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Evaluation of steel slag coarse aggregate in hot mix asphalt concrete

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ABSTRACT

This paper presents the influences of the utilization of steel slag as a coarse aggregate on the properties of hot mix asphalt. Four different asphalt mixtures containing two types of asphalt cement (AC-5; AC-10) and coarse aggregate (limestone; steel slag) were used to prepare Marshall specimens and to determine optimum bitumen content. Mechanical characteristics of all mixtures were evaluated by Marshall stability, indirect tensile stiffness modulus, creep stiffness, and indirect tensile strength tests. The electrical sensitivity of the specimens were also investigated in accordance with ASTM D257-91.

It was observed that steel slag used as a coarse aggregate improved the mechanical properties of asphalt mixtures. Moreover, volume resistivity values demonstrated that the electrical conductivity of steel slag mixtures were better than that of limestone mixtures.

1. Introduction

Hot mix asphalt (HMA) concrete is a combination of aggregate and asphalt cement. The aggregate acts as the structural skeleton of the pavement and the asphalt cement as the glue of the mixture. The mineral aggregate, including coarse and fine particles in asphalt paving mixtures, encompasses approximately 90% of volume of HMA. The properties of the aggregate have direct and significant effect on the performance of asphalt pavements [1].

The HMA industry has been pressured in recent years to incorporate a wide variety of waste materials into HMA pavements. The waste materials can broadly be categorized as follows: (a) industrial wastes such as cellulose wastes [2], wood lignins, slags [3], bottom ash and fly ash [4]; (b) municipal/domestic wastes such as incinerator residue, scrap rubber [5], waste glass [6] and roofing shingles; (c) mining wastes such as coal mine refuse. The resulting large quantities of slags produced and their potential impact on the environment have prompted materials scientists and civil engineers to explore technically sound, cost-effective and environmentally acceptable use of this material in civil and highway construction.

Steel slag is a by-product of the steel-making process. Approximately 1 tonne of stainless steel slag is generated while producing 3 tonnes of stainless steel [7]. It should be noticed in the text that fifty million tons per year of steel slag is produced as a by-product in the world. Furthermore, in Europe, every year nearly 12 million tons of steel slag is produced [8].

In Turkey, the current level of production of steel slag is about 350,000 tonnes per year at Erdemir Steel Manufacturing Factory. Steel slag, due to its high strength and durability, can be used as an aggregate not only in surface layers of the pavement but also in unbound bases and subbases. Also, based on high frictional and abrasion resistance, steel slag has gained wide utilization on industrial roads, intersections, and parking areas where high wear resistance is required [9]. Asi, conducted experiments for evaluating the skid resistance of asphalt concrete mixtures involving steel slag. In the study, it is concluded that asphalt concrete mixes containing 30% slag have the highest skid number followed by Superpave, SMA, and Marshall mixtures, respectively. Asi et al. evaluated the effectiveness of steel slag aggregate by indirect tensile strength, resilient modulus, rutting resistance, fatigue life and creep modulus tests. They reported that replacing up to 75% of the limestone coarse aggregate by steel slag aggregate improved the mechanical properties of the asphalt concrete mixes [10].

The feasibility of utilization of steel slag as aggregate in stone mastic asphalt (SMA) mixtures was investigated by Wu et al. [11]. They concerned the mechanochemistry and physical changes of the steel slag and studied it by performing XRD, SEM, TG and mercury porosimeter analysis and testing method. The results gained from their studies showed that, the utilization of steel slag as aggregate provided a new and more cost effective approach for aggregate resources [11,12]. Hassan and Khabiri [13] and Norman et al. [14]

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conducted Marshall and stability tests on asphalt concrete mixtures involving steel slag. Their research demonstrated that the recycling of steel slag in asphalt concrete was feasible. A research related to utilization of steel slag in three levels of asphalt pavement as a bitumen base, binder and wearing course was made by Kara et al. [15]. Their studies exhibited that physical properties of steel slag satisfied the requirements for using in asphaltic mixture.

An asphalt mixture generally behaves as an insulator. The addition of electrically conductive additives may produce conductive asphalt mixtures [16]. Electrically conductive material such as synthetic graphite has been successfully utilized in Snowfree® (electrically conductive asphalt pavement system formulated by Superior Graphite Co.), with cooperation of the Federal Aviation Administration (FAA) and Flood Testing Laboratories. This system is based on an electrically conductive asphalt pavement that uses synthetic graphite, asphalt and electricity to heat the airport runway surface for melting snow and ice [17].

This study aims to recognize the influences of steel slag on the mechanical properties and electrical conductivity of asphalt concrete mixtures. For this purpose, Marshall stability, indirect tensile stiffness, creep stiffness, moisture damage as well as electrical sensitivity tests were performed on four different asphalt mixtures containing two types of asphalt cement (AC-5; AC-10) and two types of aggregate (steel slag; limestone).

2. Background

The utilization of industrial by-products from the steel-making industry like blast furnace slag and steel slag has been established in a number of applications in the civil engineering industry.

Production of steel, calls for the removal of excess silicon and carbon from iron by oxidation. In the production of steel, the furnace is charged with iron ore or scrap metal, fluxing agents, usually limestone and dolomite, and coke as both fuel and reducing agent. The carbon and silicon are removed as carbon dioxide and the remaining oxidized elements are combined with added lime to form steel slag. Steel slag is a hard, dense, abrasion resistant, and dark colored material. It contains significant amounts of free iron, giving the material high density and hardness. These properties make the steel slag particularly suitable aggregate used in road construction [18].

Application of slags in road construction relies on angularity and high shear resistance of their constituent particles, which make them suitable for several pavement layers. It should be mentioned that the superior frictional resistance properties of steel slag and its resistance to permanent deformation (rutting) often overshadow the potential of this material for cracking [19].

The principal problem associated with steel slag is volume expansion due to the hydration of free lime or magnesia that are common the components of slag. High levels of free lime or magnesia can adversely affect the performance of the materials made up of slag. Historically, the method of dealing with the free lime and magnesia has been to age the slag or accelerate the hydration reaction with water or washing [20].

Steel slag used in paving mixes should be limited to replace either the fine or coarse aggregate fraction, but not both, since hot mix asphalt containing 100% steel slag is susceptible to high void space and bulking problems due to the angular shape of steel slag aggregate. Mixes with high void space (100% steel slag aggregate mixes) are susceptible to over-asphalting during production and subsequent flushing due to in-service traffic compaction [21].

The washed coarse and fine steel slag aggregates containing less than 3% by mass of nonslag constituents, and that no detectable soft lime particles or lime-oxide agglomerations are recommended [22]. The relatively high porosity of steel slag and its rough texture usually requires a slightly higher amount of asphalt cement than that of conventional asphalt mixes. Besides, steel slag aggregates have been reported to retain heat considerably longer than conventional natural aggregates. The heat retention characteristics of steel slag aggregates can be advantageous for hot mix asphalt repair work during cold weather.

3. Experimental procedure

3.1. Materials

AC-10 and AC-5 asphalt cement were used in this study. The asphalt cements were procured from Turkish Petroleum Refineries Corporation (TUPRAS). Table 1 gives a summary of the results of some tests performed on the asphalt cements.

Crushed limestone aggregate was procured from quarries around Elazig. The steel slag, chosen as a second type of coarse aggregate, was directly obtained from Erdemir Steel Manufacturing Factory. The properties of the limestone and steel slag aggregate are presented in Table 2.

Surface texture of steel slag and limestone coarse aggregates were observed by means of scanning electron microscope (SEM). The SEM consists of an electron optical column which generates and focuses an electron beam over the specimen surface. The beam impinges on the specimen and produces signals which can be detected as backscattered electrons (BE or BSE), secondary electrons (SE) and X-rays. These electrons are measured by electron detectors and converted into images. The instrument used in this study is model Leo Evo 40VP operated at 10 and 20 kV voltage for slag and limestone sample, respectively and the working distance was chosen as 17–18 mm.

The captured SEM micrographs of steel slag and limestone aggregate are shown in Figs. 1 and 2, respectively.

Based on the captured images, steel slag yields different texture and morphology compared to limestone. The surface texture of steel slag is rougher than that of limestone aggregate. This is an important factor since surface texture affects the adhesion ability of the asphalt cement. Fig. 1 also demonstrates that plenty of pores can be observed clearly on the surface of steel slag which implies that steel slag is a kind of porous material compared with limestone.

The range of chemical composition of steel slag is presented in Table 3. The values given in Table 3 are based on the information gained from Erdemir Steel Manufacturing Factory. The combined gradation of aggregate is presented in Table 4.

3.2. Preparation of samples

Two different aggregate types were used for preparing Marshall specimens. Limestone aggregate (as coarse, fine and filler fraction) constitute the first type where as steel slag aggregate (substituting

Table 1
Physical properties of the asphalt cements.

Properties	Standard	Asphalt cement types	
		AC-10	AC-5
Specific gravity (g/cm^3) at 25 °C	ASTM D70	1.036	1.035
Ductility (cm) at 25 °C	ASTM D113	100	100
Penetration, (0.1 mm), 100 g, 5 s	ASTM D5	90	138
Softening point (°C)	ASTM D36	48.2	46.7
Fraass breaking point (°C)	IP 80	−27.2	−21.4
Kinematic viscosity, 135 °C (μm^2/s)	ASTM D2170	354	236
Penetration index (PI)	–	−0.15	0.87
Penetration viscosity number (PVN)	–	−0.53	0.68

Table 2
Properties of limestone and steel slag aggregates.

Properties	Standard	Limestone aggregate			Steel slag aggregate
		Coarse	Fine	Filler	Coarse
Abrasion loss (%) (Los Angeles)	ASTM DC-131	29			20
Frost action (%) (with Na_2SO_4)	ASTM C-88	3.74			8.56
Specific gravity (g/cm^3)	ASTM C-127	2.627			3.017
Specific gravity (g/cm^3)	ASTM C-128		2.639		
Specific gravity (g/cm^3)	ASTM D-854			2.632	

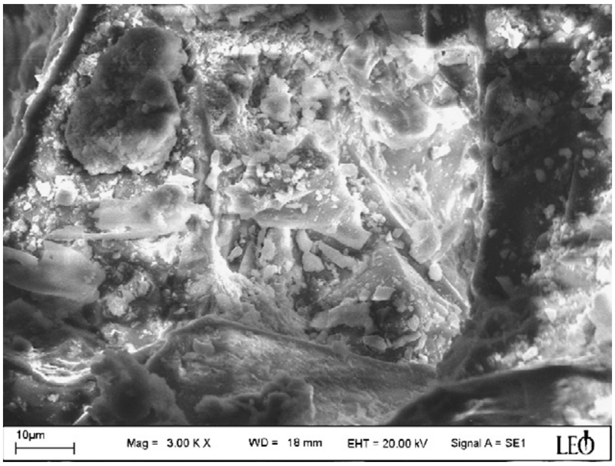

Fig. 1. SEM micrographs of steel slag.

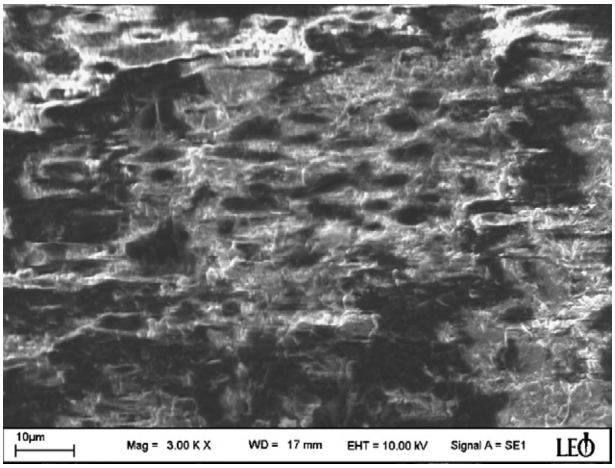

Fig. 2. SEM micrographs of limestone.

Table 3
Chemical composition of steel slag.

Compounds	Steel slag general composition (%)	Steel slag utilized (%)
CaO	47–55	51
Free CaO	6.5	6.5
SiO_2	7.5–15	12.5
Al_2O_3	1.2–1.7	1.4
MgO	1.3–1.5	1.3
Iron (FeO and Fe_2O_3)	20–26	23.5
MnO	3.5–5.3	3.7
Na_2O	–	–
K_2O	–	–
S	–	–
CaO/SiO_2	3.7–6.25	5.5

the coarse fraction of limestone aggregate) constitute the second aggregate type.

Both types of aggregate and asphalt cement (AC-10; AC-5) were heated in an oven at a temperature of at least 165 °C. AC-10 and AC-5 asphalt cements were then added into the both types of aggregate. Following mechanical mixture process for 30–45 s, Marshall control (AC-10/LS; AC-5/LS) and steel slag (AC-10/SS; AC-5/SS) specimens were prepared. Asphaltic concrete mixture specimens were prepared in triplicate for each aggregate mixture formulation.

4. Testing program

4.1. Marshall stability, flow and Marshall quotient tests

Marshall stability and flow tests are carried out on compacted specimens at various asphalt cement contents based on ASTM D1559. The asphalt cement contents corresponding to maximum bulk specific gravity, maximum stability, 4% air voids in the total mixture, and 80% voids in the aggregate filled with asphalt are used to determine the optimum asphalt cement content [23].

The Marshall quotient (MQ) (kN/mm) is also calculated as the ratio of stability (kN) to flow (mm). MQ can be used as a measure of the material's resistance to permanent deformation in service. A higher value of MQ indicates a stiffer mixture and indicates that the mixture is likely more resistant [24].

4.2. Indirect tensile stiffness modulus (ITSM) test

Stiffness modulus is considered to be a very important performance characteristic of the roadbase and base-course layers**.** ITSM test which is defined by BS DD 213 is a nondestructive test and has been identified as a potential mean of measuring the stiffness properties (Fig. 3a).

The test is performed by Universal Testing Machine (UTM-5P) [25]. The ITSM (S_m) in MPa is calculated by the following equation:

$$S_m = \frac{L(\nu + 0.27)}{Dt} \qquad (1)$$

where L is the peak value of the applied vertical load (N), D is the mean amplitude of the horizontal deformation obtained from two or more applications of the load pulse (mm), t is the mean thickness

Table 4
Combined aggregate gradation.

Sieve size	Total cumulative passing (%)
19 mm (3/4″)	100
12.5 mm (1/2″)	95
9.5 mm (3/8″)	88
4.75 mm (#4)	65
2.00 mm (#8)	39
1.18 mm (#16)	24
0.600 mm (#30)	18
0.300 mm (#50)	14
0.150 mm (#100)	10
0.075 mm (#200)	6

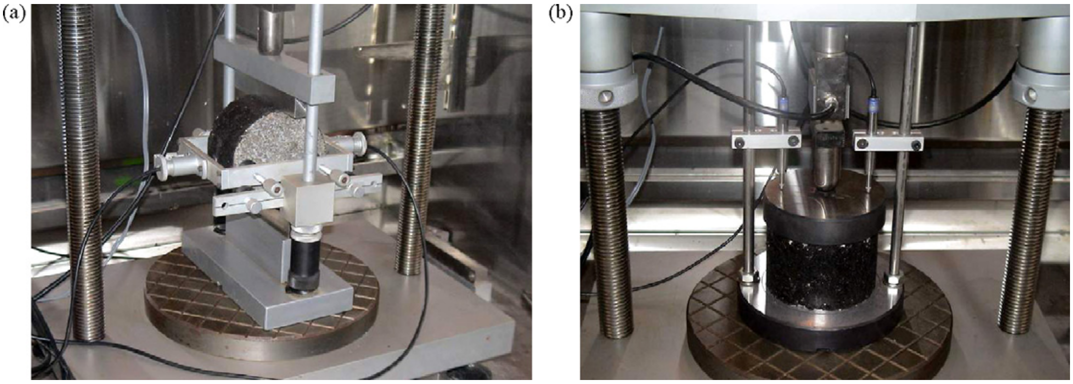

Fig. 3. ITSM (a) and creep stiffness (b) tests equipment.

of the test specimen (mm), and ν is the Poisson's ratio (a value of 0.35 is normally used). The test is normally performed at 20 °C, however in this study, additional testing temperatures were chosen as 0 and 40 °C.

4.3. *Creep stiffness test*

One method for the assessment of resistance to permanent deformation is the creep test (Fig. 3b).

The conditions under which the unconfined static uniaxial creep test is performed are: (a) standard test temperature 40 °C, for very hot climates 60 °C; (b) preloading for 2 min at 0.01 MPa, as a conditioning stress; (c) constant loading stress during the test equal to 0.1 MPa; (d) duration of test: 1 h loading and 1 h unloading [26]. During the test, axial deformation is measured as a function of time. Thus, knowing the initial height of the specimen, the axial strain, ε, and therefore the stiffness modulus S_{mix}, at any loading time can be determined:

$$S_{mix} = \frac{Applied\ stress\,(\sigma)}{Axial\ strain\,(\varepsilon)} \qquad (2)$$

4.4. *Indirect tensile strength (ITS) test*

The indirect tensile strength test (ITS) is performed at loading rate of 51 mm/min by using the Marshall apparatus. The ITS test involves loading a cylindrical specimen with compressive loads that act parallel and loading the vertical diametrical plane. The ITS test is carried out to define the tensile characteristics of the asphalt concrete which can be further related to the cracking properties of the pavement.

In order to compute the *ITS*, the following equation is used:

$$ITS = \frac{2P_{\max}}{\pi t d} \qquad (3)$$

where P_{max} is the maximum applied load (kN), t is thickness of the specimen (mm), d is diameter of the specimen (mm).

4.5. *Resistance to moisture damage*

The moisture susceptibility of asphalt mixtures is evaluated by AASHTO T 283 Test. The test is performed by compacting specimens to an air void level of 7 ± 1%. Three specimens are selected as a dry and tested without moisture conditioning; and three more are selected to be conditioned by saturating with water (55–80% saturation level) followed by a freeze cycle (−18 °C for 16 h) and subsequently having a warm-water soaking cycle (60 °C water bath for 24 h). The specimens are then tested for ITS. The ITS of the conditioned specimens is compared to the dry specimens in order to determine the tensile strength ratio (ITSR).

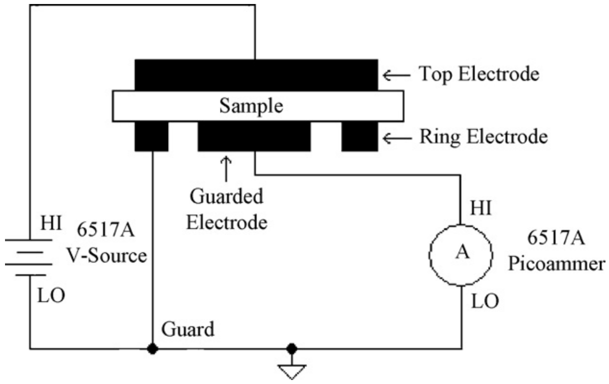

Fig. 4. Electric resistivity test apparatus diagram.

Mixture with tensile strength ratios less than 0.7 are moisture susceptible and mixtures with ratios greater than 0.7 are relatively resistant to moisture damage [27].

4.6. *Electrical resistivity*

The electrical resistivity is measured on Marshall specimens by electrical resistivity testing apparatus. This test apparatus is built in accordance with ASTM D257-91 [28]. The apparatus consists of a Keithley 6517A high resistance electrometer, a ring electrode, a guarded electrode, and a top electrode in the form of plate (Fig. 4).

The sample is placed on the bottom electrode, the top electrode is bolted down on top of the sample. A voltage of 500 V is then applied between the top and bottom electrodes and the current is measured by the Keithley 6517. The volume resistivity is calculated by the following equation:

$$\rho_V = \frac{S}{t} R \qquad (4)$$

where ρ_V is volume resistivity (Ω cm), S is the effective area of the guarded electrode (cm^2), t is thickness of the sample (cm), R is measured resistance (Ω).

5. Results and discussion

5.1. *Marshall stability and flow*

AC-10/LS, AC-5/LS, AC-10/SS and AC-5/SS asphalt concrete samples involving 4.0%, 4.5%, 5.0%, 5.5%, and 6.0% asphalt cement content by mass of aggregate were prepared in order to determine

Table 5
Marshall design results.

Property	Mixture type			
	AC-10/LS	AC-5/LS	AC-10/SS	AC-5/SS
Optimum binder content (%)	5.0	4.85	5.8	5.2
Aggregate bulk specific gravity (g/cm^3)	2.634	2.634	2.760	2.760
Mix bulk specific gravity (g/cm^3)	2.392	2.385	2.455	2.466
Air void (%)	2.53	2.97	2.93	3.29
Voids in mineral aggregate (%)	13.51	13.65	15.92	15.05
Marshall stability (kN)	17.46	16.50	20.19	19.54
Flow (mm)	2.97	2.86	2.32	2.29
MQ (kN/mm)	5.88	5.77	8.70	8.53

Table 6
Volume electroresistivity data.

Mixture type	Volume electroresistivity (Ω cm)
AC-10/LS	3.85×10^{10}
AC-5/LS	9.39×10^{11}
AC-10/SS	7.63×10^{9}
AC-5/SS	3.91×10^{10}

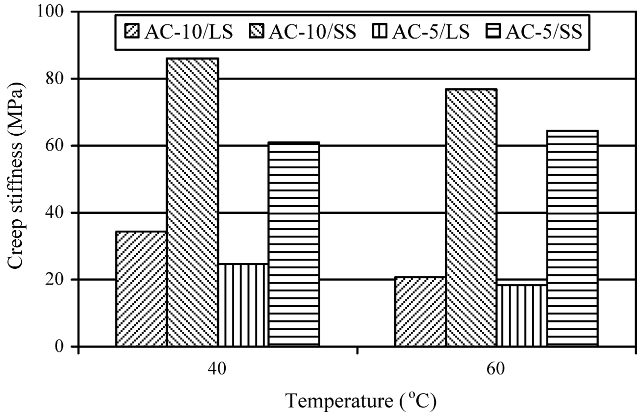

Fig. 6. Creep stiffness values of the control and steel slag asphalt mixtures.

the optimum bitumen content (o.b.c). The o.b.c for the AC-10/LS, AC-5/LS, AC-10/SS, and AC-5/SS mixtures was determined as: 5.0%, 4.85%, 5.8%, and 5.2%, respectively. Marshall design results obtained from specimens compacted at the o.b.c are presented in Table 5. It should be noted that the values are average of three specimens.

As seen in Table 5, steel slag mixtures have higher Marshall stability and lower flow values than control mixtures. The higher stability and lower flow are important criteria for Marshall tests. The Marshall stability of asphalt concrete reflects its ability to resist shoving and rutting under traffic. The Marshall flow is the ability of asphalt concrete to resist the gradual settlements and movements in the sub-grade without cracking [29].

The asphalt concrete samples containing steel slag coarse aggregate yield higher values of MQ than that of the control mixtures as indicated in Table 5. It is well recognized that the MQ is a measure of the resistance of material to shear stresses, permanent deformation. Among the tested mixtures, AC-10/SS asphalt concrete mixture exhibits the best results.

5.2. Indirect tensile stiffness modulus (ITSM) and creep stiffness

Fig. 5 presents the ITSM results for control and steel slag mixtures at 0, 20 and 40 °C.

Steel slag mixtures have higher stiffness modulus than limestone mixtures at all testing temperatures as indicated in Fig. 6. Especially the significant improvements in the ITSM values of AC-10/SS and AC-5/SS are detected at 20 °C which are increased by 2.4 and 1.9 times, respectively, as compared to the AC-10/LS and AC-5/LS asphalt mixtures. Also among the samples prepared with steel slag aggregate, AC-10/SS mixture exhibits superior ITSM values compared to AC-5/SS mixture as depicted in Fig. 5.

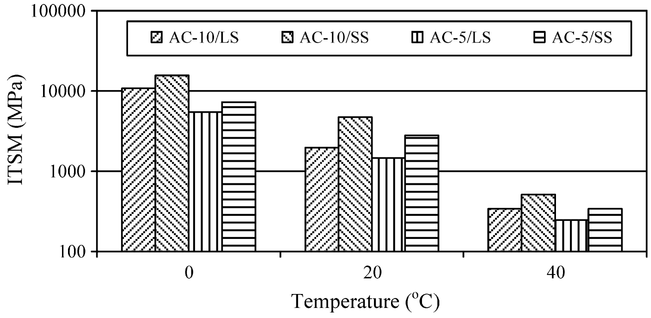

Fig. 5. ITSM values of the control and steel slag asphalt mixtures.

The creep stiffness test values are given in Fig. 6.

Compared to the control mixtures, there is a substantial improvement in the resistance to permanent deformation of the steel slag mixtures as indicated by higher creep modulus at standard test temperature of 40 and at 60 °C. In addition among the mixtures prepared with steel slag coarse aggregate, AC-10/SS yields higher creep stiffness value compared to AC-5/SS mixture as indicated in Fig. 6.

Based on the ITSM and creep stiffness test results the AC-10/SS asphalt concrete mixture exhibits the best performance.

5.3. Indirect tensile strength

The indirect tensile strength test results are presented in Fig. 7.

The ITS of the mixtures containing steel slag coarse aggregate is higher than control mixtures containing limestone coarse aggregate as depicted in Fig. 7. This indicates that mixture prepared with steel slag aggregate yields greater cohesive strength compared to mixture prepared with limestone aggregate. Also AC-10/SS exhibits the highest ITRS value which indicates the steel slag aggregate with AC-10 asphalt cement shows highest resistance to the detrimental effect of water.

5.4. Electrical resistivity

The electrical volume resistivity values for limestone and steel slag mixtures are presented in Table 6.

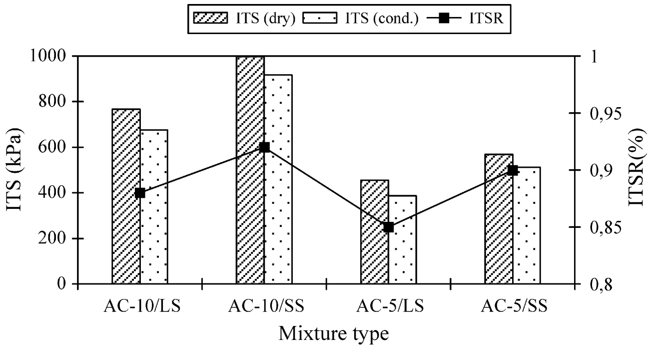

Fig. 7. ITS and ITSR values of the control and steel slag asphalt mixtures.

Based on the electrical resistivity test results, it can be seen that the volume electroresistivity of AC-10/SS and AC-5/SS asphalt mixtures are lower than the electroresistivity of AC-10/LS and AC-5/LS asphalt mixtures. This indicates that, steel slag gains the asphalt concrete mixture electrical conductivity property.

6. Conclusions

On the basis of the data obtained in this study the following conclusions are warranted:

- According to the results obtained from Marshall stability and flow tests, it should be noted that the mixtures with steel slag have better results than mixtures with limestone. It means that steel slag used as a coarse aggregate in AC-10/SS and AC-5/SS asphalt concrete mixtures increased stability and decreased flow values, and, hence mixtures with steel slag coarse aggregate have higher MQ. That is an indicator of high stiffness and resistance to permanent deformation.
- Indirect tensile stiffness modulus test results showed that the stiffness modulus values of the mixtures containing steel slag coarse aggregate were higher than mixtures with limestone coarse aggregate at all testing temperatures, especially at 20 °C. In terms of creep stiffness, the values of steel slag mixtures are substantially higher than that of the control mixtures. The higher creep stiffness of the mixtures with steel slag coarse aggregate indicates better rutting resistance.
- Higher ITS of steel slag mixtures indicate better cohesive strength than the mixtures prepared with the limestone aggregate. Based on the indirect tensile strength ratios, it can be concluded that the use of steel slag as a coarse aggregate in asphalt mixtures leads to the enhancement of resistance against moisture damage as well as moisture induced rutting damage.
- The electrical conductivity of mixtures with steel slag used as a coarse aggregate is found to be greater than the control mixtures. Improved electrical conductivity of steel slag mixtures allows using these mixtures to prepare conductive asphalt concrete in thermo-electrical asphalts pavement for de-icing of parking garages, sidewalks, driveways, highway bridges, and airport runways.

The results obtained from the present investigation indicate that the steel slag mixtures have the excellent engineering properties and good electrical conductivity, particularly, the AC-10/SS asphalt mixture showed the best performance among the tested mixtures.

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