Use of steel slag aggregate in asphalt concrete mixes

Ibrahim M. Asi, Hisham Y. Qasrawi, and Faisal I. Shalabi

Abstract: There are three major steel-manufacturing factories in Jordan. All of their by-product, steel slag, is dumped randomly in open areas, causing many environmentally hazardous problems. This research was intended to study the effectiveness of using steel slag aggregate (SSA) in improving the engineering properties of locally produced asphalt concrete (AC) mixes. The research started by evaluating the toxicity and chemical and physical properties of the steel slag. Then 0%, 25%, 50%, 75%, and 100% of the limestone coarse aggregate in the AC mixes was replaced by SSA. The effectiveness of the SSA was judged by the improvement in indirect tensile strength, resilient modulus, rutting resistance, fatigue life, creep modulus, and stripping resistance of the AC samples. It was found that replacing up to 75% of the limestone coarse aggregate by SSA improved the mechanical properties of the AC mixes. The results also showed that the 25% replacement was the optimal replacement level.

Key words: steel slag aggregate, asphalt concrete, Superpave, indirect tensile strength, fatigue, rutting, creep.

Résumé : La Jordanie possède trois grandes aciéries. Le sous-produit, le laitier d’aciérie, généré par ces aciéries est entièrement rejeté n’importe où dans des zones ouvertes, engendrant plusieurs problèmes environnementaux dangereux. La présente recherche étudie l’efficacité de l’utilisation des agrégats de laitier d’aciérie (« SSA ») à améliorer les propriétés techniques des mélanges de bétons bitumineux produits localement. La recherche a évalué en premier la toxicité du laitier d’aciérie et ses propriétés chimiques et physiques. Ensuite, les granulats calcaires grossiers dans les mélanges de bétons bitumineux ont été remplacés à 0, 25, 50, 75 et 100 % par des « SSA ». L’efficacité des « SSA » a été évaluée par l’amélioration de la résistance à la traction indirecte, le module de résilience, la résistance à la formation d’ornières, la longévité à la fatigue, le module de fluage et la résistance à l’arrachement d’échantillons de béton bitumineux. Les résultats ont montré que le fait de remplacer jusqu’à 75 % des granulats calcaires grossiers par des « SSA » améliorait les propriétés mécaniques des mélanges de béton bitumineux. Il a également été démontré que 25 % était le niveau de remplacement optimal.

Mots-clés : agrégat de laitier d’aciérie, béton bitumineux, superpavé, système de transport intelligent, fatigue, orniérage, fluage.

[Traduit par la Rédaction]

1. Introduction

The major properties that bituminous paving mixtures should have are stability, durability, flexibility, and skid resistance (in the case of wearing surfaces) (Haas et al. 1994). Suitable materials (asphalt, aggregate, and additives) and proper mix design procedure should be used to achieve good properties. In Jordan, roads are built to the best international standards, for example, those of the American Association of State Highway and Transportation Officials (AASHTO), Asphalt Institute, and the American Society for Testing and Materials (ASTM) (MPWH 1991). After a short period of service, some of these roads are showing signs of major distress due to the harsh environmental conditions and traffic loading.[2] Another factor in this early distress is the use of marginal-quality limestone aggregate.

Steel slag, a by-product of steel manufacturing, is produced during the separation of molten steel from impurities in steel-making furnaces. The slag evolves as a molten liquid and is composed of a complex solution of silicates and oxides that solidifies upon cooling. Steel slag is a recycled material that can be useful in the construction industry. For example, it is estimated that up to 7.5 × 10^6 t of steel slag is used each year in the United States (Collins and Ciesielski 1994), mainly as a granular road base or as an aggregate in construction applications. Steel slag aggregate (SSA) has been successfully used in the Middle East under hot weather conditions (Aiban and Al-Abdul Wahhab 1997).

Not all types of slag are suitable for processing as SSA: some have high percentages of free lime and magnesium oxides that have not reacted with the silicate structures and can hydrate and expand in humid environments (JEGEL 1993). Suitable SSA can be used as a replacement for normal aggregate in a variety of civil engineering applications. It can be

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I.M. Asi,[1] H.Y. Qasrawi, and F.I. Shalabi. Department of Civil Engineering, Hashemite University, Zarqa 13115, Jordan.

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[1] Corresponding author (e-mail: asi@hu.edu.jo).

[2] Asi, I.M. Role of roads in traffic safety. Paper presented at the Traffic Safety … Everybody's Responsibility Symposium, Hashemite University, Zarqa, Jordan, 18 May 2004.

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used in concrete mixes, asphalt concrete (AC) mixes, and soil stabilization.

Steel slag can be processed into coarse or fine aggregate material for use in dense-graded and open-graded hot-mix AC pavements (Norton 1979; Kandahl and Hoffman 1982; Rossini-Lake et al. 1995) and in cold mix or surface treatment applications (Noureldin and McDaniel 1990). Proper processing of steel slag and special quality-control procedures are extremely important in selecting steel slag for use in asphalt paving mixes. The swelling potential of steel slag is of particular importance because of the free lime or magnesia in the slag, which, if ignored, could result in pavement cracking (Norton 1979).

The use of steel slag in paving mixes should be limited to replacement of either the fine or the coarse aggregate fraction, but not both, because hot-mix asphalt containing 100% steel slag is susceptible to a high proportion of air voids and bulking problems because of the angular shape of the SSA.[3] Mixes with a high proportion of air voids (e.g., 100% SSA mixes) require high asphalt cement contents during production and will be susceptible to flushing due to in-service traffic compaction.

Asphalt mixes containing steel slag can be designed using standard laboratory procedures, such as the Marshall (Asphalt Institute 1997) and Superpave mix design procedures (Asphalt Institute 2001). Mixes containing SSA and conventional aggregate are usually designed volumetrically because of the significant difference in aggregate bulk relative densities.

The requirements of ASTM standards D5106 and D4792 (ASTM 2003) outline recommended properties of SSA for use in hot-mix asphalt. Some agencies, such as the Pennsylvania Department of Transportation, have adopted additional specifications, such as setting minimum aging periods for the processed steel slag to limit the risk of expansive cracking of SSA in hot-mix asphalt (PennDOT 1978). Germany and Japan have comprehensive specifications for the processing of SSA. In addition to aging requirements and aggregate expansion testing, they also include expansion testing of the hot-mix asphalt containing steel slag (JEGEL 1993).

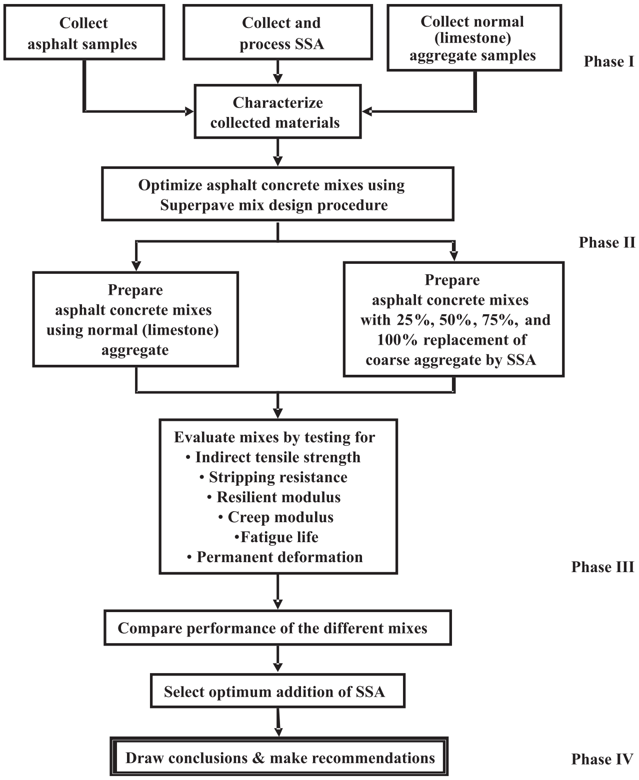
1.1. Objectives

The main objective of this study is to find means and ways of effectively utilizing waste materials coming as by-products from steel production by the steel-manufacturing companies in Jordan. To meet this objective, we planned to (*i*) study the physical, chemical, and mechanical properties of the generated SSAs to determine their suitability for use in AC mixes; and (*ii*) prepare AC mixes that contained SSAs and evaluate their properties.

1.2. Scope

Five AC mixes were investigated in this research: (*i*) an AC mix in which 100% of the aggregate was limestone; and (*ii*) mixes in which 25%, 50%, 75%, and 100% of the coarse aggregate (materials retained on sieve No. 4, size 4.75 mm) was replaced by SSA. The Superpave mix design procedure (Asphalt Institute 2001) was used to determine the optimum asphalt content (OAC) of all mixes. At the obtained OACs, 50 AC samples at each SSA content were prepared. The effectiveness of replacing the limestone aggregate by SSA was judged by the improvement in the indirect tensile strength (ITS), resilient modulus, rutting resistance, fatigue life, creep modulus, and stripping resistance of tested samples.

Fig. 1. Flow chart of the work conducted on the use of steel slag aggregate in asphalt concrete mixes.



2. Experimental program

A schematic representation of the experimental program conducted in this investigation is shown in Fig. 1. The work was divided into four phases. Phase I included collection and characterization of the limestone aggregate, asphalt cement, and SSA. The asphalt cement samples were collected from the asphalt-cement-producing refinery in Jordan. The physical properties of three representative samples from the collected asphalt cement were evaluated, and the average results are shown in Table 1. The aggregate selected for the laboratory work was crushed limestone, which was obtained near Amman, Jordan. The selected aggregate gradation was in accordance with the Jordanian Ministry of Public Works and Housing (MPWH) recommended gradation for a heavy-traffic-wearing course (Fig. 2). The physical properties of the limestone aggregate were evaluated, and the results are shown in Table 2.

The SSA, a by-product of steel manufacturing, was collected from the United Iron and Steel Manufacturing Company, Amman. The slag was sieved through a 25.4 mm (1 in.) sieve to remove larger materials. Results of the sieve analysis

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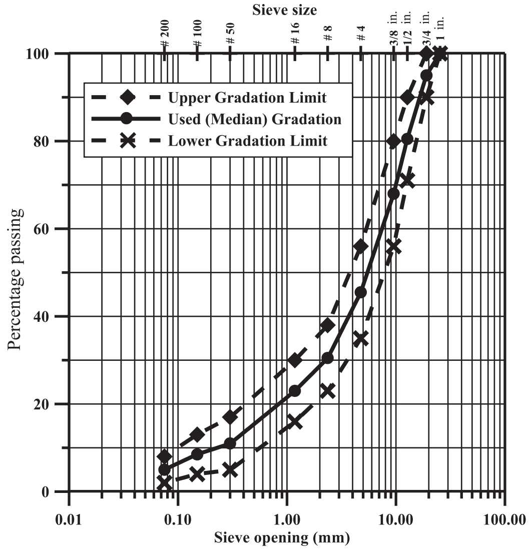
[3] Qasrawi, H., Asi, I., and Marie, I. Steel slag aggregate for road construction: an overview. Paper presented at the Industrial and Structural Wastes Workshop, Jordan Engineering Association, Amman, Jordan, 17 December 2003.

Table 1. Physical properties of the asphalt cement used in the study.

Test	Test result	Criterion
Flash point (°C)	320	230 °C minimum
Rotational viscosity at 135 °C (Pa·s)	0.488	3 Pa·s maximum
Rotational viscosity at 165 °C (Pa·s)	0.150	n/a
Penetration (*10 mm)	66	60–70
Specific gravity at 25 °C	1.019	1.01–1.06
Ductility at 25 °C (cm)	134	100 minimum
Softening point (°C)	53	48–56
Penetration of residue (% of original)	66	54 minimum
Weight loss on heating (%)	0.22	0.8 maximum
$G^*/\sin\delta$ at 64 °C (fresh) (kPa)	1.765	1.0 minimum
$G^*/\sin\delta$ at 64 °C (RTFO) (kPa)	4.010	2.2 minimum
$G^*\sin\delta$ at 28 °C (PAV) (MPa)	1.344	5.0 maximum
Stiffness S at –6 °C (PAV) (MPa)	66.67	300 maximum
Slope m at –6 °C (PAV)	0.304	0.3 minimum

Note: G^*, complex asphalt cement modulus; n/a, not applicable; PAV, pressure aging vessel; RTFO, rolling thin film oven.

Fig. 2. MPWH-specified gradation limits and used gradation. Note: 1 in. = 25.4 mm.



of the materials passing through this sieve are presented in Fig. 3. The physical properties of the slag aggregate were evaluated, and the results are shown in Table 2.

To determine the toxicity of the metal leachate obtained from the SSA, the leachate was analyzed with a graphite-furnace atomic absorption spectrophotometer. Table 3 summarizes the analytical results.

In phase II, five AC mixes were investigated. These mixes were the control mix and the mixes containing 25%, 50%, 75%, and 100% coarse SSA. The Superpave mix design procedure (Asphalt Institute 2001) was used to determine the OAC of each mix. At the obtained OAC, 50 AC samples were prepared from each mix.

In phase III, the effectiveness of replacing portions of the limestone aggregate by SSA was judged by the improvement in the ITS, resilient modulus, rutting resistance, fatigue life, creep modulus, and stripping resistance of the prepared samples.

Phase IV focused on determining the optimum percentage of limestone aggregate for replacement by SSA.

3. Methods, results, and discussion

3.1. Selection of appropriate aggregate gradation

The Superpave requirements for aggregate properties are based on both consensus and source properties. Consensus properties include coarse and fine aggregate angularity, flat and elongated particles, and clay content. Acceptance limits for the consensus properties depend on traffic level and depth of the layer below the surface (Asphalt Institute 2001). Source properties include toughness, soundness (Los Angeles abrasion), and deleterious materials. Table 2 shows the properties of the limestone and slag aggregates and the acceptance limits. It indicates that these aggregates meet both the consensus and the source (MPWH) property requirements for high-traffic volumes, regardless of depth.

Table 3 compares the leachate analysis values from this study with the United States Environmental Protection Agency land disposal regulatory limits (US EPA 1993). It can be seen that the average values of metals under consideration do not exceed the limits set for the toxicity characteristic regulatory levels. Therefore, the use of the SSA is safe and should not induce any contamination, even in areas where the groundwater table is shallow.

For designing the different AC mix, the Superpave mix design procedure was followed (Asphalt Institute 2001). Volumetric analysis was used in the Superpave mix design. The Superpave procedure has three major steps in the testing and analysis process. These steps are selection of a design aggregate structure, optimization of the asphalt content for the selected structure, and evaluation of the moisture sensitivity of the design mixture.

For the sake of comparison, two aggregate structures were selected in addition to the MPWH-recommended gradation for heavy traffic loads for the wearing course. Figure 4 shows the selected aggregate blends. Blend 1 was selected to be below the restricted zone (“below RZ”). Blend 2 had the MPWH-recommended gradation for heavy traffic loads for the wearing course. To cover the other extreme of the grada-

Table 2. Physical properties of the limestone and slag aggregate used in the study.

Property	Criteria	Limestone aggregate	Slag aggregate
Coarse aggregate angularity	100% min	100%	100%
Fine aggregate angularity	45% min	52%	58%
Flat/elongated (5:1 ratio)	10% max	0%	0%
Coarse aggregate specific gravity	n/a	2.539	3.102
Coarse aggregate absorption	n/a	2.7%	2.3%
Fine aggregate specific gravity	n/a	2.502	3.205
Fine aggregate absorption	n/a	4.1%	3.6%
Abrasion loss (500 rev), %	35% max	25.6	16.4
Abrasion ratio (100/500), %	25% max	13.8	11.5

Note: n/a, not applicable.

Fig. 3. Gradation of the obtained steel slag aggregate. Note: 1 in. = 25.4 mm.

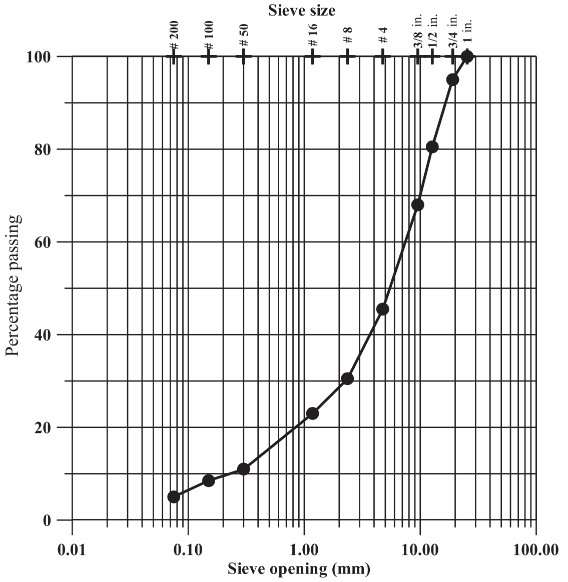
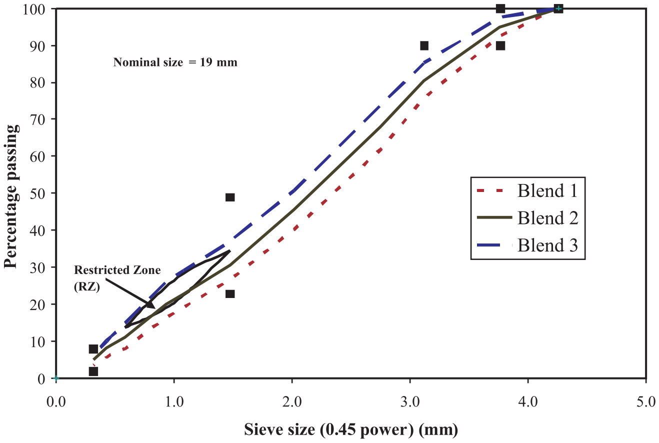


Table 3. Summary of the leachate results and comparison with regulatory limits. TCLP, toxicity characteristic leaching procedure (US EPA 1993).

Element	Average (ppm)	Regulatory limits (TCLP)
Cr	0.063	5.0
Ni	0.004	Not specified
Cd	0.000	1.0
Fe	0.019	Not specified
Zn	0.021	Not specified
Cu	0.000	Not specified
Pb	0.000	5.0

tion limits, blend 3 was selected to be above the restricted zone (“above RZ”). It can be seen that blend 2 passes through the restricted zone. The Superpave procedure does not restrict this, but it recommends special precautions during field compaction.

Fig. 4. Gradation of the different aggregate blends drawn on Superpave-recommended gradation chart.



Since a gyratory compactor is used in the Superpave mix design, the number of gyrations should be specified; this number depends on both average design high air temperature and design equivalent single-axle load (ESAL). A traffic level between 30 million and 100 million ESALs was selected. At this traffic level, and at an average design high air temperature of 39 °C, the recommended numbers of gyrations are as follows: N_{initial} = 9 gyrations, N_{design} = 126 gyrations, and N_{maximum} = 206 gyrations. These numbers of gyrations were kept constant for the rest of the study.

The initial trial asphalt binder content for the three blends was estimated to be 5.2%. Two specimens for each trial blend were compacted with the Superpave gyratory compactor. Table 4 shows volumetric results and dust proportions, together with specifications limits. Table 4 indicates that the blend 2 aggregate (MPWH-recommended gradation) failed to meet the specifications for voids in mineral aggregate and dust proportions. The blend 3 aggregate (above RZ) failed to meet the dust proportion criterion. Only the blend 1 aggregate (below RZ) met all the specifications. Therefore, it was selected for the second design stage (i.e., optimization of the asphalt content).

The OACs of the different mixes and the properties of the AC mixes at these OACs are shown in Table 5. It can be seen that OAC increases with increasing slag content. This can be attributed to the high porosity and void content of the SSA. Evaluation of the moisture sensitivity of the design

Table 4. Estimated property values of the trial blends to achieve 4% air voids at N_{design}.

		Estimated properties to achieve 4% air voids at N_{design}								
			VMA (%)		VFA (%)		% G_{mm} at $N_{initial}$		Dust proportion (%)	
Blend	Trial ACt (%)	ACt (%)	Estimate	Specification	Estimate	Specification	Estimate	Specification	Estimate	Specification
Blend 1	5.2	5.0	13.4	13 minimum	70.18	65–75	84.4	89 maximum	0.8	0.6–1.2
Blend 2	5.2	4.6	12.5	13 minimum	67.97	65–75	84.7	89 maximum	1.4	0.6–1.2
Blend 3	5.2	5.1	13.3	13 minimum	69.95	65–75	86.0	89 maximum	1.6	0.6–1.2

Note: ACt, asphalt cement; VMA, voids in mineral aggregate; VFA, voids filled with asphalt; G_{mm}, theoretical maximum specific gravity.

Table 5. Optimum asphalt content (OAC) of the different mixes and properties of the asphalt concrete mixes at these OACs.

		Properties at 4% air voids at N_{design}								
			VMA (%)		VFA (%)		% G_{mm} at $N_{initial}$		Dust proportion (%)	
% SSA added	G_{mm}	OAC (%)	Estimate	Specification	Estimate	Specification	Estimate	Specification	Estimate	Specification
0	2.403	4.80	13.0	13 minimum	69.3	65–75	84.9	89 maximum	0.9	0.6–1.2
25	2.450	5.36	15.8	13 minimum	75.0	65–75	87.1	89 maximum	0.7	0.6–1.2
50	2.548	5.43	15.6	13 minimum	74.7	65–75	86.3	89 maximum	0.7	0.6–1.2
75	2.640	5.76	14.9	13 minimum	73.5	65–75	86.0	89 maximum	0.9	0.6–1.2
100	2.874	5.82	14.3	13 minimum	72.0	65–75	84.6	89 maximum	1.4	0.6–1.2

Note: SSA, steel slag aggregate; G_{mm}, theoretical maximum specific gravity; VMA, voids in mineral aggregate; VFA, voids filled with asphalt.

Table 6. Analysis of variance (ANOVA) of the obtained indirect tensile strength (ITS) values for the different steel slag aggregate (SSA) percentages.

Summary						
	Count	Sum	Average	Variance	Standard deviation	
% SSA	15	7.5	0.5	0.134	0.366	
ITS	15	11121.09	741.406	1304.129	36.113	
ANOVA						
Source of variation	SS	df	MS	F	P value	F_{critical}
Between groups	4 117 064	1	4 117 064	6313.242	1.6×10^{-34}	4.196
Within groups	18 259.68	28	652.132			
Total	4 135 323	29				

Note: ITS, indirect tensile strength; SS, sum of squares; df, degrees of freedom; MS, mean sum of squares; *F*, statistical value.

mixture was performed according to test procedure T283 (AASHTO 2003). Obtained ratios of the ITS for all the mixes were above the minimum specification limit, which is 80%.

3.2. Performance evaluation for different mixes

To compare the performance of all the mixes, we prepared AC samples at the obtained optimum mix design asphalt contents for each mix using the below-RZ aggregate gradation. The gyratory compactor was used to compact all of the 101.6 mm diam. × 63.5 mm thick (4 in. × 2.5 in.) test samples to achieve 4% air voids. These samples were subjected to comprehensive mechanical evaluation of tensile strength, loss of ITS, resilient modulus, fatigue life, rutting behavior, and creep performance.

3.2.1. Indirect tensile strength and water sensitivity

Three samples from each mix, each having 4% air void, were tested in the Marshall stability machine in indirect tensile mode at 25 °C (Lottman test, AASHTO T283-03 (AASHTO 2003)). The failure load for each sample was recorded. The ITS for each sample was calculated using the following formula:

$$\text{ITS} = 2P / \pi t d \qquad [1]$$

where ITS is the indirect tensile strength (kPa); P is the failure load (kN); t is the sample thickness (m); and d is the sample diameter (m).

Figure 5 shows the average ITS values for the different AC mixes. The results show that the inclusion of the SSA in the AC mixes improved the ITS of these samples. This can be attributed to the improved aggregate structure of the SSA.

Statistical analysis was performed to study the significance of the SSA percentage in changing the ITS values, that is, to check whether the difference in the obtained ITS values is due to experimental error or due to the addition of the SSA. The analysis of variance (ANOVA) for the single-factor model was used for this analysis. In general, the purpose of the ANOVA is to test for the significant difference between the variable or treatment means (μ). The appropriate procedure for testing the equality of treatment means is to check the following hypothesis (Montgomery 1991):

$$H_0 : \mu_1 = \mu_2 = \ldots = \mu_a \qquad [2]$$

$$H_1 : \mu_i \neq \mu_j \qquad [3]$$

Fig. 5. Indirect tensile strength of the different asphalt concrete mixes at 25 °C.

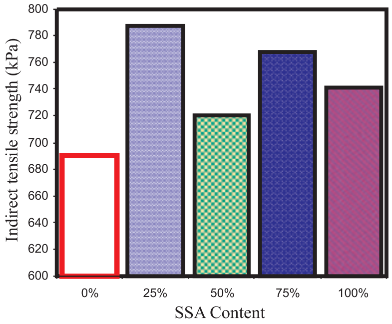
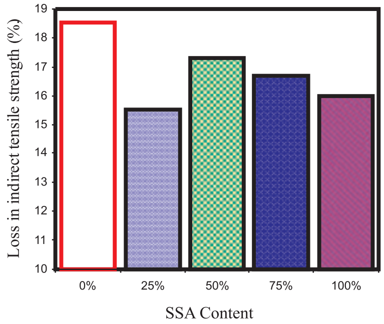


Fig. 6. Loss of indirect tensile strength for the different asphalt concrete mixes.



where μ_i, μ_j are the variable means and μ_a is the last variable mean.

If H_0 is true, there is no difference in treatment means. If H_0 is not true, there is a significant difference between treatment means (it is unlikely that the treatment means are equal).

The ANOVA calculations were performed using the statistical analysis tool included in Microsoft Excel. Statistically, the results are significant whenever the P value is less than the selected significance level (SL), which is usually 5%. This means that for 95% SL, the P value should be <0.05 to achieve a significant effect of any factor. ANOVA of the obtained ITS values (Table 6) indicated that at 5% SL, the difference between the means of the ITS values was significant; that is, the difference was due to the SSA content.

Table 7. Analysis of variance (ANOVA) of the obtained loss of indirect tensile strength (ITS) values for the different steel slag aggregate (SSA) percentages.

Summary						
	Count	Sum	Average	Variance	Standard deviation	
% SSA	5	2.5	0.5	0.156	0.395	
% ITS loss	5	84	16.8	1.37	1.170	
ANOVA						
Source of variation	SS	df	MS	F	P value	F_{critical}
Between groups	664.225	1	664.225	870.401	1.89×10^{-9}	5.318
Within groups	6.105	8	0.763125			
Total	670.33	9				

Note: ITS, indirect tensile strength; SS, sum of squares; df, degrees of freedom; MS, mean sum of squares; *F*, statistical value.

Another three samples from each mix were placed in a water bath at 60 °C for 24 h. At the end of the immersion period the samples were placed for 2 h in a water bath at 25 °C and then were tested for ITS. The stripping resistance (water susceptibility) of the different AC mixes was evaluated, according to the AASHTO T283 test procedure, by measuring the loss in the ITS after immersion in water. Figure 6 indicates that the average loss in strength due to water damage was lower in the samples that included the SSA than in the 0% SSA samples. This behavior is attributed to the porosity of the SSA aggregate, which allowed the asphalt cement to penetrate more than in the limestone aggregate, creating better bonding and resistance to stripping. Statistical analysis was performed to study the significance of SSA addition to changes in the stripping resistance of the AC mixes. ANOVA (Table 7) indicated that at 5% SL, the difference in the means of the percentage loss of ITS values was significant; that is, the difference was due to the addition of SSA.

3.2.2. Dynamic creep test

The dynamic creep test applies a repeated pulsed uniaxial stress on an asphalt specimen and uses linear variable differential transducers (LVDTs) to measure the resulting deformations in the same direction as the applied load.

The test was performed in accordance with the protocol developed by National Cooperative Highway Research Program project 9-19 (Witczak et al. 2001). The applied stress on the specimen was a feedback haversine pulse. The pulse width duration was 100 ms, and the rest period before the application of the next pulse was 900 ms. The deviator stress during each loading pulse was 207 kPa, and the contact stress that was applied so that the vertical loading shaft would not lift off the test specimen during the rest period was 9 kPa. The test was performed at 40 °C. The specimen's skin and core temperatures during the test were monitored by two thermocouples inserted in a nearby dummy specimen.

The testing continued until the maximum axial strain limit reached 10 000 microstrains or until 10 000 cycles, whichever occurred first. Three samples (100 mm × 63.5 mm at 4% air void) from each mix were tested. Figure 7 shows the relationship between the number of cycles and the axial accumulated permanent deformation for all the mixes. The creep resistance of the AC mixes was improved by 25%, 50%, and 75% replacement of the coarse limestone aggregate by SSA. In contrast, 100% replacement did not improve the creep resistance: this is because increasing the amount of the SSA required increases in the quantity of asphalt cement. The extra asphalt cement has likely lowered the mixes' creep resistance. The best creep resistance was for the 25% SSA mix. For this mix, SSA improved the interlocking of the aggregate structure, and there wasn't much increase in the required quality of the asphalt cement.

Fig. 7. Comparison of creep behavior of the different mixes at 40 °C.

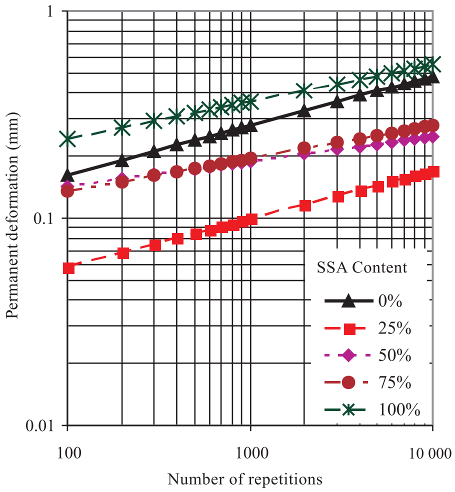


Fig. 8. Values of M_R at 25 °C and 40 °C for all the mixes.

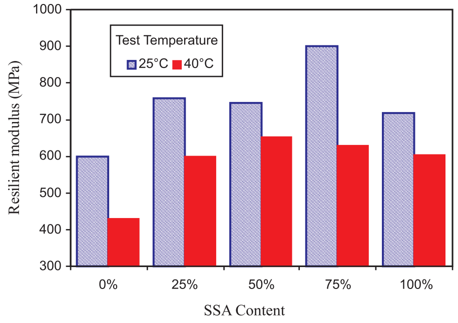


Table 8. Analysis of variance (ANOVA) of the obtained resilient modulus values at 25 °C for the different steel slag aggregate (SSA) percentages.

Summary						
	Count	Sum	Average	Variance	Standard deviation	
% SSA	15	7.5	0.5	0.134	0.366	
M_R at 25 °C	15	11 172	744.8	12 049.17	109.769	
ANOVA						
Source of variation	SS	df	MS	F	P value	$F_{critical}$
Between groups	4 154 869	1	4 154 869	689.645	2.88×10^{-21}	4.196
Within groups	168 690.3	28	6024.653			
Total	4 323 559	29				

Note: M_R, resilient modulus; SS, sum of squares; df, degrees of freedom; MS, mean sum of squares; F, statistical value.

Table 9. Analysis of variance (ANOVA) of the obtained resilient modulus values at 40 °C for the different steel slag aggregate (SSA) percentages.

Summary						
	Count	Sum	Average	Variance	Standard deviation	
% SSA	15	7.5	0.5	0.134	0.366	
M_R at 40 °C	15	8743.5	582.9	62 405.22	249.810	
ANOVA						
Source of variation	SS	df	MS	F	P value	$F_{critical}$
Between groups	2 543 923	1	2 543 923	81.529	8.72×10^{-10}	4.196
Within groups	873 675	28	31 202.68			
Total	3 417 598	29				

Note: M_R, resilient modulus; SS, sum of squares; df, degrees of freedom; MS, mean sum of squares; F, statistical value.

3.2.3. Resilient modulus test

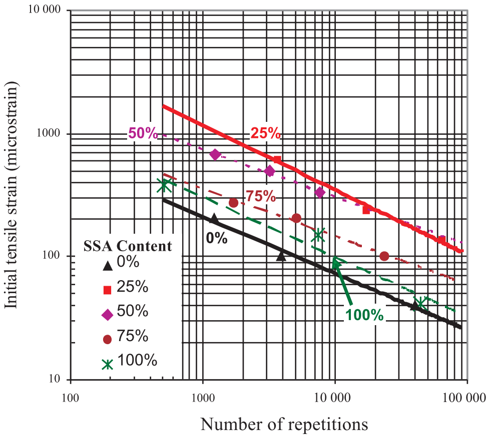
Resilient modulus is the most important variable in the mechanistic design of pavement structures. It is the measure of pavement response in terms of dynamic stresses and corresponding strains. Three samples from each mix were tested at two positions under the diametral resilient modulus (M_R) test, ASTM D 4123 (ASTM 1982), at 25 °C and 40 °C. Figure 8 shows the obtained M_R values for all the tested mixes. The results indicate that up to 75% inclusion of SSA in the mixes improved the diametral resilient modulus of these mixes. This can be attributed to the angularity of the SSA. While 100% replacement of the coarse limestone aggregate by SSA decreased the diametral resilient modulus due to the increased asphalt cement quantity.

ANOVA, for both test temperatures, was performed to study the significance of SSA addition in changing M_R. The results of the statistical analysis (Tables 8 and 9) indicated that at 5% SL, the difference in the means of the M_R values was significant; that is, the difference was due to the addition of SSA.

3.2.4. Fatigue performance

Samples from both mixes were tested diametrally under repeated pulsed uniaxial loading to determine the number of loading cycles required to cause the samples to fail. To have a wide range of failure cycles, samples were tested at different initial tensile strain levels. At least nine samples from each mix (three at each initial tensile strain level) were tested at 25 °C. Figure 9 shows the results of these tests. In this figure, regression lines were drawn through the mean values of the tested samples at each strain level. The results show a normal linear relationship between the logarithm of applied initial tensile strain and the logarithm of fatigue life, that is, the number of applied load repetitions until failure.

Fig. 9. Comparison of fatigue behavior of the different mixes at 25 °C.



Analysis of the obtained fatigue results shows significant improvement in the fatigue life of SSA mixes over that of normal mixes. This can be attributed to the angularity of the SSA. In addition, Fig. 9 shows that the best fatigue life behavior was that of the 25% SSA mix. In this mix SSA improved the interlocking of the aggregate structure, whereas

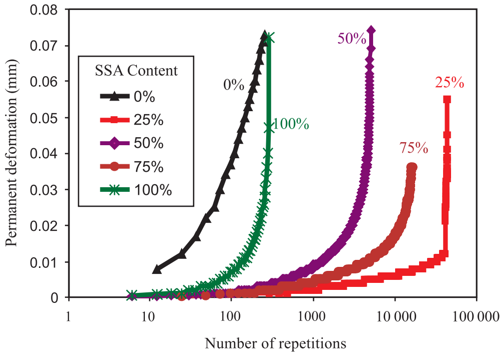


Fig. 10. Comparison of rutting behavior of the different mixes at 25 °C and at a repeated stress of 200 kPa.

in the other SSA mixes increasing the amount of the SSA increased the amount of the asphalt cement used, which lowered the fatigue life. Although, increasing the SSA quantity above 25% lowered the mixes' fatigue lives, they are still higher than that of the 0% SSA mixes.

3.2.5. Permanent deformation

Two vertical LVDTs were used to record the vertical permanent deformation while the fatigue tests were under way. Figure 10 presents the results of the tests, which were performed at a repeated stress of 200 kPa. In the rutting performance of all the mixes (Fig. 10), the trend is similar to that of fatigue testing; that is, SSA has improved the rutting resistance of the SSA mixes. Generally, this improvement is due to the improved interlocking of the aggregate structure as a result of the inclusion of the SSA. The effectiveness of the improvement decreased with increasing SSA content, because of the increased amount of asphalt cement needed: this extra cement acted as a lubricant and caused a decrease in the shear resistance of the AC mixes.

4. Conclusions

In this research, 0%, 25%, 50%, 75%, and 100% of the limestone coarse aggregate (materials retained on sieve No. 4, size 4.75 mm), were replaced by SSA and used in different AC mixes. The effectiveness of replacing limestone aggregate by SSA was judged by the improvement in the ITS, resilient modulus, rutting resistance, fatigue life, creep modulus, and stripping resistance of the tested samples. The following conclusions can be drawn:

- SSA can be used in AC mixes, since its properties meet both Superpave consensus properties and Jordanian MPWH source properties.
- Chemical and toxicity analysis of the steel slag showed that these properties are within the allowable limits, indicating that these materials can be safely used in highway construction.
- The required asphalt quantity increases with the increase in SSA content.
- Replacing up to 75% of the limestone coarse aggregate by SSA improved all the tested mechanical properties of the AC mixes.
- Full replacement (100%) of the limestone coarse aggregate by SSA improved all the tested mechanical properties of the AC mixes except creep performance.
- Although up to 75% replacement of the limestone coarse aggregate by SSA was effective, the optimal replacement percentage was 25%.

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