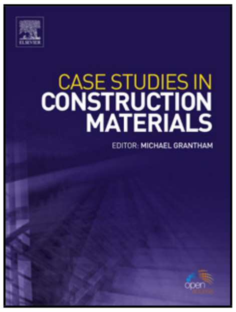

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Investigation of the Fatigue characteristics of Warm Stone Matrix Asphalt (WSMA) Containing Electric Arc Furnace (EAF) Steel Slag as Coarse Aggregate and Sasobit as Warm Mix Additive

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Highlights

- In this research, a part of natural coarse aggregates was replaced with EAF slag
- Warm mix asphalt technology (Sasobit) was employed to produce warm SMA mixture
- Fatigue characteristics of WSMA mixture were determined using flexural fatigue test
- EAF steel slag indicated great potential to substitute for natural aggregates
- Warm SMA showed weaker but acceptable fatigue performance compared to the SMA mix

Abstract

On the one hand, several million tons of steel slag is produced annually as the by-product of the steel industry in Iran and other countries and are deposited in landfills without any use, occupy vast areas, and cause environmental hazards. On the other hand, the high mixing temperature of the hot mix asphalt (HMA) increases the emission of greenhouse gases, the cost of fuel, accelerated wear of asphalt plant equipment, and less safety of workers in the field. These kinds of problems challenge the use of HMA mixtures and encourage to investigate more the WMA technology. This research intends to investigate the fatigue characteristics of warm stone matrix asphalt (WSMA), as one of the significant structural distresses of the flexible pavements, containing EAF steel slag as part of the coarse aggregate and Sasobit as the warm mix additive. The Marshal test results indicated higher Marshall stability and Marshal quotient for mixtures containing EAF steel slag compared to their similar mixtures (SMA+S vs SMA+N and WSMA+S vs WSMA+N) and all the mixtures met the NAPA specification requirements for Marshall stability, air voids, and optimum binder content. The result of draindown test for all of the mixtures was lower than the maximum amount determined by the specifications and means that the rock wool fibers, as asphalt stabilizers, preserved the asphalt mortar in the mixture well. The fatigue test results indicated that the use of EAF slag leads to comparable results to standard SMA and using warm mix additive (Sasobit) results in lower but acceptable results.

Keywords: Warm Stone Matrix Asphalt (WSMA); Draindown; EAF Steel Slag; Sasobit; Four-point Fatigue Beam Test, Fatigue Modelling

1. Introduction

The increase in the traffic volume and the axial load of vehicles passing on the roads lead to numerous distresses and short lifecycle of the conventional hot mix asphalt (HMA) pavements; thus there is a need to investigate more durable asphalt pavements. Stone matrix asphalt (SMA) is a gap-graded hot mix asphalt which relies on coarse aggregates' stone to stone contact for resistance against permanent deformation and rich asphalt mortar to provide durability [1]. This mixture was developed in Europe in the late sixties and the successful results within 20 years encouraged US road authorities to start the SMA projects in some states. SMA has high resistance to permanent deformations due to the high interlock of coarse aggregates in the stone skeleton. High asphalt content and lower air voids in SMA mixtures lead to enhanced durability of asphalt binder during the life cycle of the asphalt pavement.

The fatigue or alligator cracking is a structural pavement distress which takes place as a result of repetitive traffic loading [2]. The load repetition leads to compressive and tensile stresses in the upper and lower layers of asphalt pavement respectively. If the tensile strain in the lower layer exceeds the allowable designed tensile strain of the asphalt layer, the pavement is cracked. These cracks initiate at the bottom of the asphalt layer and propagate to the surface as longitudinal cracks. After the repeated loading, the cracks connect to each other, form many-sided sharp-angled pieces, and develop into a pattern which is similar to the back of an alligator. The problems associated with fatigue cracking include the moisture infiltration into the pavement, surface roughness, and deterioration to a pothole.

One of the by-products of the steel industry is steel slag which forms 15-20 percent of the output of the steel melting furnace [3]. This steel slags are produced in vast amounts in Iran and are often discharged in landfills without any use, occupy broad areas, and since they contain chemical compositions, cause environmental hazards. One of the methods to recycle these materials and conserve the unrenewable sources of natural aggregates by considering the concept of sustainable development is to use them in the road construction. Steel slag is sharp-angled and advantages from high compressive and abrasive strength, better roughness and frictional resistance in comparison to the natural aggregates. Basic oxygen furnace (BOF) and electric arc furnace (EAF) steel slags are two common types of slags used in asphalt mixtures.

One of the problems associated with HMA mixtures is that they cool rapidly because of the high thermal gradient between the mixture and the ambient [4]. This problem prevents adequate compaction of the mixture in the field. Rapid cooling also prevents the transfer potential of the HMA mixture to distant places. The high temperature employed to produce HMA mixtures leads to the high cost of fuel [5]. Increase in the cost of fuel in the recent years has obliged road authorities to use technologies which reduce the mixing and compaction temperatures of asphalt mixtures and as a result reduce the fuel cost. The other concern about the HMA mixtures is from the environmental aspect. The high temperature of the HMA production process results in more emissions. The strict environmental regulations passed in the recent years oblige road agencies and contractors to use technologies which release fewer emissions in comparison to HMA mixtures [4].

Alonso et al. [6] evaluated the effect of different warm mix additives on the fatigue characteristics of the HMA mixes. The used additives included wax (organic additive), zeolite (water containing and foaming additive), and Tensoactive (chemical additive). The HMA mixture (control mix) was produced at the temperature of 160°C, and the warm mix asphalt (WMA) mixtures were prepared at 140°C. The result of four-point fatigue beam test in control strain mode indicated the similar fatigue performance of WMA mixtures to the control mix and the WMA mixtures containing Tensoactive showed less fatigue life in this test.

Masoudi et al. [7] studied the long term performance of warm mix asphalt mixture containing electric arc furnace (EAF) steel slag. They found out that using warm mix asphalt and replacing mineral aggregates with steel slag aggregate increases the Marshall Stability, stiffness, resilient modulus and indirect tensile strength of the mixture. Moreover, they noticed that warm asphalt mixtures containing steel slag experience less aging compared to control specimens (HMA with limestone). Hence, they recommended utilizing warm mix asphalt containing EAF steel slag.

NCHRP 9-49A investigated the long term field performance of warm mix asphalt mixtures by doing experiments on the new and in-service asphalt pavements in different states of the US [8]. The roads were different from each other in climate conditions (wet, dry, freezing and non-freezing) and the technology and additive used for constructing warm mix asphalt (including organic wax, chemical and foaming). The results of this report is as follows:

1- The performance of WMA mixture in fatigue cracking is comparable to HMA and these cracks are mainly seen after 4 or more years of age.

2- The performance of WMA in Rutting is comparable to HMA and rutting is started after 3 years of age but it becomes more differentiable after 6 or more years of service.

3- Reduced production temperature of WMA can have an influence on field density, thus the in-place density of WMA is generally lower than HMA pavements.

4- Distress distribution appears to be climatic related: Within dry zones (freeze or non-freeze), rutting appears to be the major type of distress regardless of HMA or WMA. In wet freeze zones, cracking is the dominant distress type and in wet non-freeze zones, cracking and rutting can both happen.

Kavussi et al. [9] investigated the effect of replacement of various portions of coarse limestone aggregates with EAF slags (0, 25, 50, 75, and 100 percent replacement and complete replacement of all limestone filler, fine and coarse fractions with EAF slag) and recommended the optimum amount of replacement. The result of Marshall mix design showed higher optimum asphalt content for mixtures containing EAF slag in all fractions of coarse, fine, and filler. Moreover, as the EAF percentage increases in the coarse fraction, the optimum binder content increases. The statistical analysis of the Marshall tests indicated that the replacement of 50-75 percent of the coarse fraction with EAF slags could be optimal. They also concluded that although 75 percent replacement of the coarse fraction with EAF slag increases the optimum asphalt content approximately 15 percent, it substantially improves Marshall parameters. Asi et al. [10] replaced 0%, 25%, 50%, 75%, and 100% of limestone coarse aggregates in HMA mixes with steel slag and found out that replacing up to 75% of limestone coarse aggregates with steel slags improved the fatigue life of asphalt mixes.

Ziari et al. [11] studied the effect of replacing coarse, fine or all portions of limestone aggregates by EAF steel slag in warm mix asphalt mixtures. The results showed that generally steel slag increases the fatigue life of the mixtures when used in either coarse or fine fractions by 50% to 75% of replacement.

Behnood and Ameri [12] evaluated the feasibility of using steel slag in SMA mixtures. To this end, they incorporated two types of slags from Mobarake and Esfahan factories in fine and coarse fractions. The results of Marshall tests showed better performance of mixtures containing steel slag compared to the control mixture containing limestone aggregates. The mixtures containing slag in the fine fraction had the most amount of optimum asphalt content which was not suitable. The result of the indirect tensile test indicated the increased resistance of the mixtures containing slag to moisture susceptibility. Moreover, the result of the creep test revealed less amount of permanent deformation for the mixtures containing slag in coarse fraction. Finally, they concluded that replacing the coarse fraction of the SMA mixture with steel slag will improve Marshall stability and resistance to moisture damage and permanent deformations.

In another research, Ameri et al. [13] evaluated the performance of warm mix asphalt (WMA) mixture containing EAF steel slag. This study aimed to determine the feasibility of utilizing steel slag in mixtures produced with warm mix asphalt technology. To this end, they used steel slag in coarse and fine fractions of the HMA and only in the coarse fraction of the WMA specimens. The laboratory experiments performed on the specimens revealed that using steel slag in coarse fraction of WMA mixture increases Marshall stability, tensile strength, and resistance to moisture damage and permanent deformations.

In the case of SMA mixtures produced with warm mix asphalt additives (which is abbreviated as WSMA in this research), there is a few research available. Al-Qadi et al. [14] investigated the effect of curing time and reheating on the performance of stone matrix asphalt mixtures produced with different warm mix additives such as Sasobit, Evotherm, and foamed asphalt. The performed tests included complex modulus, loaded wheel track, indirect tensile strength, and semicircular beam fracture. The WSMA mixtures containing warm mix additives showed similar changes due to the curing time in comparison to the control SMA mixture, and the result indicated that longer curing times are not required before the opening of WMA pavements to the traffic. The reheating process of asphalt mixtures led to greater modulus, tensile strength, and rutting resistance, but smaller resistance to fracture. Among the WSMA mixtures produced with warm mix additives, Sasobit indicated the smallest variation in mixture properties attributable to reheating.

Vavrik et al. [15] evaluated the performance of field-produced warm SMA produced with the Evotherm additive. The conducted tests included dynamic modulus and flexural beam fatigue. The results showed the similar dynamic modulus of warm SMA and SMA control mixture. Moreover, the fatigue life of warm SMA mixtures produced with Evotherm improved compared to the control mixture.

Zaumanis et al. [16] evaluated the performance of warm SMA mixtures produced with warm mix additives of Sasobit (organic additive) and Rediset WMX (chemical additive). The properties of modified asphalt binders such as penetration, softening point, dynamic viscosity were tested. The results showed that adding Sasobit reduces the viscosity of asphalt binder at high temperatures and increases it at intermediate temperatures. Adding Rediset to the binder led to slight changes in viscosity. Furthermore, the properties of mixtures prepared at four compaction temperatures with Marshall hammer and gyratory compactor methods were determined. The comparison of tests result of warm SMA mixtures with the reference SMA indicated that it is possible to reduce 30°C the compaction temperature of both warm SMA mixtures compared to the control mixture so that the density and mechanical characteristics of the mixture are maintained at intermediate to high temperatures.

There are not many studies focusing on the fatigue characteristics of WSMA mixtures. This research aims to investigate the effect of EAF steel slag, warm mix asphalt technology, and their simultaneous use on the fatigue characteristics of SMA mixtures and compare it with the fatigue behavior of standard SMA produced with natural limestone aggregates. To this end, Marshall stability and flow, draindown, and four-point fatigue beam tests were conducted on four different asphalt mixtures (two SMA and two WSMA mixtures) containing EAF slag and natural limestone aggregates.

2. Materials

2.1. Aggregates

The aggregates used in this study include limestone and cured EAF steel slag as a substitute for 75 percent of the coarse aggregate fraction. The limestone aggregates were obtained from the Majidi asphalt plant in Mashhad, Iran. The EAF steel slags were procured from Mobarake steel manufacturing company in Esfahan and were cured in water for more than 7 days in order to reduce their expansion [3].

The surface texture of the aggregates was observed using scanning electron microscope (SEM) and has been presented in Fig. 1 and 2. As it can be seen, the morphology and texture of the EAF slag are different from those of the limestone. EAF slag has higher porosity than limestone aggregates (Fig. 1). Typically, porosity increases the asphalt content needed to produce asphalt mixture. The qualitative comparison of the EAF and limestone aggregates in Fig. 2 indicates the higher roughness of EAF slag. This higher roughness could improve the adhesion between asphalt and EAF slag in comparison to limestone aggregates.

Elemental composition of the aggregates affects the mixture behavior. One of the disadvantages of steel slags is their expansion because of the existence of elements like calcite. The curing of them with water before using in the asphalt mixture could solve this problem [3]. The most important components of EAF steel slag consist of silicon dioxide (SiO_2), calcium oxide (CaO), and ferric oxide (Fe_2O_3). The high abrasive strength of steel slags is due to the existence of metallic elements like Fe_2O_3, Al_2O_3 in their composition [9]. Regarding these facts, both limestone and cured EAF aggregates were analyzed using x-ray fluorescence (XRF) test, and their chemistry was presented in Table 1.

Table 2 shows the properties of aggregates used in this study. The gradation of the SMA mixture was selected according to NAPA gradation in a way that the stone to stone contact is provided. Table 3 indicates the gradation used in this study.

2.2. Asphalt binder

The PG 64-22 asphalt binder was obtained from Majidi asphalt plant around Mashhad, Iran. Table 4 indicates the result of laboratory tests done on this asphalt binder.

2.3. Additive

Two additives were used in this study. At first, to prevent the draindown potential of the SMA mixture and to stabilize asphalt binder into the mixture, rock wool fibers were used as 0.3 percent of the mixture's weight. Secondly, because of the acceptable performance of Sasobit as an organic additive of the warm mix technology and its availability in Iran, it was used 2 percent by the weight of asphalt binder.

3. Sample Preparation and Testing Program

To determine the effect of EAF steel slag, warm technology, and the simultaneous use of steel slag and warm additive, SMA and WSMA samples containing steel slag and natural aggregates were prepared. Table 5 shows the description of different mixtures prepared in this study with the abbreviation used for them.

3.1. Marshall stability, flow, and Marshall Quotient

For each type of mixtures, the test samples were prepared according to Marshall method (ASTM D1559) with five asphalt rates (5% - 7.5%) at 0.5 increments. The optimum binder content of the SMA mixtures is selected so that a 3-4 percent of air voids and a minimum VMA of 17% is provided. Also, based on the

NAPA SMA guideline, the Marshall stability of the mixtures at their optimum asphalt content should not be less than 6.2 KN. The Marshall properties of SMA mixtures were evaluated. The Marshall quotient which is shown in abbreviated form as MQ and is an indicator of the resistance of asphalt mixtures to shear stresses, permanent deformations, and rutting, was calculated for each SMA and WSMA mixture in their optimum asphalt content. Higher MQ value shows the better performance of mixture. It should be noted that the optimum asphalt content was determined according to NAPA specification requirements presented in Table 6.

3.2. Draindown Test

As it was mentioned before, one of the main problems of SMA mixtures is the draindown of asphalt because of the lack of fine aggregates in gradation. The rock wool fibers were used as the stabilizer to absorb asphalt, keep it into the mixture, and solve the draindown problem. The basket test was utilized to determine the efficiency of rock wool for this purpose. In this test, according to AASHTO-T305, the uncompacted sample is poured into a wire basket, and the weight is measured. Then the basket is positioned on a pre-weighed paper plate, and the assembly is placed in an oven with the temperature of 175°C for 60±5 minutes. After the specified time, the assembly is removed from the oven, and the mass of the plate plus the draindown material is measured to determine the percent of the drained mixture using the following equation:

$$D = \frac{M_f - M_i}{M_t} \times 100\,, \qquad (1)$$

In which D is the draindown percent, M_f is the final mass of the plate, M_i is the initial mass of the plate, and M_t is the initial total mass of the sample.

3.3. Flexural Fatigue Test

In this research, the four-point fatigue beam test was utilized according to AASHTO T321 standard to measure the fatigue life of SMA and WSMA specimens with $63 \times 381 \times 50$ mm dimensions. The test conditions included haversine waveform, frequency of 10 Hz, 0.1 sec pulse interval, the temperature of 20°C, and strain control mode. The fatigue life of Different mixtures was determined in 4 strain levels of 600, 700, 800, and 900 microns. Three specimens were tested for each strain level, and entirely 12 specimens were prepared for each mixture. According to the test standard, the fatigue life of the specimen is defined as the number of cycles needed to reduce its stiffness to 50% of the initial stiffness modulus obtained in the 50th cycle. The initial strains are plotted versus the number of load cycles to failure on logarithmic scales to develop the fatigue models of the mixtures. A straight line can approximate this plot and express it by:

$$N = a\,(\varepsilon_t)^{-b}\,, \qquad (2)$$

In which N_f is the number of load cycles to failure, the a parameter is the fatigue constant (the value of N_f when ε_t=1), and b is the inverse slope of the straight line.

The logarithmic form of the eq.1 could be expressed as:

$$Ln\, N_f \;=\; Ln\, a - b\, Ln\, (\varepsilon_t) \qquad (3)$$

4. Results and Discussion

4.1. Marshall test results

Table 7 shows the result of Marshall tests. The optimum asphalt binder content for each mixture was determined in which the specification requirements are met. The analysis of Marshall test results for mixtures containing EAF slag and natural aggregates indicates that SMA and WSMA mixtures containing EAF slag (SMA+S and WSMA+S) have higher Marshall Stability and Quotient compared to their similar mixture (SMA+N and WSMA+N). This is because of the better interlock of sharp-angled slags, the high cohesion between slag and asphalt binder, and the high roughness and angle of internal friction of slag particles.

The comparison of Marshall test results for similar SMA and WSMA mixtures (SMA+S vs. WSMA+S and SMA+N vs. WSMA+N) to determine the effect of warm mix additive indicates the better performance of SMA mixtures. Regarding the fact that Sasobit crystalizes into the asphalt binder at intermediate temperatures and increases its stiffness, the reason behind the weak performance of WSMA mixtures could be the inadequate coverage of aggregates by the modified asphalt binder at the lower mixing temperature of WSMA mixtures.

Considering Marshall stability and Quotient results, the SMA mixture containing EAF slag (SMA+S) and the WSMA containing natural limestone aggregates (WSMA+N) presented the best and worst performances respectively. The excellent performance of SMA+S is due to the presence of EAF slag and the lower viscosity of asphalt binder in SMA mixture compared to the WSMA one which results in the better coverage of aggregates by the asphalt binder and better cohesion between them. However, all of the SMA and WSMA mixtures showed acceptable performance and met the specification requirements entirely.

4.2. Draindown Results

Fig. 3 shows the result of the draindown test for different mixtures. The result of this test for all of the mixtures is lower than the maximum amount determined by the specifications and means that the rock wool fibers preserve the asphalt mortar in the mixture well. The result of this test for SMA mixtures is higher than the WSMA ones. This subject could be justified by the higher mixing temperature of the SMA mixtures in comparison to WSMA ones.

4.3. Fatigue test results

The results of conducted flexural fatigue test on the SMA and WSMA specimens could be explained in the following sections.

4.3.1. The air void of fatigue test specimens

According to NAPA specification requirements [1], the air voids of SMA specimens should be between 3 and 4 percent. For each mixture, three specimens were tested and the average results could be observed in table 8. The results indicate that the specification requirements are met.

4.3.2. Initial flexural stiffness

The flexural stiffness is one of the most significant parameters influencing the fatigue life of mixtures and indicates the resistance to flexural deformation. The initial stiffness is defined as the fraction of stress and strain ($S = \frac{\sigma}{\varepsilon}$) in the 50th cycle of the fatigue test. The results of initial stiffness presented in Fig. 4 show the higher stiffness for all mixes in comparison to the control mix (SMA+N). This increase in stiffness could be due to the stiffening effect of the Sasobit in WSMA mixtures in the fatigue test temperature (20°C) which forms crystalline particles into the asphalt binder and also the higher stiffness and better interlock of EAF slags in comparison to the natural limestone aggregates. The WSMA+S has the higher initial stiffness which could be justified by the simultaneous presence of Sasobit and EAF slag in this mixture.

4.3.3. Initial phase angle

The phase angle (δ) is defined as the time lag between the applied stress and the resulting strain and is an indicator of the viscose or elastic behavior of the materials. For an utterly elastic material, the phase angle is equal to zero (there is an instant response), and it approaches 90 degrees when a viscous fluid such as a hot asphalt binder is tested. The asphalt mixture is a viscoelastic material, so its phase angle is between 0 and 90 degrees. Fig. 5 shows the results of phase angle for WSMA and SMA mixtures.

The obtained phase angle for all of the mixtures is lower than the initial phase angle of the control mixture (SMA+N) which shows more elastic behavior of them. This subject is due to the presence of Sasobit in WSMA mixtures which increases the stiffness of the asphalt binder and as a result the mixture stiffness. As it was mentioned in previous section, the use of slag increases the stiffness of the mixture and leads to lower phase angle and more elastic behavior. The WSMA mixture containing EAF slag indicated the lowest phase angle and more elastic behavior than others which is due to the simultaneous use of Sasobit and EAF steel slag.

4.3.4. Fatigue life and modelling

The result of fatigue test performed on WSMA and SMA mixtures has been presented in Table 9.

The results show the better performance of mixtures containing EAF slag (SMA+S and WSMA+S) in 600µ strain level. Considering the higher stiffness of these mixtures, the better performance in this strain level could be due to the better interlock of EAF slags, more angle of friction of slags compared to the natural aggregates, and the cohesion between asphalt binder and these aggregates. As the level of strain increases, the effect of flexibility of the mixture on the fatigue life increases and the obtained fatigue life for the mixtures containing natural aggregates becomes approximately better than similar mixtures containing EAF slags.

The comparison of similar SMA and WSMA mixtures (SMA+N vs. WSMA+N and SMA+S vs. WSMA+S）indicates the similar fatigue performance in average strain levels such as 600 and 700µ (except for the SMA+S and WSMA+S mixtures in 600µ strain level) and the better performance of SMA mixtures in high strain levels such as 800 and 900µ. This subject indicates that as the strain level increases, the stiffening effect of Sasobit in the asphalt binder results in less flexibility of the mixture, influences the fatigue life, and leads to the rapid failure of the mixtures. The other reason could be the inadequate coverage of aggregates by the modified asphalt binder due to the lower temperature of the WSMA mixtures in proportion to the SMA ones which shows its effect on the fatigue life more in high strain levels.

Table 10 indicates the fatigue models developed for different mixtures. The high R^2 verifies the goodness of fit of these models. The fatigue curves presented in Fig. 6 and the inverse slope of fatigue models in Table 9 shows that the fatigue life of all mixtures decreases with high intensity in comparison to the control mixture (SMA+N).

5. Conclusion

In this research, on the one hand, the electric arc furnace (EAF) steel slag was used as the substitute to 75% of the coarse aggregate fraction of the SMA mixture to evaluate its performance as a recycled material. On the other hand, Sasobit which is a warm mix asphalt (WMA) organic additive and could reduce the mixing temperature of the asphalt mixture 25-30 degrees was utilized to solve the problem of HMA mixes. The objective of this research study was to investigate the effect of EAF steel slag, Warm mix asphalt technology (using Sasobit additive), and their simultaneous use, on the fatigue characteristics of the SMA mixture.

The following conclusions were obtained from this study:

1. All of the SMA and WSMA mixtures met the NAPA specification requirements entirely for SMA specimens prepared with Marshall mix design.
2. The results of the fatigue test indicated the similar performance of SMA containing EAF slag to the control mixture containing natural aggregates (SMA+S vs SMA+N). Considering the higher stiffness and less flexibility of the mixture containing slag in comparison to the control mix containing natural limestone aggregates, the reason behind the acceptable performance of this mixture could be the better interlock of slags and the increase in cohesion between slag and asphalt binder. These two factors lead to the more extended fatigue life of the specimen and show that natural coarse aggregates could be replaced with recyclable EAF steel slags.
3. In the case of only employing the WMA technology (WSMA+N) and also the concurrent use of EAF steel slag and this technology (WSMA+S), the fatigue test results revealed the similar performance of these mixtures in 600 and 700 microns strain levels in comparison to the control mixture (SMA+N) but the weaker performance in relatively high strain levels such as 800 and 900 microns. This weak performance in high strain levels could be due to the stiffening effect of Sasobit in asphalt binder and the high stiffness of the EAF steel slag which lead to more stress in the mixture and its rapid failure. The other reason could be the inadequate coverage of aggregates by the modified asphalt binder using the Sasobit additive in the mixing temperature of the WSMA

mixtures compared to the SMA control mixture which shows its effect on the resistance to fatigue of the asphalt mixture in high strain levels. Since Sasobit is entirely soluble in the asphalt binder in temperatures more than 120°C, the problem of inadequate coverage of aggregates could be reduced by increasing the mixing temperature to some extent.

4. The analysis of fatigue life of specimen indicated that the fatigue life is very sensitive to the strain level so that the increase in strain level from 700 to 800 microns led to approximately 70 percent reduction in fatigue life of specimens.
5. The fatigue life of all SMA and WSMA specimens in the recommended strain level of AASHTO T-321 fatigue test standard (250-750 microns) is more than 10000 cycles. This fact indicates that the stiffness of these mixtures does not decrease rapidly during the loading and their performance is acceptable.

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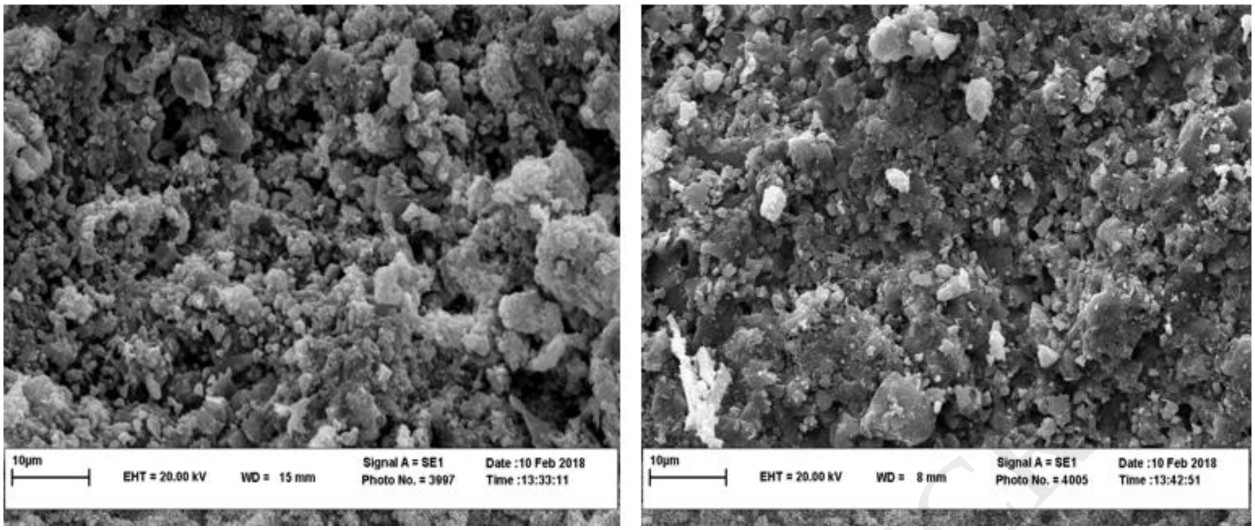

Fig. 1. The porosity of the aggregates: EAF slag (left), Limestone (right)

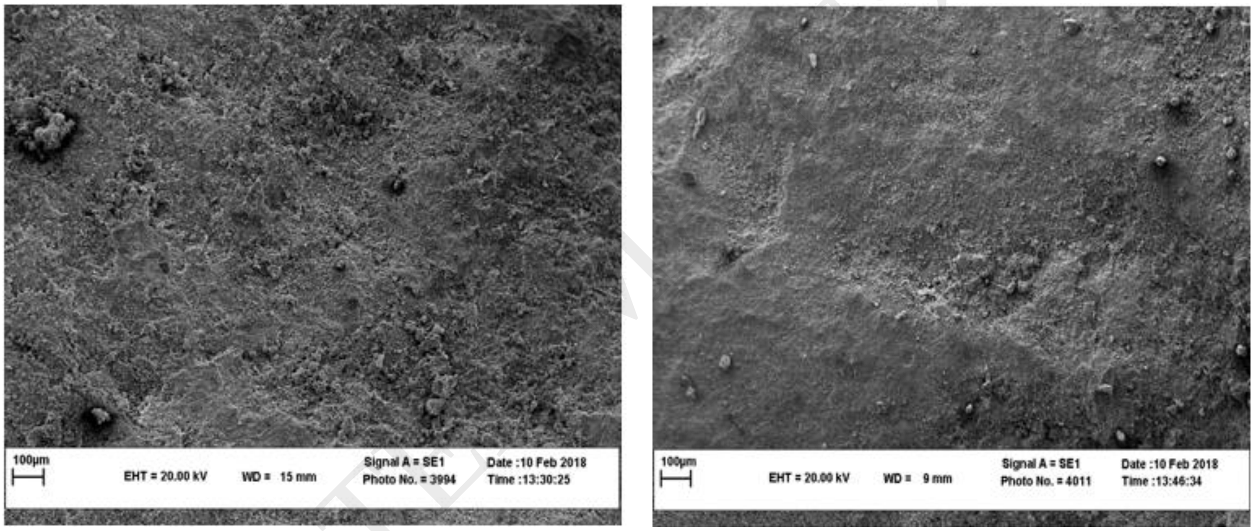

Fig. 2. The qualitative comparison of the roughness of aggregates: EAF slag (left), Limestone (right)

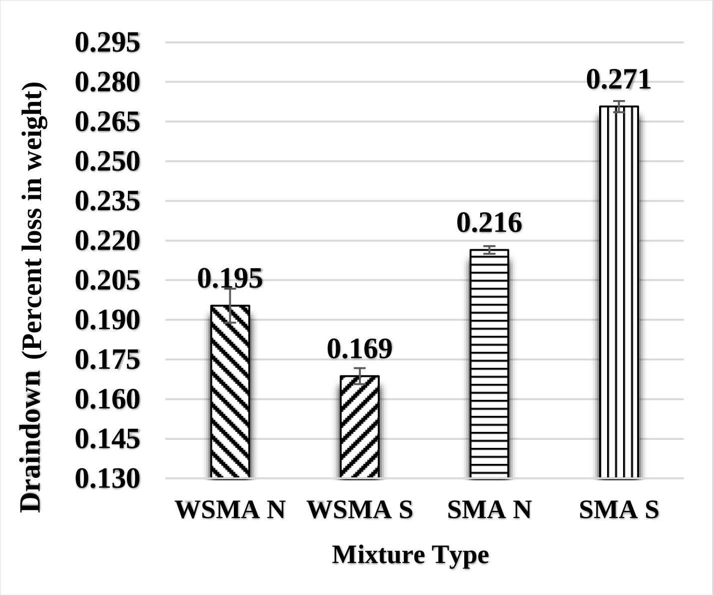

Fig. 3. The Draindown of mixtures at optimum asphalt binder content

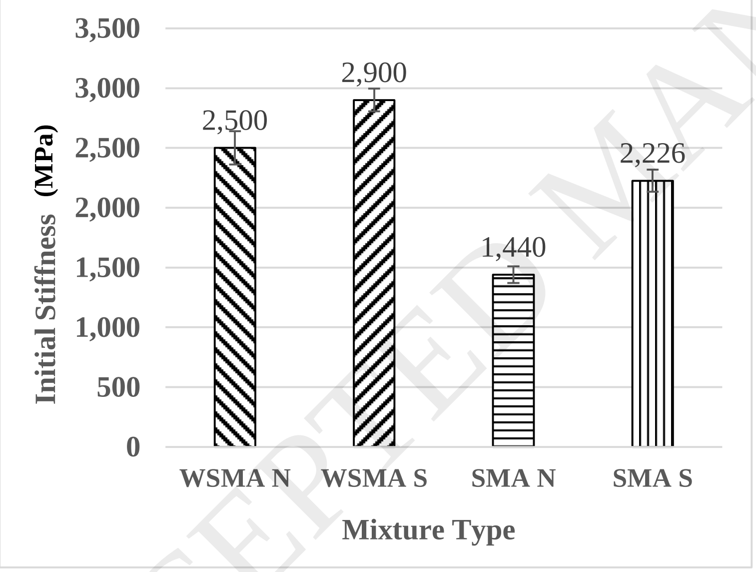

Fig. 4. The initial stiffness of the mixtures

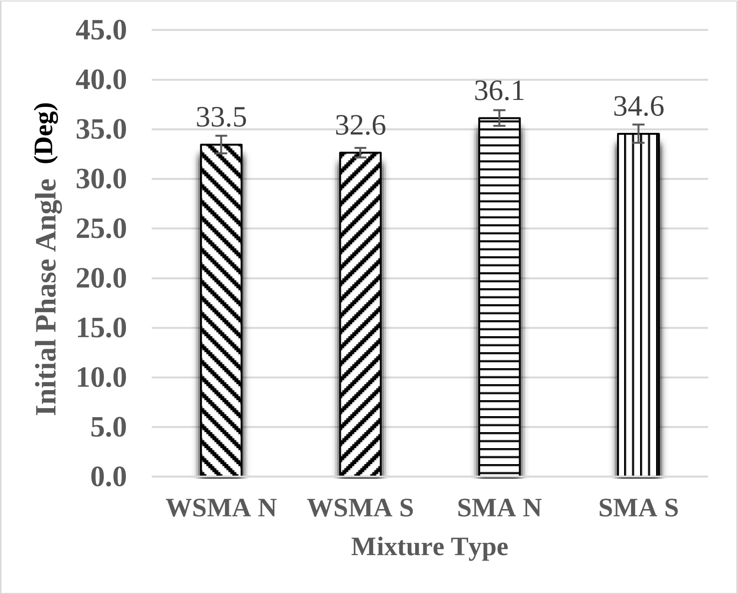

Fig. 5. The initial phase angle of the mixtures

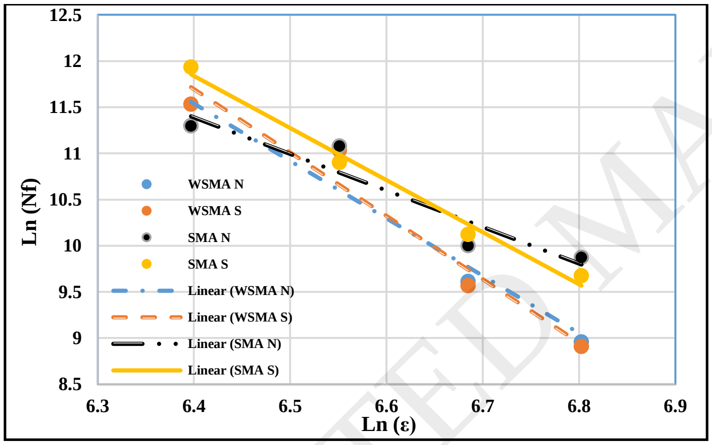

Fig. 6. Fatigue Curves of the mixtures

Table 1. Chemical composition of the aggregates used in this research study

Aggregate Type	**Oxide Content (%)**											
	SiO_2	**Al_2O_3**	**Na_2O**	**MgO**	**K_2O**	**TiO_2**	**MnO**	**CaO**	**P_2O_5**	**Fe_2O_3**	**SO_3**	**LOI**
EAF Slag	**20.54**	**4.86**	**0.86**	**5.66**	**0.58**	**0.74**	**0.44**	**28.04**	**0.49**	**28.36**	**0.16**	**8.71**
Limestone	**10.49**	**1.04**	**0.14**	**11.60**	**0.38**	**0.06**	**0.03**	**35.24**	**0.06**	**0.96**	**0.00**	**39.77**

Table 2. Properties of coarse and fine aggregates

Property	Test Method	Limestone			EAF Slag
		Coarse	Fine	Filler	Coarse
Bulk Sp. Gr.	ASTM C-127	2.69			3.412
	ASTM C-128		2.61		
	ASTM D-854			2.76	
Water Absorption (%)	ASTM C-127 & C-128	1.18	1.45		1.49
Los Angeles Abrasion coefficient (%)	ASTM C-131	23.98			11.28
Sand equivalent (%)	AASHTO T-167		69.5		
Fractures particles (two faces) (%)	ASTM D-5821	92			100
Plasticity Index	ASTM D-4318		Non-plastic		

Table 3. Gradation of the SMA mixture

Sieve Size (mm)	Gradation (percent passing by weight)	
	Selected Gradation	Permissible limit (NAPA)
19	100	100
12.5	90	85-95
9.5	47	75 maximum
4.75	24	20-28
2.36	20	16-24
0.600	14	12-16
0.300	13	12-15
0.075	9	8-10

Table 4. The tests result of PG64-22 asphalt

Test	Standard	Unit	Result	Specification Requirement
Density (in 25℃)	**ASTM D70**	**gr/cm^3**	**1.018**	**---**
Flash Point	**ASTM D92**	**℃**	**334**	**Min 230**
Penetration (in 25℃)	**ASTM D5**	**0.1 mm**	**64.3**	**---**
Softening Point	**ASTM D36**	**℃**	**51.2**	**---**
Viscosity @ 135℃	**ASTM D4402**	**Pa.s**	**0.336**	**Max 3**

Table 5. Composition of Asphalt Mixtures

Type of mixture	**Description**	**Additive**	**Mixing and Compaction Temp. °C**
SMA+S	**SMA mixture containing EAF slag as substitute to 75 percent of the coarse fraction**	-----	**Mixing: 165°C** **Compaction: 150 °C**
SMA+N **(Control Mix)**	**SMA mixture containing limestone as coarse, fine, and filler fraction**	-----	**Mixing: 165°C** **Compaction: 150 °C**
WSMA+S	**SMA mixture produced with warm mix additive, containing EAF slag as substitute to 75 percent of the coarse aggregate fraction**	**Sasobit** **(2% by weight of the asphalt binder)**	**Mixing: 140°C** **Compaction: 125-140**
WSMA+N	**SMA mixture produced with warm mix additive, containing limestone as coarse, fine, and filler fraction**	**Sasobit** **(2% by weight of the asphalt binder)**	**Mixing: 140°C** **Compaction: 125-140**

Table 6. Napa requirements for laboratory compacted SMA Mixtures [1]

Property	Requirement	Notes
Void content (%)	**3-4**	**Usually 3.5-4**
VMA (%)	**17 Min**	**---**
Asphalt Content (%)	**6 Min**	**---**
Marshall Stability	**≥6.2 kN**	**---**
Draindown	**0.30 Max**	**---**

Table 7. The summary of Marshall test results

Item	SMA+S	SMA+N	WSMA+S	WSMA+N
			2% Sas	2% Sas
Optimum asphalt Content (%)	6.1	6	6.1	6
Bulk Density	2.723	2.378	2.705	2.372
Marshall stability (kgf)	931	799	816	778
Marshall flow (mm)	2.93	2.68	2.65	2.74
Marshall quotient (MQ) (kgf/mm)	311	299	307	283
Air voids (%)	3.70	3.77	3.71	3.79
Voids in mineral aggregates (%)	17	16.9	17.6	17.2
Voids filled with asphalt (%)	78.3	77.6	79	77.9

Table 8. The result of air void of fatigue test specimens

Mixture	**Va**
WSMA+N	**3.73**
WSMA+S	**3.88**
SMA+N	**3.67**
SMA+S	**3.79**

Table 9. The average fatigue life of SMA and WSMA mixtures

Type of Mixture	Number of cycles to failure at different strain levels			
	600µ	700µ	800µ	900µ
WSMA+N	80990	64970	15007	7790
WSMA+S	102030	61940	14340	7403
SMA+N	80845	64950	22050	19423
SMA+S	152925	54413	24950	15945

Table 10. Fatigue models developed for SMA and WSMA mixtures

Type of mixture	Fatigue Model	Coefficient of determination (R^2)
WSMA+N	**$N_f = 9.71E\text{-}16\ (\varepsilon)^{-6.218}$**	**R^2 = 0/9153**
WSMA+S	**$N_f = 9.15E\text{-}18\ (\varepsilon)^{-6.868}$**	**R^2 = 0/9547**
SMA+N (Control mix)	**$N_f = 1.57E\text{-}8\ (\varepsilon)^{-3.959}$**	**R^2 = 0/8946**
SMA+S	**$N_f = 9.53E\text{-}14\ (\varepsilon)^{-5.640}$**	**R^2 = 0/9875**