Evaluation of Long Term Ageing of Asphalt Mixtures Containing EAF and BOF Steel Slags

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Abstract

This study was conducted in order to evaluate the effects of long term ageing on toughness and resilient modulus of asphalt concrete mixtures containing Electric Arc and Basic Oxygen Furnace steel slags. After initial evaluation of the properties of steel slags using X-ray Diffraction and Scanning Electric Microscope, eleven sets of laboratory mixtures were prepared. Each set was treated replacing various portions of limestone coarse aggregates of the mixture (≥ 2.36 mm) with steel slags. The main laboratory program consisted of the determination of resilient modulus at three testing temperatures of 5, 20 and 40˚C (ASTM D4123) and indirect tensile strength of the samples at 20˚C. In order to evaluate the long term performance of mixtures containing slags, the specimens were subjected to ageing according to AASHTO PP2 standard method. Results showed that the peak tensile strength, area up to peak tensile strength and total dissipated energy density of the specimens containing Electric arc furnace slag were greater than the control mixtures. Fracture energy was almost the same for both mixes containing basic oxygen furnace slag and limestone. Results also indicated that the resilient modulus of mixtures increased along with an increase in slag contents in asphalt mixtures. The ratio of aged to unaged resilient modulus of the specimens decreased upon increasing slag contents. It was concluded that mixtures containing electric arc furnace slag exhibited less susceptibility to ageing compared with mixtures containing basic oxygen furnace slag and limestone. At 5oC, the highest ratio belonged to control mixtures, which might indicate that at lower temperatures, the susceptibility to ageing of the control mixtures were more pronounced

Keywords: EAF and BOF slag, resilient modulus, IDT, fracture energy, ageing

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1. Introduction

Lack of mineral aggregates and environmental issues lead to a progressive increase in using recycled materials in road construction. Steel slag, a byproduct of steel industries, is one of the recycled materials. Annual production of steel slags in Iran exceeds 3 million tons, most of which are disposed of. It is the specific physical characteristics of these products, including high specific gravity, angular shape, and rough surface texture make steel slags prone to be used in asphalt mixtures. One of the major drawbacks of steel slags in pavement layers, which should be controlled, is their volume expansibility potential owing to free lime and magnesium hydration [Waligora et al. 2010, Sofilić et al. 2010]. Basic Oxygen Furnace (BOF) slag and Electric Arc Furnace (EAF) slags are the two most commonly used slags in asphalt mixtures [Shaopeng and Yongjieet al. 2006,2007, Sofilić et al. 2010].BOF slag is a byproduct in batch processing of steel production factories when iron is converted to steel. The slag is produced by blowing oxygen into molten iron mixed with additional fluxes and recycled steel scrap. The process refines iron by fusion with a flux, such as limestone or dolomite, under oxidizing conditions. Impurities in iron, such as carbon and silicon, are either oxidized to gases or chemically combined with slag. Electric Arc Furnace (EAF) steel slag is produced in an electric induction furnace [Airey, et al. 2004 and Xie, et al. 2013].

Hot Mix Asphalt (HMA) is composed of graded aggregates bounded with a mastic mortar. Physical properties and performance of HMA is governed by properties of aggregates, including shape, surface texture, gradation, modulus; and bitumen binder properties, including grade, complex modulus, relaxation characteristics and cohesion. In addition, interaction of bitumen and aggregates in a mixture will result in exhibiting desired mechanical properties which of course are very complicated [You and Buttlar 2004].Asphalt mixtures containing steel slag, similar to conventional asphalt mixtures, unavoidably encounter aged-hardening due to oxidation of bitumen binder. The bitumen in asphalt mixtures hardens as a result of ageing process, thus increasing the mix stiffness. Hardening was primarily associated with loss of volatiles in asphalt during the construction phase and progressive oxidation of the in-place material in the field [Bell, 1989]. On the other hand, it was suggested that susceptibility towards ageing is aggregate dependent [Bell and Sosnovske, 1994]. This is in conformity with the findings of the study by Hamzah and Teoh (2008) where the authors found out that mixtures incorporating 100% steel slag are less susceptible to ageing compared with mixtures containing 50% granite aggregates [Hamzah and Teoh, 2008]. A hypothesis indicated that the greater the adhesion, the greater would be mitigation of ageing [Belland Sosnovske, 1994].Hence, ageing of asphalt-aggregate mixtures is influenced by both asphalt and aggregate. Assessing ageing of asphalt alone does not appear to predict the mixture performance adequately due to the apparent mitigation effects which aggregate has on ageing. Aggregate chemistry plays a key role in adhesion. Each aggregate of a given mineralogical type with a specific history has a unique surface chemistry. The electro kinetic properties as well as the electron donating and accepting abilities of the aggregate vary according to the active metal species on the aggregate surface. Evaluation of asphalt-aggregate interactions shows that the aggregate chemistry is much more influential than the asphalt composition for both adhesion and sensitivity to water. Ageing of asphalt in road pavement occurs in the presence of aggregate. Hence, it is normal to evaluate ageing process with aggregate present [Belland Sosnovske, 1994]. Moreover, the nature of the aggregate directly affects its adhesion to bitumen and its resistance to fragmentation. Therefore, if aggregate-bitumen adhesion is poor (because of its chemical properties [Petersen, 2002]), this produces many weak points where cracking process will eventually develop and propagate throughout the asphalt mixture. The results of another study showed that the coarse aggregate type is an important factor that can considerably affect fatigue life of the mixtures [Moreno and Rubio, 2013].

Previous studies suggested that asphalt mixtures incorporating steel slag aggregate may also improve the resistance against rutting and cracking. [Liz Hunt and Glenn, 2000, Esmaeili et al., 2005, Shaopeng, 2007]. Asi et al (2007) replaced 25-100 % of the coarse aggregates of a mixture with steel slag and found that the fatigue life and resilient modulus of the slag mixtures were increased appreciably [Asi et al., 2007]. The mixtures with slags in Pasetto and Baldo research always showed higher stiffness modulus values than those with natural aggregate [Pasetto, Baldo, 2010, 2011].

A few studies have been conducted regarding ageing of asphalt mixtures containing steel slag. Airey G.D. et al (2004) showed that using BOF and BFS slag significantly increase the mixture density, stiffness modulus, and susceptibility to age hardening compared to primary aggregate (limestone) mixtures. They believe that the increased hardening (oxidation) of the slag mixtures compared to the control mixture was probably linked to the chemical composition of the slag aggregate, which may act as a catalyst for excessive oxidative hardening of the bitumen. Hamzah and Teoh presented the resilient modulus properties of steel slag asphalt mixtures subjected to short term oven ageing. They found that the susceptibility to ageing is aggregate dependent and indicated that the greater the adhesion, the greater the mitigation of ageing; hence, aged slag mixtures exhibit superior adhesion compared to aged control mixtures.

Therefore, the objective of this study was to investigate the effects of EAF and BOF steel slags on the toughness and resilient modulus of mixtures and evaluating long term performance through ageing the mixtures. Moreover, the two slag types were compared in terms of asphalt mixture properties.

2. Experimental Program

2.1 Materials

Three types of aggregates namely limestone, EAF and BOF steel slag from Mobarakeh steel complex and Isfahan steel company were used to be mixed in various proportions. The binder was 60/70 penetration grade bitumen from refinery of Isfahan. The major physical and mechanical properties of aggregates and bitumen have been reported in Tables 1 and 2.

2.2 Materials Composition

Chemical composition and mineralogical properties of the EAF and BOF slag and limestone used in this research were determined using XRD and XRF method, where a Cu cathode is used to diffract x-ray on the samples. In these tests, The aggregates passing a 4.75-mm (No. 4) sieve and remained on 2.33-mm (No.4) sieve were selected by dry sieving and thoroughly washed to remove dust or other coatings from the surface then used for XRF and XRD testing. Through pick point and pattern analysis of the X rays, using a software (X-Pert MPD), each pick is attributed to one or several probable crystalline phases. The diffraction test was conducted on

Table 1. Physical and mechanical properties of aggregates

Test	**Standard**	**Limestone Aggregate**			**EAF**			**BOF**		
		Coarse	**Fine**	**Filler**	**Coarse**	**Fine**	**Filler**	**Coarse**	**Fine**	**Filler**
Bulk Specific Gravity	ASTM C-127	2.65			3.05			2.78		
	ASTM C-128		2.58			2.95			2.68	
	ASTM D-854			2.76			---			---
Water Absorption (%)	ASTM C-127& 128	1.1	1.5		1.8	2.1		2.2	3.45	
Los Angeles coefficient (%)	ASTM C-131	20.4			13.4			19.6		
Frost Action (%) (with Na2SO4)	ASTM C-88	0.1	2.04		0.2	0.5		0.2	0.4	
Sand Equivalent (%)	AASHTO T-167		72.8			78.8		70.2		
Fractured Particles (≥two faces) (%)	ASTM D-5821	80			98			98		
Index of aggregate particle shape and texture	ASTM D3398	10.8			12.7			18.5		
Uncompacted Void Content of fine and Coarse Aggregate	AASHTOT304-96 and AASHTO T 326-05	42	45		53	52	52	50		

Table 2. Physical properties of asphalt cement

Test	AASHTO Standard	Result
Density (g/cm3)	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, mm2/s	T-201	688
Ductility, cm, (25 °C)	T-51	>100
Flash Point (°C)	T-48	289

the samples through changing 2θ angle between 10° to 90°, while the voltage (i.e. electrical current) and ray rotation speed were 40 kV, 30 mA, and 1.2 °/min, respectively. Figure 1 presents XRD spectrum of the EAF and BOF.

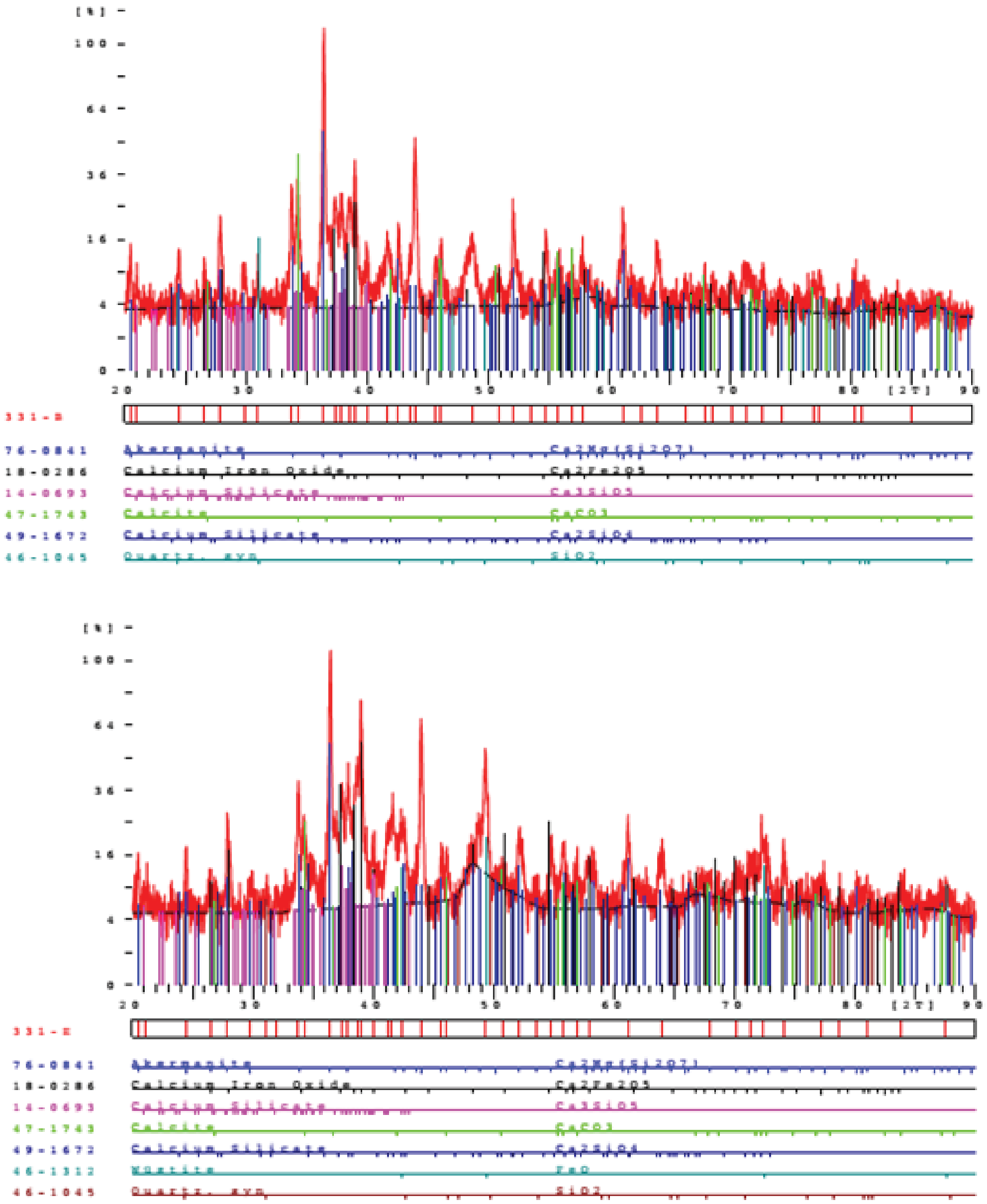

Figure 1. XRD Spectrum result of the tested EAF and BOF

Crystalline mineralogical phases of the steel slags were also analyzed applying X-PERT software. In the output graphs, vertical and horizontal axes depict partial intensity and 2θ parameters, respectively. XRD spectrum pattern of both steel slags were very complicated and involved a large number of spots. The high overlapping spots implied the presence of considerable amounts of inorganic materials in slags. 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 molten slags during the first 20 hours (after being tapped out from the furnace), steel slags do 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 the 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.

As it can be seen in Table 3, the main mineral components of EAF and BOF slag were Fe_2O_3, CaO, and SiO_2. The presence of aluminum oxide with other metallic elements in slag components is the main contributor for the high abrasive resistance of the slag materials. The SiO_2/CaO ratio characterizes the slags as substantially alkaline aggregates and therefore suitable to guarantee the necessary adhesion with the weakly acid bitumen [Pasetto and Baldo, 2011].

2.3 Morphological Characteristics

Scanning Electron Microscope (SEM) was used to evaluate and compare surface characteristics, pore dimensions, and crystalline structure of the steel slag and those with limestone aggregates particles. In SEM testing, 4.75mm particles were used. Figure 2 shows the surface of mineral aggregates, magnified to 1000X. It is noted that EAF and BOF steel slags had rougher surface and a coarser texture (compared with the limestone aggregate). Due to the high surface porosity of the slags and more absorbed bitumen on their surfacing, it is expected that these materials exhibit strong adhesion with bitumen. Examination of the SEM photos showed that the limestone aggregates had negligible porosity with very fine grains, while EAF and BOF slag had a coarse texture with a porous surface and abundant pores (with diameter of 1 μm to 1 mm on their surfaces).

Table 3. Chemical composition of EAF and BOF slag and limestone

Aggregate	Oxide content (%)													
Type	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
BOF	0.749	2.31	18.46	4.59	15.57	45.17	4.67	0.29	2.44	1.69	0.04	0.29	3.03	.66

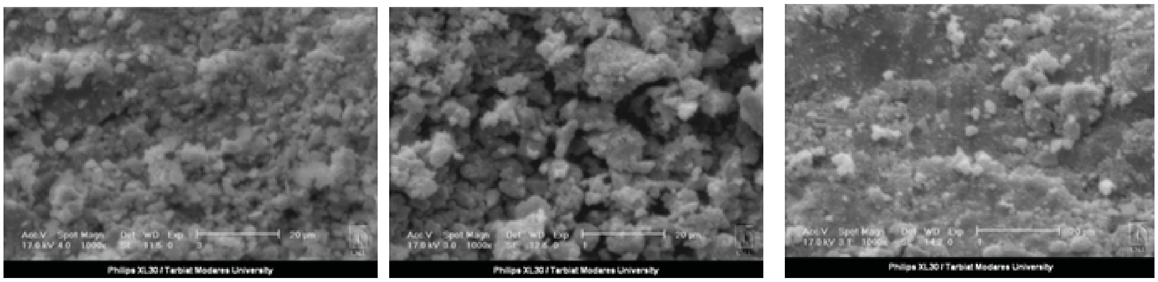

Figure 2. Morphological characteristics of aggregates from SEM photos

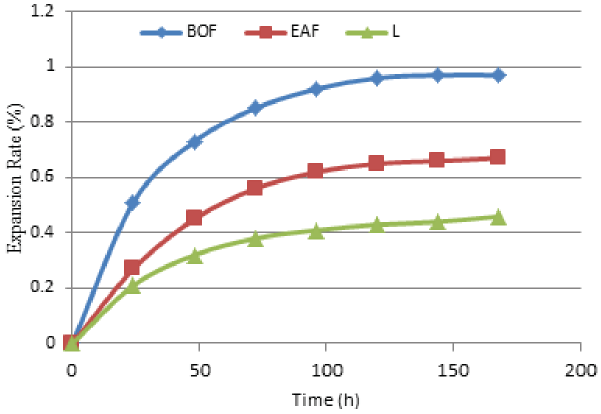

Figure 3. Expansion rates of various mixtures

2.4 Expansion Potential

Expansion potential of asphalt mixtures containing slag materials was determined preparing three asphalt mixtures containing different ratios of slag. The samples were prepared and put in a 60°c water bath (the applied temperature accelerates carbonate hydration process). In the meantime, samples' volumes were measured in 24 lapses. Figure 3 shows volumetric changes of samples, including samples containing purely limestone aggregates with no slags (0.0 %), those containing EAF slag, and the samples containing BOF slag.

As shown in Figure 3, due to the small amount of free carbonate remained in slag, expansion rate for slag mixtures (particularly for BOF slag mixtures) is higher than those of conventional limestone materials. Despite this, as the expansion rates after one week is still less than 1 %, even in the full slag mixture, the expansion potential of slag mixtures can be considered to be negligible in asphalt mixtures.

3. Testing Program

The main laboratory program consisted of determination of resilient modulus at three testing temperatures of 5, 20 and 40˚C (according to ASTM D4123) and Indirect Tensile Strength (ITS) testing (according to ASTM D6931) at 20˚C using a Universal Testing Machine (UTM14). The specimens were placed in the temperature control chamber for at least 6 hours before testing until the target temperature was attained. A total of 99 specimens were prepared. These were divided into two groups. The first group consisted of 33 cylindrical specimens for ITS testing and the second group consisted of 66 specimens for resilient modulus determination. From these, 33 specimens were aged using long-term oven ageing procedure ,which consisted of force-draft oven ageing of compacted asphalt mixture specimens at 85°C for 120 hours according to AASHTO PP2, and 33 specimens were kept unaged. Upon performing resilient modulus testing, the same specimens were used for ITS determination.

4. Mixture Design

Marshall mixture design method (ASTM D-6927) was used to determine the optimum binder contents of the various mixtures. 165 Marshall specimens, consisting of eleven sets of samples that contained different slag contents were prepared. Mixtures included: three control sets i.e. one mixture made with limestone aggregates (L) and two other mixtures, made with purely BOF slag (B-F) and EAF slag (E-F) and eight sets of combined mixtures in which 25 %, 50 %, 75 %, and 100 % of the natural coarse aggregate particles (2.36mm ≤) were replaced with EAF (E-25, E-50, E-75 and E-100) and BOF slag (B-25, B-50, B-75, B-100) materials. Aggregates gradation was selected based on maximum nominal size of 12.5 mm (Figure 4). At first, the optimum binder contents of the above mixture compositions were determined. Then, the trend of variation in Marshall parameters, due to the addition of slag materials, were analyzed. Table 4 reports the results.

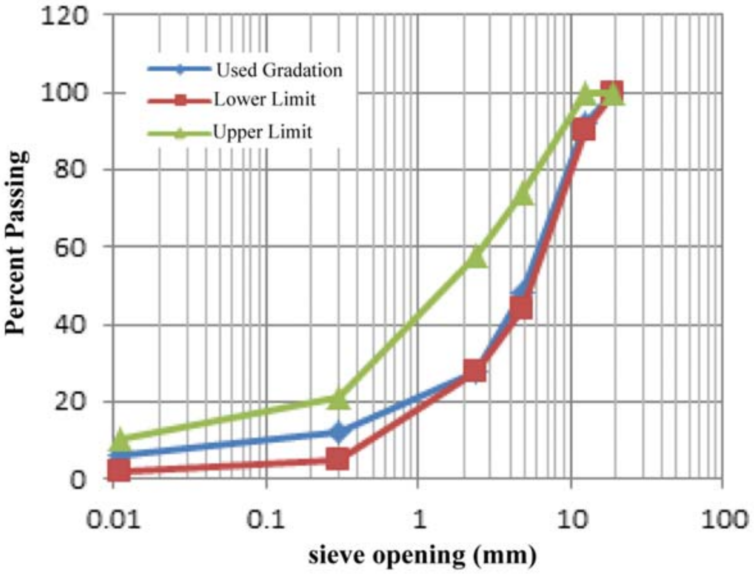

Figure 4. Selected gradation

Table 4. Marshall test results

Items	L	E-25	E-50	E-75	E-100	E-F	B-25	B-50	B-75	B-100	B-F	Specifications
Optimum Asphalt Content (%)	4.6	4.7	4.9	5	5.2	5.7	4.9	5.1	5.2	5.5	7.5	-
Density (g/cm3)	2.37	2.43	2.49	2.54	2.57	2.59	2.39	2.41	2.45	2.47	2.39	-
Marshall Stability (kg.f)	1080	1170	1300	1370	1400	1580	1440	1450	1550	1530	1700	≥800
Marshall Flow (mm)	4.1	3.8	3.9	4.0	3.9	3.9	4.6	4.7	5	4.2	5.2	3-5.3
Marshall Quotient (kg.f/mm)	263	308	333	342	359	405	313	308	310	364	327	-
Air voids (%)	4	4	4	4	4	4	4	4	4	4	4	3-5
Voids in Mineral Aggregate (%)	14.6	15.2	16.4	16.7	17.0	18.2	15.1	15.6	16.2	16.7	19.4	A
Voids Filled with asphalt (%)	70	70	74	75	75	72	75	76	74	76	80	60-75
Effective Asphalt content (%)	4.32	4.34	4.27	4.2	4.31	4.41	4.31	4.35	4.41	4.38	4.25	-
Dust to Binder Ratio ($P0.075/P_{be}$)	1.15	1.15	1.17	1.19	1.16	1.13	1.16	1.15	1.13	1.14	1.17	0.6-1.2

The results indicated that the optimum binder contents were greater in mixtures containing larger amounts of slags. Marshall stability increased as a result of increased slag content. Marshall Stabilities at 60ºC for E-F and B-F mixtures were about 50 percent greater than that of the control mixture. This might be as a result of greater internal friction of slag materials. In fact, the slag had quite sharp particles and very high angularities and these properties will surely play an important role in increasing Marshall stabilities.

Flow values were generally similar in both mixtures. Also, the substitution of limestone with slag materials resulted in increased densities in mixtures. This was a result of greater densities of slag materials. In the control specimen, the VMA value was determined to be 14.6%,while this varied from 15.1 to 19.4% in mixtures containing various amounts of slag materials. The results also showed that the inclusion of both EAF and BOF slags resulted in increased Marshall Quotient parameters. This was attributed to the rougher texture of slag aggregates, providing more angularity compared with limestone aggregates.

5. Testing Results

5.1 Resilient Modulus Testing

Resilient modulus of an asphalt mixture, is an important parameter in elastic theory based pavement design methods. Most paving materials are not elastic but experience some permanent deformation after each load application [Kavussi and Modarres, 2010]. However, if the load is small (compared with the strength of materials), and it is repeated a large number of times, the deformation under each loading is nearly completely recoverable and proportional to the load. In this case, it can be considered as an elastic material [Huang, 2004]. In each mixture combination, three samples were tested in two positions under Diametral Resilient Modulus (Mr) testing at 5, 20 and 40°C (according to ASTM D 4123 standard method). The samples were tested applying a

Haversine loading pulse at 1 Hz, load application with a 0.9-second rest period. The maximum applied loading was 1200 N with 200 repetitions of pre-conditioned loading. For an applied dynamic load of P, the total Mr value was calculated using Eq. 1 as follows:

$$M_r = \frac{P(\mu+0.27)}{t\,\delta_h} \quad (1)$$

Where P is the maximum dynamic load (N); μ the Poisson's ratio (assumed 0.35); t the specimen length (mm); and δ_h the total horizontal recoverable deformation (mm).

Figures 5-7 shows the average resilient modulus of the aged and the unaged samples containing various amounts of slags at different temperatures.

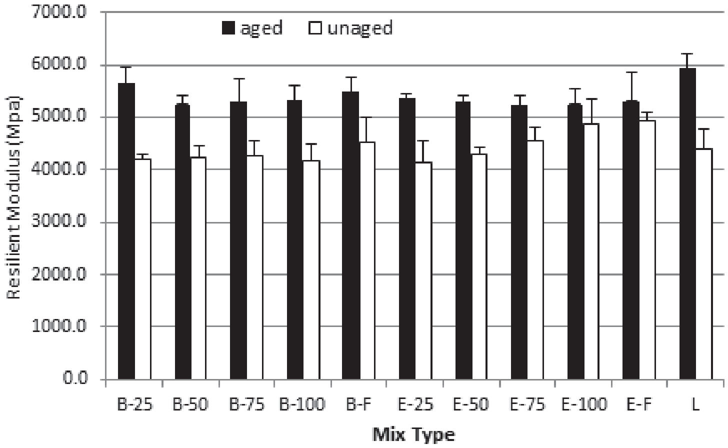

Figure 5. Average resilient modulus of aged and unaged specimens at 5oC

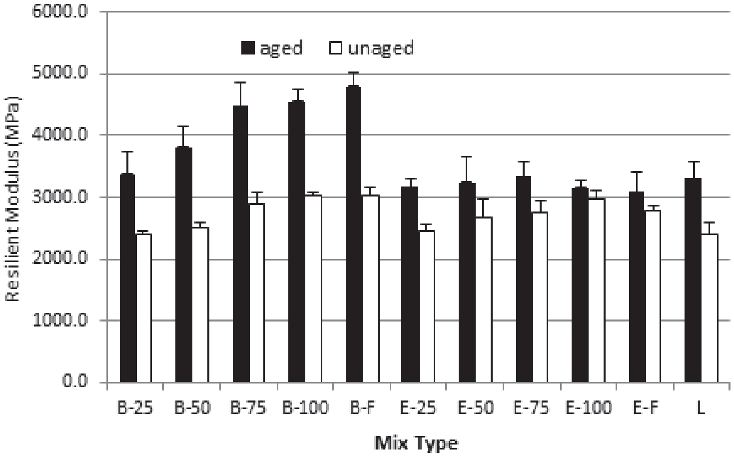

Figure 6. Average resilient modulus of aged and unaged specimens at 20oC

The results indicate that for unaged samples, inclusion of EAF and BOF materials in mixtures resulted in an increase in resilient modulus of mixtures at 20 and 40oC compared with the control mixture. However, at 5oC, only mixtures that contained EAF slag had higher resilient modulus and BOF mixtures showed the same behavior as control mixture. The increase in resilient modulus can be attributed to the angularity of the slags. The resilient modulus of the specimens containing 100% slag, were less than mixtures having100% coarse slag aggregates. This can be due to the increased asphalt cement content in the slag mixtures.

Temperature variations significantly influence the resilient modulus of asphalt mixtures. For the asphalt specimens tested in this work, resilient modulus of mixtures decreased about80% when the test temperatures were increased from 5°C to 40°C. Figures 8 and 9 show the resilient modulus results at different

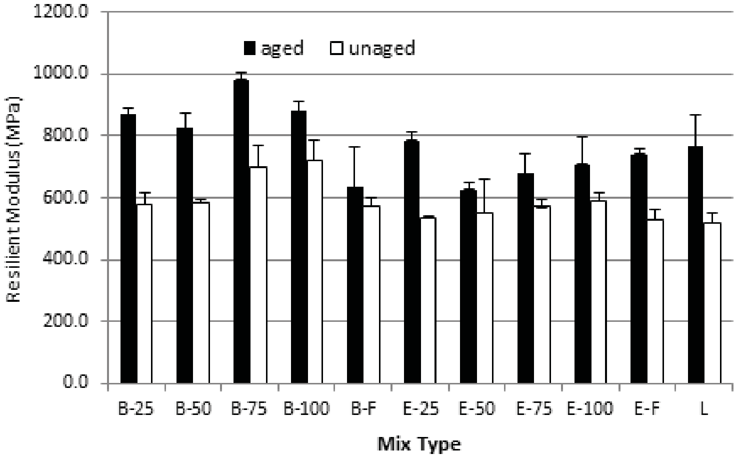

Figure 7. Average resilient modulus of aged and unaged specimens at 40oC

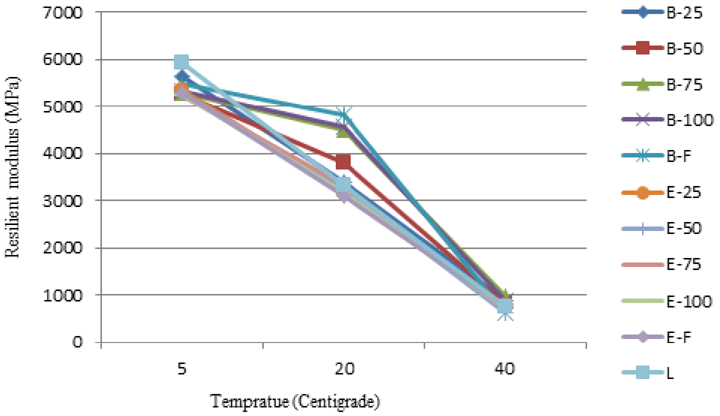

Figure 8. Average resilient modulus at different temperatures of aged specimens

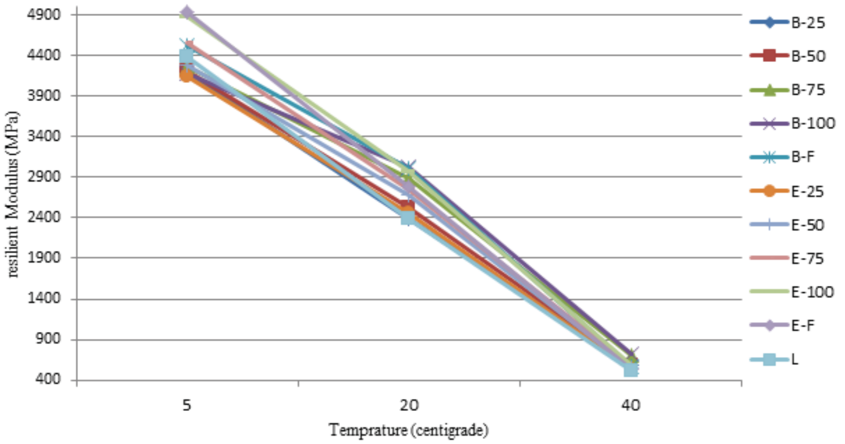

Figure 9. Average resilient modulus at different temperatures of unaged specimens

temperatures of aged and unaged specimens. As it can be seen in these figures, for unaged specimens, the variation of resilient modulus values at different temperatures were almost the same. However, for aged specimens, maximum variation of resilient modulus belonged to the control mixtures. This indicates that the control mixtures were more susceptible to ageing.

The ratios of the aged to unaged resilient modulus of the specimens are shown in Figure 10. As it can be noticed, the ratio of aged to unaged resilient modulus of specimens decreased along with an increase in the slag contents. However, for the specimens containing 100% slag, this ratio increased slightly due to the increased asphalt cement content. This figure also indicates that mixtures containing EAF slag exhibited less susceptibility to ageing compared with BOF and control mixtures. At 5oC the highest ratio belonged to control mixtures. This could indicate that at lower temperatures, the ageing susceptibility of the control mixtures was more pronounced.

5.2 Indirect Tensile Strength Testing Results

The indirect tensile strength test is used to determine the tensile properties of the asphalt concrete which can be further related to the cracking properties of the pavement [Anagnos and Kennedy, 1972]. This test involves loading a cylindrical specimen with vertical compressive loads; this generates a relatively uniform tensile stress along the vertical diametrical plane. Failure usually occurs by splitting along this loaded plane [Aksoy, 2005]. This test was performed at 20oC in indirect tension at 50 mm/min deformation rate. The tensile strength of specimens was determined using Eq.2:

$$S_t = (2 \times P_{ult}) / (\pi \times d \times t) \qquad (2)$$

where: S_t , tensile strength of specimens; P_{ult} , ultimate applied load required to fail specimens; t, thickness of the specimens, d, diameter of the specimens.

Fracture energy density, which is defined as the area under stress–strain curve up to the peak loading, is the potential energy required to cause cracking. This has often been used for fatigue performance comparison purposes of asphalt mixtures since it is able to consider both stress and strain properties in one term

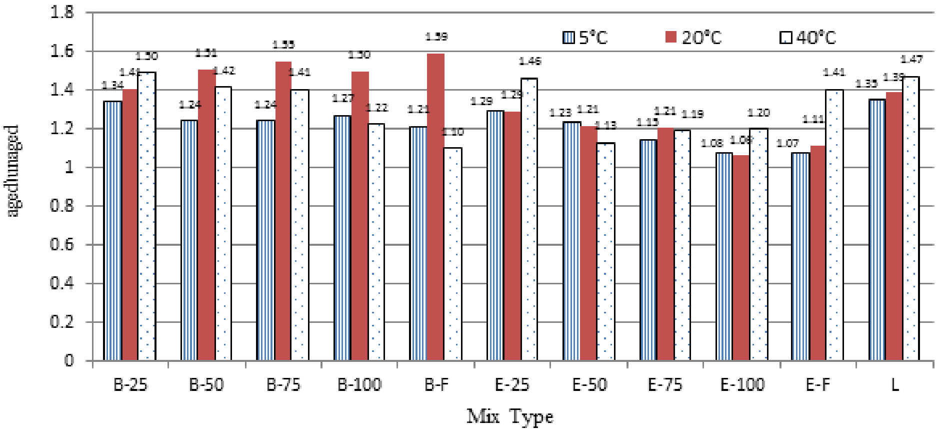

Figure 10. Average ratio of resilient modulus of aged to unaged specimens at different temperatures

until the crack initiation phase [Li et al, 2012]. Visco-elastic materials (e.g. asphalt concrete mixtures) exhibit hysteresis behavior under cyclic loading. By measuring the area of hysteresis loop under cyclic loading, “dissipated energy density” is determined. Unlike elastic materials, in visco-elastic materials, the dissipated energy is not only related to damage growth, but also it is related to time-dependence properties of asphalt mixtures [Lee, 1996]. A typical stress–strain relationship, obtained from ITS testing of an asphalt concrete mixture has been shown in Figure 11. Fracture energy density (FE_{IDT}) is the sum of the elastic strain energy density (EE_{IDT}) and the total dissipated creep strain energy density at failure (DE_{IDT}). Dissipated Creep Strain Energy (DE_{IDT}) was first introduced by Birgisson and Roque [Roque et al., 2002, Birgisson et al., 2007]. It is observed from this figure that FE_{IDT} presents the area under stress–strain curve up to failure and EE_{IDT} is the area formed by failure strain (ε_f), resilient modulus (M_r) and the ITS strength (σ_{IDT}), Besides, DEIDT is the difference between FE_{IDT} and EE_{IDT} [Li et al. 2012]. Calculation of DE_{IDT} depends on resilient modulus and ITS results. The dissipated creep strain energy limit (DE_{IDT}) is determined from Eq.3 as follows:

$$DCSE_{IDT}=FE-EE \tag{3}$$

Where FE is the area under stress-strain curve to failure strain (ε_f); and EE is the elastic energy, determined from Eq.4 as follows:

$$FE=\int_0^{\varepsilon_f} s(\varepsilon)d\varepsilon \tag{4}$$

In research works, it is resulted that the total dissipated energy density is highly correlated with fatigue life of asphalt mixtures [Li et al. 2012]. At a given strain level, a mixture with a high DE_{IDT} presents a good fatigue performance irrespective of mixture type, binder content and volumetric properties. These latter authors stated in their work that DE_{IDT} obtained from IDT testing represents well the fatigue performance of mixtures as DE_{IDT} is the unique engineering property related to fracture resistance of mixtures [Li et al. 2012].

Tables 5-7 indicate the IDT testing results, including the peak tensile strength, area up to peak tensile strength and total dissipated energy density of the samples.

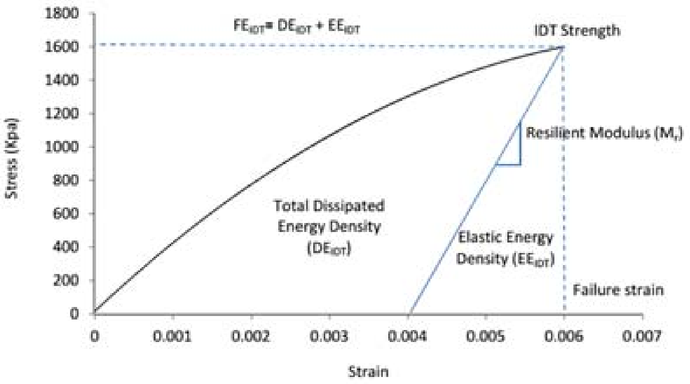

Figure 11. Fracture and dissipated energy density from IDT strength test

Table 5. IDT test results of IDT samples

Mix ID	B-25	B-50	B-75	B-100	B-F	E-25	E-50	E-75	E-100	E-F	L
Peak tensile stress (kPa)	776	741	824	691	764	653	885	756	706	725	620
	797	695	817	727	763	784	744	747	760	720	730
	666	688	637	724	756	744	687	786	781	724	726
Average	746	708	759	714	761	727	772	763	749	723	692
Area up to peak (kPa)	454	408	438	450	438	457	461	559	598	458	441
	439	465	408	456	483	413	470	509	589	548	449
	391	461	456	459	371	477	461	483	455	505	422
Average	428	444	432	455	431	449	464	517	547	503	437
Total Dissipated Energy Density (DEIDT)	318	317	346	374	354	350	426	435	474	465	333
	334	348	323	294	390	315	372	398	471	438	312
	309	353	366	320	303	368	391	383	367	451	308
Average	321	340	345	329	349	344	396	405	437	452	318

Table 6. IDT Test results of aged samples (resilient modulus test samples)

Mix ID	B-25	B-50	B-75	B-100	B-F	E-25	E-50	E-75	E-100	E-F	L
Peak tensile stress (kPa)	783	724	890	665	682	772	765	664	768	787	772
	842	748	739	754	714	745	655	777	730	815	718
Average	812	736	815	709	698	758	710	721	749	801	745
Area up to peak (kPa)	448	368	359	410	509	429	508	679	536	547	403
	477	431	446	454	441	428	474	504	459	530	422
Average	463	399	403	432	475	429	491	591	498	538	413
Total Dissipated Energy Density (DEIDT)	357	301	296	364	459	336	383	567	427	438	342
	398	361	390	378	380	349	409	430	373	442	348
Average	377	331	343	371	420	342	396	498	400	440	345

Table 7. IDT Test Results of unaged samples (resilient modulus test samples)

	B-25	B-50	B-75	B-100	B-F	E-25	E-50	E-75	E-100	E-F	L
Peak tensile stress (kPa)	738	666	720	739	729	704	675	761	764	677	667
	688	783	714	716	726	582	670	736	769	699	587
Average	713	724	717	728	727	643	672	749	767	688	627
Area up to peak (kPa)	452	423	444	458	419	396	566	527	550	472	445
	418	448	447	432	449	411	568	544	539	597	425
Average	435	436	445	445	434	404	567	536	544	534	435
Total Dissipated Energy Density (DEIDT)	367	335	344	367	348	307	389	411	393	382	348
	320	236	370	338	365	327	363	404	411	428	309
Average	343	285	357	353	357	317	376	408	402	405	329

Figures 12-14 also show the peak tensile strength, area up to peak tensile strength and total dissipated energy density of the samples.

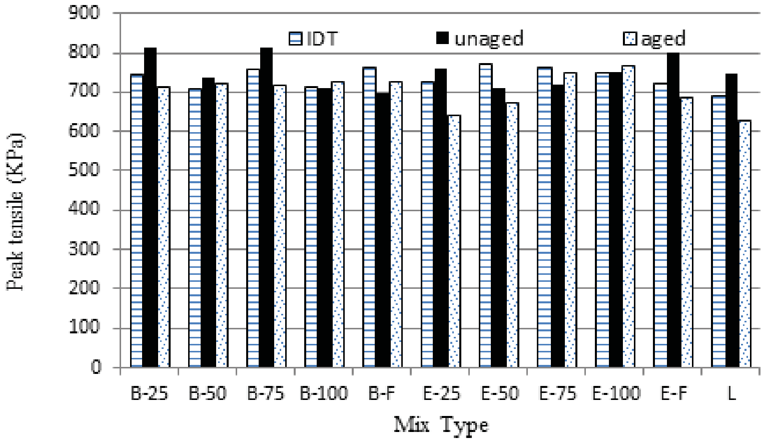

Figure 12. Average peak tensile strength of specimens

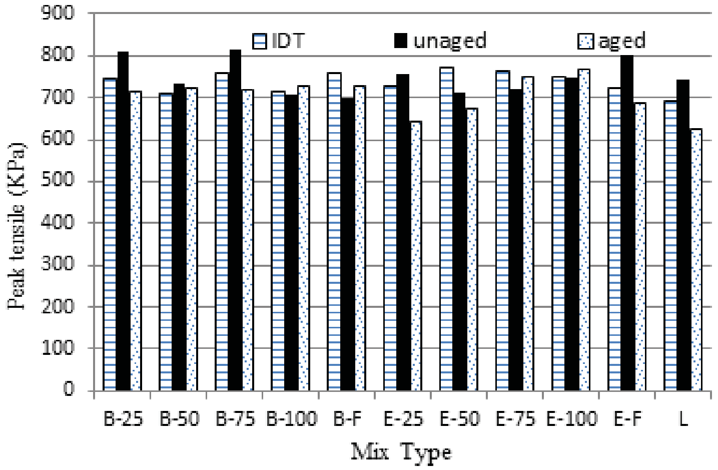

Figure 13. Average area up to peak Tensile strength of specimens

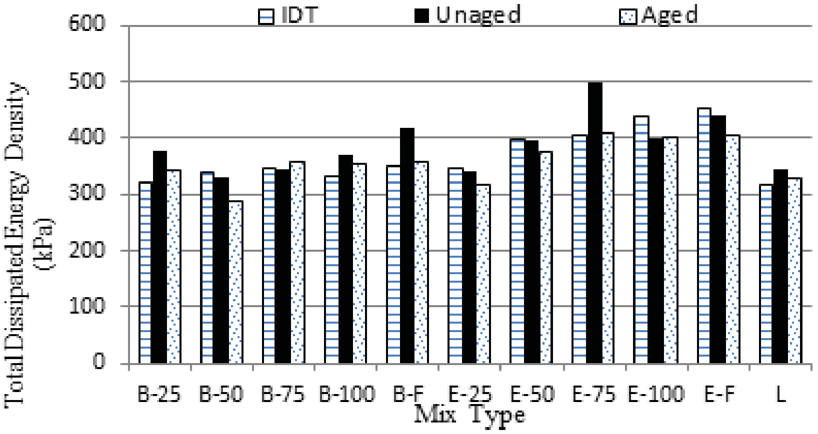

Figure 14. Average total dissipated energy density of stress-strain curve of specimens

The results show that the peak tensile strength, area up to peak tensile strength and total dissipated energy density of the specimens containing EAF slag were greater than the control mixtures. This can be attributed to the improved adhesion between bitumen and the EAF slag. Fracture energies of EAF mixtures were greater than those of BOF and limestone mixtures, indicating that more work would be taken until EAF mixtures are failed. The Fracture energies were almost the same for BOF and limestone mixtures.

Fatigue failure is induced by excessive tensile strain. Hence, an improvement in the tensile property of a mixture is considered as improvement in its fatigue resistance. It is thought that the mixtures with higher tensile strength are more likely to resist cracking than mixtures with low tensile strength value. The fracture energy to failure and total fracture energy were strongly increased by the addition of EAF. This indicates that EAF slag mixtures are capable of increasing the threshold of energy required for mixtures to be cracked and more work would be required until EAF mixtures are failed.

5.3 Statistical Analysis

A statistical analysis was carried out in order to evaluate the significance of the amounts of EAF and BOF slags in mixtures 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 slag in mixtures. To this purpose, a t-test was carried out. The aim of t-testing is determining a possible significant difference between the variables or the treatment means. This test was carried out using SPSS software version 16.0. The results are significant whenever the P value is less than the selected significance level, which is usually 5%. Hence, in this work, the t-testing was performed to study the significance of the EAF addition in affecting fatigue life of mixtures.

The statistical analysis of the resilient modulus testing results (Table 8) indicates that the difference in the means between the resilient modulus of the aged and unaged specimens for all mixtures was significant. The results also show that at 20oC, the difference between the means of the resilient modulus of the specimens containing 50% or higher percentage of slag and control mixture, in both aged and unaged conditions were significant; that is, the difference was due to the slag addition. However, at 5oC, the difference between the means of the resilient modulus of the unaged specimens containing BOF slag and control mixture was not significant and only E-100 and E-F specimens have meaningful differences. The results also indicate that at 40oC, the difference between the means of the resilient modulus of all the specimens in both aged and unaged conditions were not significant.

The statistical analysis of the IDT testing results (Table 9) shows that the difference in the means between the peak tensile strength of specimens containing different percentages of slag and the control mixture were not significant in both aged and unaged conditions which means that the addition of slag does not change the peak tensile strength of the mixtures significantly. The results also reveal that the difference in the means between the area under stress-strain curve up to peak tensile strength for specimens containing BOF slag and control mixture were not significant for both aged and unaged conditions. However, the area under stress-strain curve up to peak tensile strength for specimens containing 50% or higher percentages of EAF slag was significantly increased compared with control mixture for unaged specimens.

The statistical analysis of the total dissipated energy density indicates that the difference in the means between the total dissipated energy density of specimens containing 50% or higher percentage of EAF slag and control mixture were significant in both aged and unaged conditions. However, the addition of BOF slag does not change the total dissipated energy density of the mixtures significantly compared with the control mixture.

Table 8. Summary of statistical Test results of resilient modulus testing for different samples

Compared samples	P-value	Compared samples	P-value	Compared samples	P-value
Aged to unaged at 5^oc	9.23E-05	Unged BOF samples to control sample at 5^oc	0.320073	Unged samples to control sample at 20^oc	6.49E-22
Aged to unaged at 20^oc	6.49E-22	Unged E-100 samples to control sample at 5^oc	0.046179	Unged samples to control sample at 40^oc	0.746
Aged to unaged at 40^oc	1.44E-21	Unged E-F samples to control sample at 5^oc	0.04177	Aged samples to control sample at 40^oc	0.998071
Aged Slag samples to control sample at 5^oc	0.984213	Aged samples to control sample at 20^oc	3.08E-08		

Table 9. Summary of statistical test results of ITS testing for different samples

Compared samples	P-value	Compared samples	P-value	Compared samples	P-value
Peak tensile strength of unconditioned samples to control sample	0.80086	area up to peak of unconditioned E-50 samples to control samples	0.032527	total dissipated energy density of aged BOF samples to control samples	0.407205
Peak tensile strength of unaged samples to control samples	0.121829	area up to peak of unaged E-50 samples to control samples	0.047361	total dissipated energy density of unaged BOF samples to control samples	0.408915
Peak tensile strength of aged samples to control samples	0.397031	area up to peak of aged E-50 samples to control samples	0.051395	total dissipated energy density of unconditioned E-50 samples to control samples	0.011567
area up to peak of unaged BOF samples to control samples	0.960228	area up to peak of aged BOF samples to control samples	0.383584	total dissipated energy density of aged E-50 samples to control samples	0.041198
area up to peak of unconditioned BOF samples to control samples	0.90124	total dissipated energy density of unconditioned BOF samples to control samples	0.669288	total dissipated energy density of unaged E-50 samples to control samples	0.013643

6. Conclusions

From the experimental testing carried out on limestone mixtures containing various amounts of EAF and BOF slag, the following conclusions can be drawn:

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

2) Their free carbonate and magnesium contents of the slags resulted in low expansion rates in asphalt mixtures. Hence, application of these materials in asphalt mixtures has no adverse effect in mixtures in terms of moisture absorption and expansion.

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

4) The results showed that the peak tensile strength, area up to peak tensile strength and total dissipated energy density of specimens containing EAF slag were greater than the control mixtures. This can be attributed to the improved adhesion in these mixtures. Fracture energies in EAF mixtures were greater than those of BOF and limestone mixtures, indicating that more work would be required until EAF mixtures failed. The Fracture energies

were almost the same in both BOF and limestone mixtures.

5) Increased slag contents in asphalt mixtures resulted in their increased resilient modulus. This was attributed to the rough texture of slag aggregates, providing more angularity between the particles, and more adhesion in the mixtures, compared with purely limestone content mixtures.

6) The ratio of aged to unaged resilient modulus of specimens decreased upon increasing the slag contents. However, for specimens containing 100% slag this ratio increased slightly due to the increased asphalt cement content.

7) Mixtures containing EAF slag exhibited less susceptibility to ageing, compared with both BOF and control mixtures. At 5oC the highest ratio belonged to control mixtures, which indicates that at lower temperature, the susceptibility to ageing of control mixtures was more pronounced. This finding enhanced the hypothesis which suggested that the greater the adhesion, the greater the mitigation of ageing.

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