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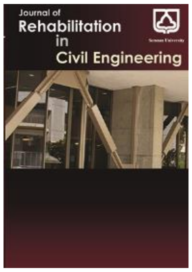

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Fatigue Behavior Analysis of Asphalt Mixes Containing Electric Arc Furnace (EAF) Steel Slag

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ABSTRACT

This research was conducted in order to evaluate fatigue behavior of asphalt mixes containing Electric Arc Furnace (EAF) steel slag. After initial evaluation of the properties of EAF steel slag using X-ray Diffraction (XRD) and Scanning Electric Microscope (SEM), six sets of laboratory mixtures were prepared. Each set were treated replacing various portions of limestone aggregates of the mix with EAF steel slag. Four point bending beam fatigue tests were performed in both controlled strain and stress mode of loading at various strain and stress levels to characterize the fatigue behavior of asphalt mixes containing different percentages of EAF slag. Different approaches based on stiffness and dissipated energy were used to analyze the fatigue tests data. The results show that the inclusion of EAF in mixes improved the fatigue life considerably under both stress and strain control mode of loading. In the stress control mode, very good correlations were observed between responses and fatigue life of mixes. However, correlation coefficients in the strain control mode were relatively lower than those in the stress control mode (particularly in the tests that were based on 50% reduction of initial stiffness).

1. Introduction

Steel slag is a byproduct of the steel industries which is used as aggregates in unbound layers of pavement; it is also used in asphalt layers as base or surfacing courses. Basic Oxygen Furnace (BOF) slag and Electric Arc Furnace (EAF) slags are the two most commonly used slags in asphalt mixes [1-3]. The annual output of steel slag in Iran is more than 3 million tons which most of them are disposed. Approximately 50% of the steel produced in Iran comes from electric arc furnaces (EAF). On the other hand, the demand of natural aggregate resources causes environmental problem and increase the cost of projects sharply because of lack of such aggregates. Some positive physical characteristics of these products include high specific gravity, angular shape, and rough surface texture, make steel slag suitable material in asphalt mixes which could be resulted in decreased rehabilitation cost [4 , 5].

Fatigue cracking is a major distress mode in flexible pavements. The strain resulting from horizontal tensile stresses ultimately leads to fatigue failure after certain number of load repetitions [6]. The physical properties and performance of HMA is governed by the properties of the aggregate (e.g., shape, surface texture, gradation, skeletal structure, modulus, etc.), properties of the asphalt binder (e.g., grade, complex modulus, relaxation characteristics, cohesion, etc.), and asphalt aggregate interaction (e.g., adhesion, absorption, physiochemical interactions, etc.). As a result, the properties of asphalt mixtures are very complicated [7]. Fatigue performance is also affected using different types of aggregate. Bazin and Saunier (1967) evaluated the fatigue behavior based on several types of aggregate and concluded that the type of aggregate plays an important role in the fatigue behavior of the mixes [8, 9]. Accurate prediction of the fatigue life of asphalt mixtures is a difficult task due to the complex nature of fatigue phenomenon under various material, loading, and environmental conditions. For the past several decades, significant research efforts have focused on developing reliable fatigue prediction models. However, better understanding of this fatigue behavior of asphalt pavements particularly as newer materials are being used in HMA pavements is needed.

Although several works performed on bituminous mixes containing steel slag, have shown improved resistance of these mixes against rutting and cracking, few studies were conducted to study their fatigue behavior. In a research work, it was shown that replacing a fine crushed sand with steel slag resulted in improved stiffness and tensile properties of these mixes [10]. These authors showed also that coarse steel slag, combined with limestone and various filler portions and a polymer modified binder, resulted in great fatigue life and resistance of HMA mixes against permanent deformation. In an other research by Airey et al., BOF and BF slags combination have been used to produce both the base material as well as the surfacing material. This research shows that the fatigue performance of the slag mixtures was found to be comparable to that of the control mixtures [11]. Other researchers replaced 0, 25, 50, 75, and 100% of limestone coarse aggregates of an HMA mix with steel slag and found that replacing up to 75% of limestone coarse aggregates with steel slags improved mechanical properties of asphalt mixes [12]. In other research works, two types of EAF steel slags were substituted with mineral aggregates [13, 14]. These researchers found that at the same stress level, as the stiffness was increased, less deformation was developed and consequently cracking resistance of mixes were increased. Mixes containing slag exhibited greater fatigue resistance compared with the conventional HMA mix. Mechanical properties of asphalt mixes containing waste concrete and steel slag were determined in another research [15]. Using three types of aggregates; namely dacite, recycled concrete and steel slag, these researchers found that fatigue life of a mix containing steel slag was significantly greater than that of the control HMA mix [15].

Although few studies were conducted about fatigue behavior of asphalt mixes containing slag (as mentioned above), but a compressive study which concentrate on this topic has not been performed. Hence, the major objective of this study was to analyze the fatigue behavior of asphalt mixes containing EAF steel slag aggregate.

2. Experimental Program

2.1. Materials

Two types of aggregates namely limestone, and steel EAF slag from Mobarakeh Steel complex were used to be mixed in various proportions. The binder was 60/70 penetration bitumen from Refinery of Isfahan. The main physical and mechanical properties of the aggregates and bitumen are reported in Tables 1 and 2.

Table 1. Physical and mechanical properties of aggregates

Test	Standard	Limestone Aggregate			Steel Slag		
		Coarse	Fine	Filler	Coarse	Fine	Filler
Bulk Specific Gravity	ASTM C-127	2.65			3.05		
	ASTM C-128		2.58			2.95	
	ASTM D-854			2.76			---
Water Absorption (%)	ASTM C-127& 128	1.1	1.5		1.8	2.1	
Los Angeles coefficient (%)	ASTM C-131	20.4			13.4		
Frost action (%) (with Na_2SO_4)	ASTM C-88	0.1	2.04		0.2	0.5	
Sand Equivalent (%)	AASHTO T-167		72.8			78.8	
Fractured Particles (≥two faces) (%)	ASTM D-5821	80			98		
Index of aggregate particle shape and texture	ASTM D3398	10.8			12.7		
Uncompacted Void Content of fine and Coarse Aggregate	AASHTOT304-96 and AASHTO T 326-05	42	45		53	52	

Table 2- Physical properties of bitumen

Test	AASHTO Standard	Result
Density of Bitumen (g/cm^3)	T-228	1.013
Penetration, (0.1 mm), 100 g, 5 s	T-49	63.7
Softening point (°C)	T-53	51.7
Kinematic viscosity, @135 °C, mm^2/s	T-201	688
Ductility, cm, (25 °C)	T-51	>100
Flash point (°C)	T-48	289

2.2. XRD and XRF analysis

Chemical and mineralogical composition of EAF steel slag and limestone aggregate were determined applying XRD and XRF testing methods. Through pick points and pattern analysis of X Rays, with using a software (X-Pert MPD), each pick is attributed to one or several probable crystalline phases. Figure 1 presents XRD spectrum of the steel slag used in this research.

XRD spectrum pattern of the steel slag was very complicated and involved a large number of spots. The high overlapping spots implied the presence of considerable amounts of inorganic materials in EAF. The crystalline structure of the material and its chemical components formation are related to the cooling process that is applied in the factory. A low speed cooling will result in a more crystalline structure of the material. Due to the gradual slow cooling process of the EAF molten slag at the first 20 hours (after being tapped out from the furnace), EAF steel slag does not have enough time to develop a crystalline structure. After this timing in the factory, the slag is being cooled to ambient temperature by spraying water on it. As a result of this, the slag solidifies in a glassy amorphous structure. The high background line (i.e. the almost horizontal black line in Figure 1) implies that part of the components of the slag is in amorphous state. Although the sub-peak surfaces were measured, it was not possible to detect these materials through the analysis. However, the visual inspection implied that almost one third of these components were amorphous.

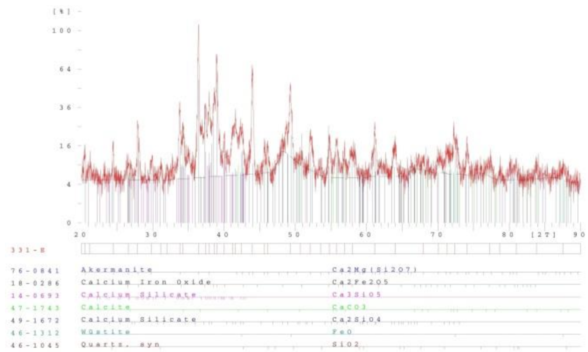

Figure 1- XRD Spectrum result of the tested steel slag

With reference to Table 3, the main mineral components of Mobarakeh EAF steel slag were found to be Fe_2O_3, CaO, and SiO_2. The presence of aluminum oxide together with other metallic elements in the slag components are probably the main contributor of the high abrasive resistance of the slag materials. CaO/SiO_2 ratio implies that the EAF slag is substantially of alkaline nature. This would of course contribute to the adhesion properties of EAF samples in bituminous mixes[13, 14].

Table 3- Chemical composition of EAF slag and limestone

Aggregate Type	Oxide content (%)													
	SO_3	L.O.I	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	P_2O_5	Sr	Na_2O	MnO	V
Limestone	0.39	41.59	5.56	0.67	0.38	45.8	5.7	0.17	---	0.06	0.02	---	---	---
EAF	0.48	1.11	17.47	4.03	25.75	38.86	5.01	0.25	2.11	1.5	0.03	0.34	2.32	0.69

2.3. Morphological characteristics

Scanning Electron Microscope (SEM) was used to evaluate and compare surface characteristics, pore dimensions, and crystalline properties of the steel slag and those of the control limestone aggregates. Figure 2 shows the surface of the mineral aggregates magnified 7500 times. SEM photos showed that EAF steel slag has a rough surface and it has a coarser texture (compared with the limestone aggregate). Due to high surface porosity of the slags and more absorbed bitumen on their surfacing, it is expected that these materials exhibit strong adhesion with bitumen.

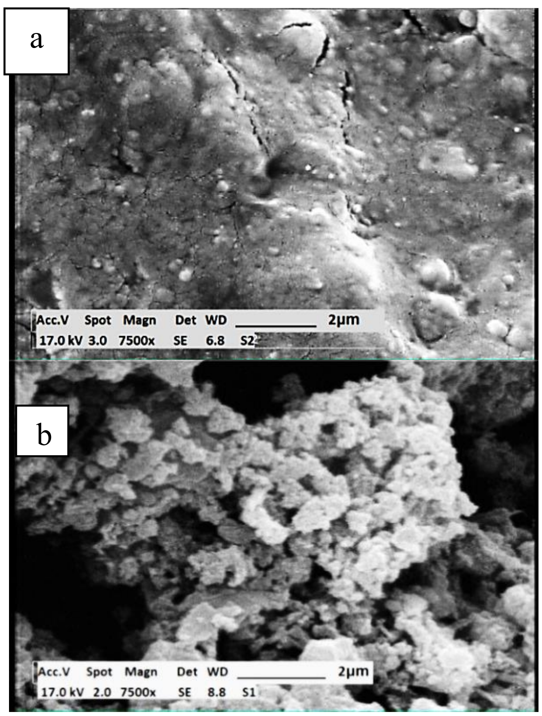

Figure 2. Morphological characteristics of aggregates from SEM photos (a: limestone aggregate, b: slag aggregate)

2.4. Mix Design

Marshall mix design method (ASTM D-6927) was used to determine the optimum binder contents of the various mixes. Some 100 Marshall specimens, consisting of six sets of samples that contained different slag contents were prepared. These included two distinct sets of the specimens ranging from control limestone aggregates (L) to purely steel slags (E-F). The rest of four sets were consisted of combined mixes in which 25% (E-25), 50% (E-50), 75% (E-75), and 100% (E-100) of the limestone coarse aggregate particles ($\geq$2.36mm) were replaced with EAF slag materials. Aggregates gradation were selected based on maximum nominal size of 12.5 mm. At first, the optimum binder contents of the above mix compositions were determined. Then, the trend of variation in Marshall parameters, due to the addition of EAF materials were analyzed. Table 4 reports the results.

The results indicated that the optimum binder contents were greater in mixes containing larger amounts of EAF. Marshall stability was increased as a result of increased EAF ratio. This at 60ºC in E-F mixes were almost 50 percent greater than that in the control mix. This might be as a result of greater internal friction of EAF slag materials. In fact, the slag had quite sharp particles and very high angularities. These properties will surely play an important role in increasing Marshall stabilities. Flow values were generally similar in both mixes. The substitution of limestone with EAF materials resulted in increased densities in mixes too. This is was a result of greater densities of EAF materials. In the control specimen, VMA value was determined to be 14.6%. While this varied from 15.2 to 18.2% in mixes containing various amounts of EAF materials.

2.5. Fatigue Testing

Although various fatigue testing could be performed, in this research four points bending test method was used to assess fatigue resistance properties of slag content mixes. AASHTO T321-07 testing method was followed to prepare and test the beam specimens. Slab samples were prepared and were cut at beam sizes of 380×63×50 mm. Fatigue tests were conducted both at stress and strain control modes. A fixed frequency of 10 Hz was applied and all the tests were performed at 20˚C. Testing were continued until the specimens were failed. Three stress levels of 800, 1000 and 1200 kPa and three strain levels of 500, 700 and 800 micro strains were applied. The reason of selecting these stress and strain levels, was the fact that these levels resulted in three different fatigue lives which were between 10000 to 1000000 fatigue lives (based on standard). At each stress and strain level, three samples were tested and their average results were reported. Sinusoidal wave form testing mode was applied since it produced the intended stress and strain wave form that occurs in field conditions [16]. Bulk specific gravity of the beam samples were determined before that these were tested under fatigue. This was in order to make sure that the air void contents of the samples conform with the ranges suggested by the above mentioned standard method. All the specimens were placed in a temperature controlled cabinet at 20˚C for at least 6 hours before testing.

Table 4. Marshall testing results

Items	L	E-25	E-50	E-75	E-100	E-F	Specifications
Optimum Asphalt Content (%)	4.6	4.7	4.9	5	5.2	5.7	-
Density (g/cm3)	2.37	2.43	2.49	2.54	2.57	2.59	-
Marshall Stability (kg.f)	1080	1170	1300	1370	1400	1580	≥800
Marshall Flow (mm)	4.1	3.8	3.9	4.0	3.9	3.9	3-5.3
Marshall Quotient (kg.f/mm)	263	308	333	342	359	405	-
Air voids (%)	4	4	4	4	4	4	3-5
Voids in Mineral Aggregate (%)	14.6	15.2	16.4	16.7	17.0	18.2	A
Voids Filled with asphalt (%)	70	70	74	75	75	72	60-75
Effective Asphalt content (%)	4.32	4.34	4.27	4.2	4.31	4.41	-
Dust to Binder Ratio ($P0.075/P_{be}$)	1.15	1.15	1.17	1.19	1.16	1.13	0.6-1.2

3. Results and Discussion

In this research, fatigue life (failure criterion) of mixes were determined based on the following methods:

a) 50% reduction of initial stiffness;

b) Rowe and Bouldin method (by plotting the stiffness ratio versus the number of load cycles); where fatigue life is defined as the peak of the curve [17]; and,

c) Pronk and Hopman method, based on dissipated energy (by plotting stiffness ratio versus number of load cycles); where fatigue life is defined as peak of the curve [18]); and,

d) RDEC method: As an energy based approach, RDEC is fundamental and has been demonstrated to be valid for different testing methods such as flexural bending beam fatigue, uniaxial tension, and various materials, including both asphalt concrete and Portland Cement Concrete mixes [19, 20].

Figure 3 shows initial stiffness of specimens at strain and stress control modes of loading. This figure indicates that incorporating EAF slag, does not change initial stiffness of mixes considerably (except for E-100 and E-F mixes). The high stiffness of these mixes is probably attributed to high angularities of slag particles.

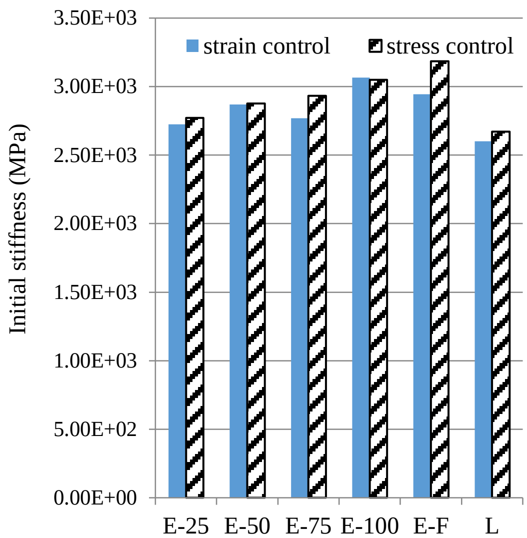

Figure 3. Initial stiffness of specimens

Figures 4 to 7 report fatigue lives of mixes at different strain levels, based on Rowe and Bouldin, Pronk and Hopman, method of 50% reduction of initial stiffness, and RDEC method. As shown in these figures, the fatigue lives (obtained from all the above mentioned methods) were increased with increasing slag ratios. Maximum fatigue life was achieved with E-100 mix. The increase in fatigue life, as observed from the experimental fatigue testing results, was probably due to the increased adhesion between bitumen and slag particles, strengthening the interface and help to prevent aggregate particles from movement.

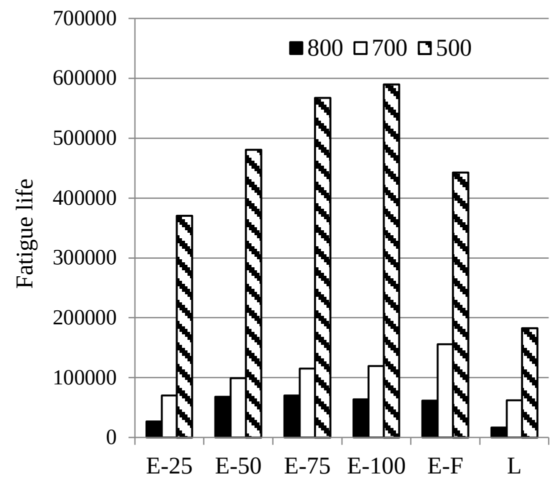

Figure 4. Fatigue life of specimens based on Rowe and Bouldin method (Strain control)

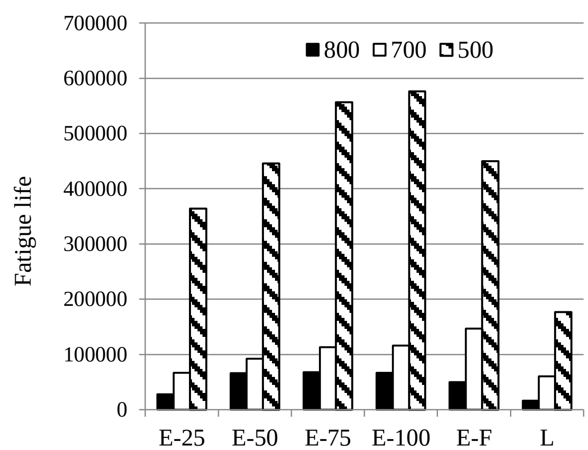

Figure 5. Fatigue life of specimens based on Pronk and Hopman method (Strain control)

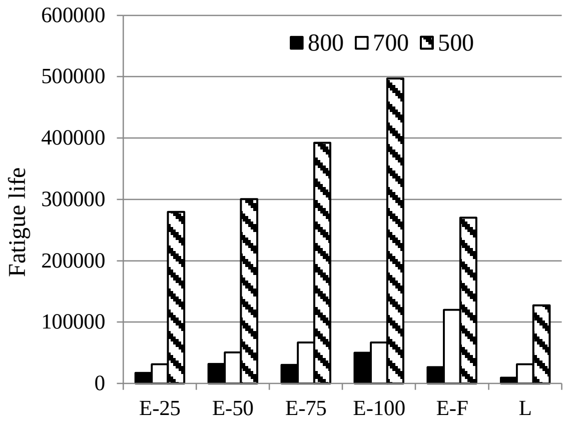

Figure 6. Fatigue life of specimens based on 50% stiffness reduction method (Strain control)

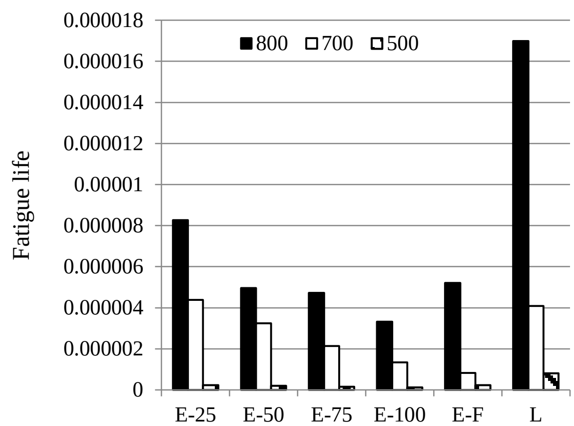

Figure 7. PV of specimens (Strain control)

Figures 8 to 10 report fatigue lives of mixes at different stress levels, based on Rowe and Bouldin, Pronk and Hopman, and RDEC methods. As shown in these figures, similar to strain control mode, the fatigue lives, derived from all the above methods, were increased as a result of increased slag ratios.

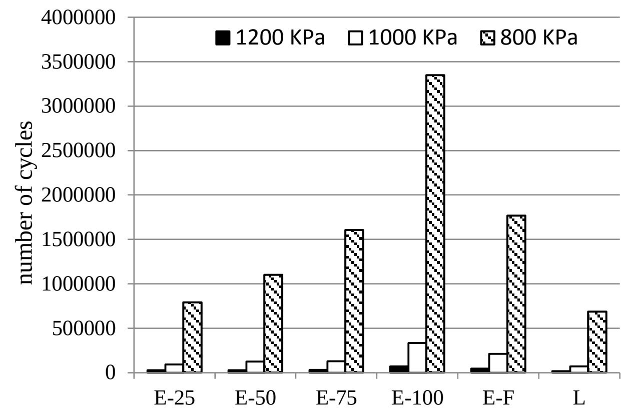

Figure 8. Fatigue life of specimens based on Rowe and Bouldin method (Stress control)

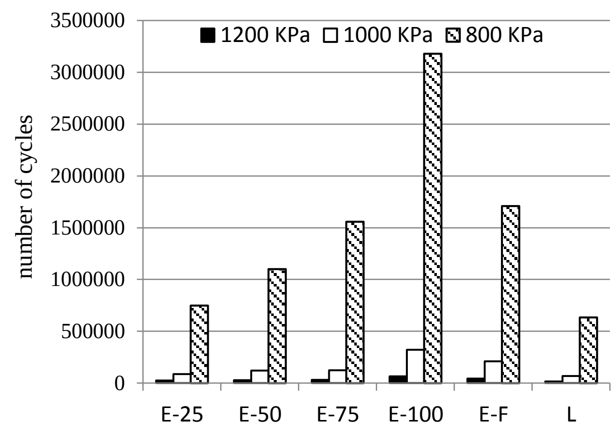

Figure 9. Fatigue life of specimens based on Pronk and Hopman method (Stress control)

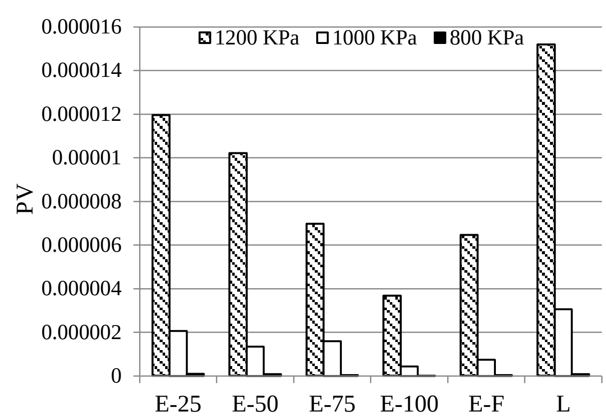

Figure 10. PV of specimens (Stress control)

The increased fatigue lives were more pronounced at strain control mode testing. Maximum fatigue life was achieved again with E-100 mixes. Table 5 reports the average fatigue life of the specimens. As it can be noticed from this table, fatigue lives based on 50% stiffness reduction were generally lower than those obtained from the other methods. Fatigue life of mixes obtained from Rowe and Bouldin, and Pronk and Hopman methods were almost similar. The differences between fatigue lives of mixes were considered to be mainly due to the definition of failure criteria of each of the above methods.

Table 5. Average fatigue life of specimens based on different methods

Method	Rowe and Bouldin			Pronk & Hopman			50% stiffness reduction		
stress level (kPa)	1200	1000	800	1200	1000	800	1200	1000	800
E-25	27043	90617	789260	27117	88170	747720	22390	81646	739642
E-50	27517	124857	1099217	28893	120613	1099403	20780	95953	959957
E-75	31793	129707	1606063	33043	125630	1557133	27500	95200	1308934
E-100	69847	332577	3349967	67257	322157	3178633	49090	309900	2847083
E-F	46287	209287	1767267	45713	210410	1708000	35556	193090	1419443
L	15260	69903	688127	15433	70193	633190	13690	55286	661940
Strain level (micro strain)	800	700	500	800	700	500	800	700	500
E-25-A	26840	70536	370350	27666	66883	364150	17123	31046	279353
E-50-A	68183	99196	480470	65966	92166	446240	31583	50740	300443
E-75-A	70506	114983	566940	67833	113333	556666	30353	66613	392083.3
E-100-A	64136	119680	589820	66666	115833	576666	50163	66830	497226
E-F-A	61563	155810	442383	49666	146500	450000	26556.67	120120	270116
L-A	16693	62540	182635	16000	60500	176666.7	9240	31290	127500

Fatigue life results (obtained from all the above mentioned methods), both at stress and strain control modes, indicated that mixes containing EAF materials had higher fatigue lives, compared with those in the control mix. Since the stiffness of mixes do not change considerably (except for E-100 and E-F mixes), the increased fatigue lives might be as a result of high angularities of EAF slag particles (resulting in better internal friction). In addition, enhanced adhesion between EAF aggregate particles and bitumen will result in preventing crack initiation and propagation throughout the asphalt mix which will finally result in increased fatigue life of mixes.

As previously stated, a mix containing 100% coarse aggregates of EAF slag exhibited the highest fatigue life at both stress and strain control modes with greater fatigue lives at stress control mode. This might be justified as a result of increased stiffness of these mixes. In fact, mixes with a greater stiffness are more resistant to cracking under stress-controlled fatigue testing. In strain-controlled mode testing, the increased fatigue life might be due to better adhesion between bitumen and aggregate particles which may be shown by increased toughness of mixes at IDT testing.

4. Statistical and Regression Analysis

Statistical analysis was carried out in order to evaluate the significance of the amounts of EAF slag in mixes, affecting the testing results. The aim was mainly to control whether the differences in the testing results were due to experimental error or due to the addition of slags in mixes. With this purpose, t-test was carried out. The aim of t-testing is to test for the significant differences between variables or treatment means. This test was carried out using SPSS software. The results are significant whenever the P value is less than the selected significance level, which is usually 5%.

In this work, the t-testing was performed to study the significance of EAF addition in affecting fatigue life of mixes. The results indicate that in mixes containing EAF slag at 500 and 800 micro strain levels, the differences in fatigue lives at strain controlled mode (based on Pronk and Hopman and Rowe and Bouldin methods) were significant and the differences were due to the amounts of EAF slag in the mix. However, at 700 micro strain level, the differences in the means of fatigue life of mixes containing more than 75% EAF slag was significant. As expected, the same results were obtained with Pronk and Hopman and Rowe and Bouldin methods.

Statistical analysis of the achieved fatigue lives (based on Pronk and Hopman, and Rowe and Bouldin methods) at stress control mode, indicated that irrespective of the stress level, the differences in the means of fatigue life in mixes containing 50% or greater EAF slag was significant and the differences were due to the addition of EAF slag to a mix.

In order to develop fatigue models of asphalt mixes containing various amounts of EAF slag, a series of regression analysis were drawn and regression coefficients were determined to draw a series of fatigue models. Using regression equations along with software aided analysis, models can be developed to predict fatigue behavior of mixes. In order to develop fatigue models, fatigue lives based on 50% reduction of initial stiffness were used. Regression analysis of the results for the different models are reported in Table 6.

Table 6. Fatigue models for all mix compositions

Mix ID	$a(\frac{1}{\sigma_{N50\%}})^c$	R^2	Mix ID	$a(\frac{1}{\varepsilon_{N50\%}})^c$	R^2
Stress control			Strain control		
E-25	$3.39E33(\sigma_{N50\%})^{-9.524}$	0.9322	E-25	$3.55E22(\varepsilon_{N50\%})^{-6.329}$	0.9686
E-50	$8.43E32(\sigma_{N50\%})^{-9.259}$	0.9805	E-50	$1.03E20(\varepsilon_{N50\%})^{-5.376}$	0.9194
E-75	$1.50E35(\sigma_{N50\%})^{-10.000}$	0.9529	E-75	$1.71E21(\varepsilon_{N50\%})^{-5.780}$	0.9438
E-100	$1.64E35(\sigma_{N50\%})^{-9.901}$	0.9599	E-100	$2.712E21(\varepsilon_{N50\%})^{-5.814}$	0.8973
E-F	$1.31E33(\sigma_{N50\%})^{-9.259}$	0.9733	E-F	$2.19E21(\varepsilon_{N50\%})^{-5.814}$	0.787
L	$1.50E33(\sigma_{N50\%})^{-9.434}$	0.9728	L	$5.99E20(\varepsilon_{N50\%})^{-5.780}$	0.8832

For the stress controlled mode testing results, very good correlations were observed between responses and fatigue lives at all the regression models. However, R2 values in the strain control models were relatively less than those in the stress control mode testing results, specially for the models based on 50% reduction of initial stiffness.

5. Conclusions

From the laboratory tests that were carried out on limestone mixes containing various amounts of EAF slags in this research, the following conclusions can be drawn:

Increased slag contents resulted in increased Marshall Stability and Marshall Quotient parameters. This was attributed to rougher texture of slag aggregates providing more angularity compared with limestone aggregates.

SEM photos of the slags showed that these material have a rough surfaces and angular particles. This could indicate that these materials can develop stronger adhesion with bitumen, compared with conventional mixes.

The results show that the inclusion of EAF in mixes improved fatigue life of mixes considerably. This finding was confirmed by performing fatigue testing under stress and strain control modes and the other different methods of analysis.

Statistical analysis results indicated that at 500 and 800 micro strain levels, the differences in the means of fatigue life (in strain control mode), based on Pronk & Hopman and Rowe and Bouldin methods for mixes containing EAF slag, were significant, indicating that the differences were due to the addition of EAF slag. In contrast, at 700 micro strain level, the difference in the means of fatigue life of mixes containing more than 75% EAF slag was significant.

Statistical analysis of the fatigue lives, based on Pronk & Hopman and Rowe and Bouldin methods in stress control mode, showed that irrespective of stress level, the differences in the means of fatigue life of mixes containing 50% or more EAF slag were significant and the differences were mainly due to the addition of EAF slag.

With stress controlled mode fatigue testing results, good correlations were observed between responses and fatigue lives of mixes applying all the regression models. However, the coefficient of determination (R2) in strain control modes, were relatively lower than those in stress controlled mode.

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