

Research Article

Laboratory Investigation of Fatigue Characteristics of Asphalt Mixtures with Steel Slag Aggregates

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There are many steel-manufacturing factories in Iran. All of their byproducts, steel slag, are dumped randomly in open areas, causing many environmentally hazardous problems. This research is intended to study the effectiveness of using steel slag aggregate (SSA) in improving the engineering properties, especially fatigue life of Asphalt Concrete (AC) produced with steel slag. The research started by evaluating the physical properties of the steel slag aggregate. Then the 13 types of mixes which contain steel slag in portion of fine aggregates or in portion of coarse aggregates or in all portions of aggregates were tested. The effectiveness of the SSA was judged by the improvement in Marshall stability, indirect tensile strength, resilient modulus, and fatigue life of the AC samples. It was found that replacing the 50% of the limestone coarse or fine aggregate by SSA improved the mechanical properties of the AC mixes.

1. Introduction

Flexible pavements usually experience three major distresses including fatigue cracking, low temperature cracking, and rutting. Fatigue cracking is caused by repeated loading and it can result in significant reduction in the serviceability of flexible pavements. The fatigue performance of flexible pavement could be measured by cracking performance of asphalt mixtures in the laboratory [1].

Nowadays using waste materials in the asphalt paving industries is rapidly developing. The steel slag is a byproduct of steel manufacturing, which is obtained during the separation of molten steel from impurities in steel-making furnaces. One-ton stainless steel slag is obtained during production of 3 tons of stainless steel [2]. During production of steel, excess silicon and carbon are being removed from iron. In this process, furnace fills with iron or scrap metal, fluxing agent, lime stone, and coke as fuel. Carbon dioxide, which was removed from steel, combines with limestone, and forms steel slag [3].

Regarding the high frictional and abrasion resistance of steel slag, it has satisfactory performance in high traffic

volume [4]. Asi et al. investigated skid resistances of asphalt concrete mixtures containing steel slag as an aggregate. In this study asphalt concrete containing 30% steel slag had the best performance among other samples [5].

The steel slag has been utilized as coarse or fine aggregate in asphalt pavements and had a reliable response. One of the important considerations about steel slag is its expansion potential. Presence of free lime and magnesia in the steel slag makes it susceptible to wet condition and if it has been ignored, it may result in cracking [6]. For expansion problem the aggregate of asphalt mixture should be aged; for example, in washed coarse and fine steel slag aggregate the soft lime particles or lime-oxide agglomeration is less than 3% by mass of nonslag component [7].

Wu et al. investigated utilization of steel slag in stone mastic asphalt [8]. Asi et al. studied the effect of the steel slag aggregate on performance characteristics of hot mix asphalt. They conducted indirect tensile strength test, resilient modulus, rutting resistance, fatigue life, and creep modulus tests and also it was reported that mixtures containing up to 75% steel slag as a coarse aggregate had better mechanical properties than usual HMA [5].

TABLE 1: Engineering properties of aggregate sources.

Test type	Result		Test method
	Limestone	Steel slag	
Bulk specific gravity (g/cm^3)	2.493	2.641	ASTM C127
Absorption coarse aggregate (%)	0.7	1.7	ASTM C127
Absorption fine aggregate (%)	1.6	2.4	ASTM C128
Los Angeles abrasion loss (%)	23.8	21.68	AASHTO T96
Two fractured faces (%)	94	96	ASTM D5821

TABLE 2: Gradations of designated aggregate.

Sieve size	Total cumulative passing
9.50 mm	95%
4.75 mm	75%
2 mm	50%
0.3 mm	15%
0.075 mm	6%

TABLE 3: Asphalt binder properties.

Property	Bitumen 60/70	Test method
Specific gravity @25°C (g/cm^3)	1.03	ASTM D-70
Penetration @25°C (0.1 mm)	66	ASTM D-5
Softening point (°C)	53	ASTM D-36
Ductility @25°C (cm)	102	ASTM D-113
Flash point (°C)	305	ASTM D-92
Fire point (°C)	317	ASTM D-70

2. Materials and Methods

The aggregates selected in this study [9] were crushed limestone with a maximum nominal size of 9.5 mm from Tehran mine of cowboy horse. The steel slag used in this study is from Isfahan Steel Manufacturing Company. Their gradations and other properties are presented in Tables 1 and 2.

The slag was sieved through 9.5 mm (3/8 in) sieve, to remove larger aggregates. For mitigation of expansion potential, the steel slag aggregates were washed. In this procedure hydration of free lime and magnesia was accelerated. One type of binder (60/70 mm/10 grade) chosen in this study is from Tehran Pasargadae Oil Company. Its properties are presented in Table 3.

2.1. Samples Preparation. Three different sets of mixtures, which consist of two different contents of steel slag aggregate, were prepared. In the first type 25%, 50%, 75%, and 100% of the limestone coarse aggregate in the Asphalt Concretes (AC) were replaced by steel slag. In the second type 25%, 50%, 75%, and 100% of the limestone fine aggregates were replaced by steel slag and finally in the third type 25%, 50%,

TABLE 4: Type of asphalt mixtures samples.

Mixture name	Type of steel slag aggregate combination
Control	No steel slag aggregate
CSS-100	100% of coarse portion
CSS-75	75% of coarse portion
CSS-50	50% of coarse portion
CSS-25	25% of coarse portion
FSS-100	100% of fine portion
FSS-75	75% of fine portion
FSS-50	50% of fine portion
FSS-25	25% of fine portion
WSS-100	100% of whole aggregates
WSS-75	75% of whole aggregates
WSS-50	50% of whole aggregates
WSS-25	25% of whole aggregates

75%, and 100% of the whole aggregates were replaced by steel slag. Table 4 shows the specification of each mixture.

Optimum binder content was determined with Marshall method. Samples with 6 different (4–6) bitumen ratios were prepared at 0.5% increments. For each binder content three samples were prepared and 75 compaction blows for each side of sample were utilized.

Samples for Marshall test and sample for resilient modulus and indirect tensile strength test were compacted with Marshall hammer. For the beam fatigue samples, the mixture was first compacted using rolling wheel compactor and then specimens of size $63 \times 50 \times 380$ mm were cut.

2.2. Testing Programs

2.2.1. Marshall Stability, Flow, and Marshall Quotient Test. Marshall test was performed on compacted specimens at various binder contents based on ASTM D 1559. Regarding bulk specific gravity, maximum stability, air voids in total mixture, and voids in aggregate filled with bitumen, the optimum binder content was selected [10].

2.2.2. Indirect Tensile Strength Test. The tensile property of asphalt concrete is evaluated through indirect tensile strength test [11]. Tensile strength of material shows maximum indirect tensile strength and strain in which material can endure before failing. In this test cylindrical specimen was loaded between two loading strips along the vertical diametrical plane which cause relatively uniform tensile stress along this plane. The tensile strength of specimen was determined by the following equation:

$$\sigma = \frac{2P}{\pi t d}, \quad (1)$$

where σ is indirect tensile strength, P is maximum load, t is the thickness of specimen, and d is the diameter of specimen.

2.2.3. Resilient Modulus. Resilient modulus (MR) is the most important parameter used in the mechanistic design of



FIGURE 1: Some samples of beam fatigue.



FIGURE 2: Sample under four-point beam fatigue test.

pavement structures. It is the measure of pavement response in terms of dynamic stresses and corresponding strains. Methods based on elastic theory require elastic properties of pavements as inputs.

The resilient modulus of bituminous mixtures, determined in accordance with ASTM D 4123 method, is the most popular form of stress-strain measurement used to evaluate the elastic properties of asphaltic mixtures at 25°C [12]. For each type of mixtures, three specimens were tested.

2.2.4. Four-Point Beam Fatigue Test. The beam fatigue test according to AASHTO T321-07 was utilized to evaluate fatigue life of asphalt mixtures. The test was performed under 600 strain levels at temperature of 25°C. A repeated sinusoidal load was applied at frequency of 10 Hz without rest periods [13]. Three specimens were tested. Figures 1 and 2 show some specimens before and during the test, respectively.

3. Results and Discussion

3.1. Marshall Stability, Flow, and Marshall Quotient Test. Table 5 shows the result of Marshall test. The results are the mean value of three specimens. In general, steel slag increases Marshall stability and decreases flow. Effect of steel slag as a coarse aggregate replacement in improvement of Marshall stability is more significant than fine aggregate replacement.

WSS-100 has the highest Marshall stability among other mixtures. Because of steel slag aggregate structure, the use of steel slag generally enhances air void and this increment is more tangible in mixtures which have steel slag in their coarse portion.

3.2. Indirect Tensile Strength Test. The average values of indirect tensile strength tests for three specimens are shown

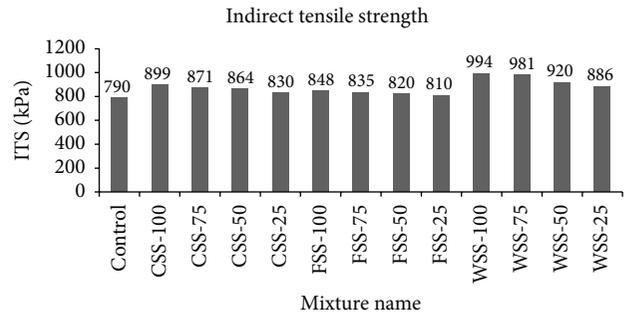


FIGURE 3: ITS test results of samples.

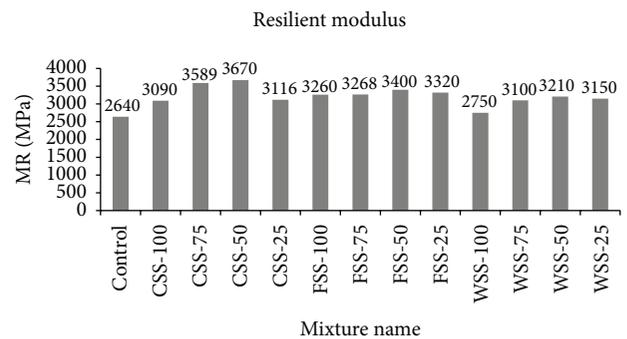


FIGURE 4: Resilient modulus of samples.

in Figure 3. It can be seen that all of the mixtures containing steel slag aggregate have high values of tensile strength. Mixtures containing steel slag in their coarse portions show the higher increase in the indirect tensile strength. This indicates that the structure of steel slag aggregate improves cohesion in asphalt mixtures. In coarse steel slag aggregates the effect of angularity is more significant than fine aggregates and this causes excessive increase in indirect tensile strength. WSS-100 has the most indirect tensile strength among other mixtures.

3.3. Resilient Modulus Test. Resilient modulus values for mixtures are presented in Figure 4. It indicates mixtures with steel slag aggregate have higher values of resilient modulus. Mixtures with 50% steel slag, as a virgin aggregate regardless of coarseness, fineness, or whole portion of aggregate, have better results in contrast to other mixtures. This can be attributed to higher binder content and stiffness of steel slag aggregates.

3.4. Fatigue Results. Figure 5 shows the results of 4-point-beam fatigue test. The results are the average of three samples. In general steel slag increases the fatigue life of asphalt mixtures. This increment for mixture with steel slag aggregate in the coarse portion is about 15% but for mixtures with steel slag aggregate in their fine portion is about twice of control mixtures. An important consideration about utilization of steel slag is its expansion potential. Results indicate that mixtures with 100% steel slag aggregate have lower fatigue responses. In fatigue performance of steel slag asphalt mixtures, two

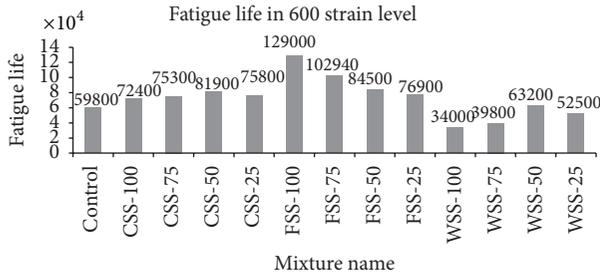


FIGURE 5: Fatigue life of samples in 600 strain levels.

TABLE 5: Marshall design results.

Type of mixture	Optimum binder content (%)	Mix bulk specific gravity (g/cm ³)	Air void (%)	Marshall stability (kN)	Flow (mm)
Control	5.2	2.41	4.49	8.9	3.21
CSS-100	5.5	2.69	2.99	13.86	3.01
CSS-75	5.1	2.61	3.31	13.2	3.11
CSS-50	4.9	2.54	4.00	12.7	3.14
CSS-25	5	2.50	4.14	12.1	3.4
FSS-100	5.5	2.69	4.19	11.9	2.76
FSS-75	5.4	2.99	4.02	11.6	2.97
FSS-50	5.6	2.56	3.97	12.1	2.92
FSS-25	5.2	2.49	3.82	11.3	2.74
WSS-100	5.8	2.93	4.28	14.4	2.69
WSS-75	5.8	2.89	3.97	13.6	2.87
WSS-50	5.3	2.70	3.64	12.9	2.86
WSS-25	5.3	2.60	3.49	11.15	3.03

main characters of samples play a major role (first, air void and second, expansion potential). When steel slag aggregate replaces fine portion of limestone aggregate, the amount of increment in the air void is negligible; furthermore, washing of steel slag aggregate has more effect on decreasing the expansion potential of fine steel slag aggregate than coarse steel slag aggregate. According to these results, AC with 100% steel slag aggregates (WSS-100) is not recommended.

4. Conclusion

According to the results obtained from Marshall and indirect tensile strength tests, mixtures with steel slag aggregate have better results in contrast to limestone asphalt mixtures and this can be due to the structure and angularity of steel slag aggregates. Fatigue tests results show that the use of steel slag aggregates in both fine and coarse portion of aggregate improves fatigue performance of asphalt mixtures, but 100% steel slag asphalt mixtures have ineligible results in fatigue test. Replacement of steel slag aggregates as fine limestone aggregates has better results than coarse limestone aggregates. Better performance of fine steel slag aggregates is due to lower air void of these mixtures among other combinations of steel slag aggregate and limestone aggregates. Regarding

performance of seven types of asphalt mixtures in all tests, mixtures with 50% steel slag aggregate in their fine, coarse, or whole aggregate have the best performance among other types of mixtures. In mixtures with 50% steel slag aggregate, detrimental effect of excessive air void resulting from steel slag aggregate structures can be modified with excessive stiffness of these aggregates. According to the results of fatigue test, fine steel slag aggregate is a reliable alternative for limestone fine aggregates in places with high volume of traffic loading where fatigue cracking is much probable.

Suggestions for further studies in this field are as follows:

- (i) laboratory evaluation of various bitumen in order to determine fatigue characteristics of asphalt mixtures with steel slag aggregates;
- (ii) laboratory investigation of fatigue characteristics of asphalt mixtures with steel slag aggregate in the saturated condition;
- (iii) laboratory evaluation of subzero temperatures on fatigue of asphalt mixtures with steel slag aggregate.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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