclusions

This study aimed to evaluate the effect of SBR on permanent deformation of asphalt mixtures. Based on the test results, the following conclusions were obtained:

1. With addition the optimum content (6%) of SBR to the bitumen, the permanent deformations of asphalt mixtures decreased by 39 and 60% at 40 and 50 ˚C, respectively. In addition, with the temperature rising from 40 to 50 ˚C, the permanent strain of unmodified asphalt mixture increased by 61%. Whereas the same property only increased by 5% in SBR-modified sample. This shows the effectiveness of SBR on enhancing the rutting resistance of asphalt mixtures, especially under the condition of rising temperature.

2. The resilient modulus trends and the creep modulus of SBR-modified samples were at a higher level than those for unmodified samples at the same ambient temperatures. Moreover, after around 6000 cycles, the general trend of resilient modulus curves of unmodified samples tends to decrease. While the general trends of resilient modulus of SBR-modified samples were at an approximately constant level. It can be concluded that in near-to-last load cycles, the compactive deformation of unmodified samples seized and the shear flow tended to initiation. However, in the SBR-modified samples, the compactive deformation was slowly progressing up until the last loading cycle. The main reason of this lies in the elastic properties of the SBR network, which preserved the stone materials and prevented and/or postponed the excessive plastic deformations.

3. Modification of bitumen with SBR enhances the creep modulus of asphalt mixtures. With the 6% SBR addition, the creep modulus of the samples increased by 64 and 133% at 40 and 50 ˚C, respectively. Also with the temperature rising from 40 to 50 ˚C, the creep modulus of the unmodified mixture decreased by 34%. Whereas the same reduction for the SBR-modified sample was only 6%. As mentioned earlier, this shows better stability of the SBR-modified samples against rising temperature compared to the unmodified ones.

4. Modification of bitumen with appropriate amount of SBR can be a suitable method for construction of durable roads particularly in the regions with hot climate. The SBR has lower price than another common polymeric product, SBS. Therefore, using it as a binder modifier, along with meeting the technical requirements for durable asphalts, can decrease the total cost of road construction.

References

1. Al-Khateeb, G.G., Al-Suleiman Obaidat, T.I., Khedaywi, T.S., Elayan, M.S. Studying rutting performance of Superpave asphalt mixtures using unconfined dynamic creep and simple performance tests. Road Materials and Pavement Design. 2018. 19(2). Pp. 315–333. DOI: 10.1080/14680629.2016.1261722
2. Mirzapour Mounes, S., Karim, M.R., Khodaii, A., Almasi, M.H. Evaluation of permanent deformation of geogrid reinforced asphalt concrete using dynamic creep test. Geotextiles and Geomembranes. 2016. 44(1). Pp. 109–116. DOI: 10.1016/j.geotexmem.2015.06.003
3. Tayfur, S., Ozen, H., Aksoy, A. Investigation of rutting performance of asphalt mixtures containing polymer modifiers. Construction and Building Materials. 2007. 21(2). Pp. 328–337. DOI: 10.1016/j.conbuildmat.2005.08.014
4. Gokhale, S., Choubane, B., Byron, T., Tia, M. Rut Initiation Mechanisms in Asphalt Mixtures as Generated under Accelerated Pavement Testing. Transportation Research Record. 2005. 1940(1). Pp. 136–145. DOI: 10.1177/0361198105194000115

5. Khodaii, A., Mehrara, A. Evaluation of permanent deformation of unmodified and SBS modified asphalt mixtures using dynamic creep test. Construction and Building Materials. 2009. 23(7). Pp. 2586–2592. DOI: 10.1016/j.conbuildmat.2009.02.015
6. Baumgardner, G.L., Hardee, J.R., Negulescu, I.I., Williams, E.R., Howard, I.L., St. John, R.C. Quantitative analysis of functional polymer in recycled tire rubber used in modified asphalt binders. Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions. 2014. 83(January). Pp. 583–611. DOI: 10.1080/14680629.2014.927413
7. Vamegh, M., Ameri, M., Chavoshian Naeni, S.F. Experimental investigation of effect of PP/SBR polymer blends on the moisture resistance and rutting performance of asphalt mixtures. Construction and Building Materials. 2020. 253. Pp. 119197. DOI: 10.1016/j.conbuildmat.2020.119197
8. Ameri, M., Yeganeh, S., Erfani Valipor, P. Experimental evaluation of fatigue resistance of asphalt mixtures containing waste elastomeric polymers. Construction and Building Materials. 2019. 198. Pp. 638–649. DOI: 10.1016/j.conbuildmat.2018.11.017
9. Abdel-Goad, M.A.H. Waste polyvinyl chloride-modified bitumen. Journal of Applied Polymer Science. 2006. 101(3). Pp. 1501–1505. DOI: 10.1002/app.22623
10. Zhai, R., Ge, L., Li, Y. The effect of nano-CaCO3/styrene–butadiene rubber (SBR) on fundamental characteristic of hot mix asphalt. Road Materials and Pavement Design. 2018. 21(4). Pp. 1006–1026. DOI: 10.1080/14680629.2018.1532924
11. Ming, L.Y., Feng, C.P., Siddig, E.A.A. Effect of phenolic resin on the performance of the styrene-butadiene rubber modified asphalt. Construction and Building Materials. 2018. 181. Pp. 465–473. DOI: 10.1016/j.conbuildmat.2018.06.076
12. Cong, Y., Liao, K., Huang, W., Zhai, Y. Performance of SBR-modified asphalt. Petroleum Science and Technology. 2006. 24(10). Pp. 1187–1194. DOI: 10.1081/LFT-200053905.
13. Zhang, B., Xi, M., Zhang, D., Zhang, H., Zhang, B. The effect of styrene-butadiene-rubber/montmorillonite modification on the characteristics and properties of asphalt. Construction and Building Materials. 2009. 23(10). Pp. 3112–3117. DOI: 10.1016/j.conbuildmat.2009.06.011
14. Zhang, F., Hu, C. The research for SBS and SBR compound modified asphalts with polyphosphoric acid and sulfur. Construction and Building Materials. 2013. 43. Pp. 461–468. DOI: 10.1016/j.conbuildmat.2013.03.001.
15. Hossein Hamedi, G., Ghalandari Shamami, K., Mazhari Pakenari, M. Effect of ultra-high-molecular-weight polyethylene on the performance characteristics of hot mix asphalt. Construction and Building Materials. 2020. 258. Pp. 119729. DOI: 10.1016/j.conbuildmat.2020.119729
16. Kuttah, D.K., Sato, K., Koga, C. Evaluating the dynamic stabilities of asphalt concrete mixtures incorporating plasterboard wastes. International Journal of Pavement Engineering. 2015. 16(10). Pp. 929–938. DOI: 10.1080/10298436.2014.973023
17. Hao, P., Zhai, R., Zhang, Z., Cao, X. Investigation on performance of polyphosphoric acid (PPA)/SBR compound-modified asphalt mixture at high and low temperatures. Road Materials and Pavement Design. 2019. 20(6). Pp. 1376–1390. DOI: 10.1080/14680629.2018.1447503
18. Ren, S., Liang, M., Fan, W., Zhang, Y., Qian, C., He, Y., Shi, J. Investigating the effects of SBR on the properties of gilsonite modified asphalt. Construction and Building Materials. 2018. 190. Pp. 1103–1116. DOI: 10.1016/j.conbuildmat.2018.09.190
19. Jiang, J., Ni, F., Zheng, J., Han, Y., Zhao, X. Improving the high-temperature performance of cold recycled mixtures by polymer-modified asphalt emulsion. International Journal of Pavement Engineering. 2020. 21(1). Pp. 41–48. DOI: 10.1080/10298436.2018.1435882
20. Liu, B., Liang, D. Influence of SBS and SBR on the properties of emulsified asphalt. Petroleum Science and Technology. 2017. 35(10). Pp. 1008–1013. DOI: 10.1080/10916466.2017.1303720
21. Witczak, M. Specification Criteria for Simple Performance Tests for Rutting, Volume I: Dynamic Modulus (E*) and Volume II: Flow Number and Flow Time. The National Academies Press. 2007. Washington, DC. DOI: 10.17226/23120
22. Zhou, F., Scullion, T., Sun, L. Verification and modeling of three-stage permanent deformation behavior of asphalt mixes. Journal of Transportation Engineering. 2004. 130(4). Pp. 486–494. DOI: 10.1061/(ASCE)0733-947X(2004)130:4(486)
23. Goh, S.W., You, Z. A simple stepwise method to determine and evaluate the initiation of tertiary flow for asphalt mixtures under dynamic creep test. Construction and Building Materials. 2009. 23(11). Pp. 3398–3405. DOI: 10.1016/j.conbuildmat.2009.06.020
24. Behnood, A., Modiri Gharehveran, M. Morphology, rheology, and physical properties of polymer-modified asphalt binders. European Polymer Journal. 2019. 112. Pp. 766–791. DOI: 10.1016/j.eurpolymj.2018.10.049
25. Gong, M., Yang, B., Zhang, H., Sun, Q. Comparative study on durability of different composite modified asphalt mixtures. Road Materials and Pavement Design. 2019. Pp. 1–20. DOI: 10.1080/14680629.2019.1688672
26. Ahari, A.S., Forough, S.A., Khodaii, A., Nejad, F.M. Modeling the Primary and Secondary Regions of Creep Curves for SBS-Modified Asphalt Mixtures under Dry and Wet Conditions. Journal of Materials in Civil Engineering. 2014. 26(5). Pp. 904–911. DOI: 10.1061/(asce)mt.1943-5533.0000857
27. Kanitpong, K., Bahia, H. Relating adhesion and cohesion of asphalts to the effect of moisture on laboratory performance of asphalt mixtures. Transportation Research Record. 2005. (1901). Pp. 33–43. DOI: 10.3141/1901-05
28. Faheem, A.F., Bahia, H.U., Ajideh, H. Estimating results of a proposed simple performance test for hot-mix asphalt from superpave gyratory compactor results. Transportation Research Record. 2005. (1929). Pp. 104–113. DOI: 10.3141/1929-13

Information about authors:

Navid Lotfi Omran

ORCID: https://orcid.org/0000-0002-6438-132X

E-mail: navid.lotfii.omran@gmail.com

Komeil Rajaee

ORCID: https://orcid.org/0000-0001-6449-874X

E-mail: rajaee.geotech@gmail.com

Seyed Morteza Marandi, *PhD*
ORCID: https://orcid.org/0000-0003-0044-1781
E-mail: marandi@uk.ac.ir

Received 30.12.2020. Approved after reviewing 13.10.2021. Accepted 17.10.2021.