G.U. Journal of Science
21(3): 97-103 (2008)

GUJS
www.gujs.org

Effects of Steel Slag Usage as Aggregate on Indirect Tensile and Creep Modulus of Hot Mix Asphalt

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Received: 05.06.2006 Revised: 28.03.2007 Accepted: 27.02.2008

ABSTRACT

In this study indirect tensile modulus and long term deformation behaviour of the hot mix asphalt (HMA) containing steel slag, basalt and limestone were investigated using 5 pulses Universal Testing Machine. Optimum bitumen content was determined for three types of mixtures according to the Marshall procedure. Indirect tensile modulus ITM (S_m) and creep modulus (S) tests were applied in order to investigate the effects of the steel slag usage on the pavement. To investigate the effects of air void on indirect tensile and creep modulus of mixtures, the mixtures prepared were also subjected to different numbers of compaction blows between 35 and 75 at optimum bitumen content to maintain different air void content. The steel slag mixes were compared with basalt and limestone mixes. The highest S_m values were obtained with steel slag mixes. In terms of creep modulus the basalt mixes were found to have higher values than the others. However the steel slag mixes provide a remarkable value as basalt mixes. This study also indicates that a certain correlation exists between air voids and indirect tensile and creep modulus, and provide to compare these properties according to air void contents.

Key Words: Steel slag; Hot mix asphalt, Indirect tensile modulus, Creep modulus.

1. INTRODUCTION

Preventing the exhaustion of natural resources and enhancing the usage of waste materials has become a significant problem of the modern world. Especially in Turkey it is estimated that 400-million tons of waste material come into being as a result of the 870 million tons of steel fabricated within a year. A lot of studies have been done concerning the protection of natural resources, prevention of environmental pollution and contribution to the economy by using this waste material.

Steel slag, a by-product of the steel making process, is readily available in Erdemir. In previous years steel slag was considered a waste material having no economic asset, but nowadays it is known that 100 percent of blast furnace slag and 75-80 percent of steel slag can be reused. A large amount of steel slag was deposited in slag storing yards which occupied farmland, silted rivers and polluted the environment for many years. Steel slag is produced as a by-product during the oxidation of steel pellets in an electric arc furnace. This by-product that mainly consists of calcium carbonate is broken down into smaller sizes. One way to utilize the steel slag is to incorporate it into hot mix asphalt (HMA). Steel slag aggregate has been used in asphaltic mixtures since the early 1970's in Canada [1]. This process has been used successfully in the midwestern and eastern United States with reported improvement in pavement performance. Their experiences indicate that the addition of steel slag may enhance the performance characteristics of the pavement. Since the slag is rough, the material improves the skid resistance of the pavement. Also, because of the high specific gravity and angular, interlocking features of the crushed steel slag, the resulting HMA is more stable and resistant to rutting [2, 3, 4].

Steel slag has been used to construct pavements for nearly one hundred years. Since it was discovered that the residue from the manufacture of steel could be crushed and processed into a product that looked like crushed rock, other testing was performed to determine the usefulness of this “waste” product. It was discovered that the highly angular, rough textured, vesicular, pitted surfaces provide the particle interlock,

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and if properly compacted, will provide the high stability required for good serviceable pavements. The slag is usually added as part of the coarse aggregate fraction of the mixture at a percentage of 20% to 100%, depending on the application of the mixture [5]. Kandhal denoted that a considerable amount of steel slag is produced in the southwestern part of Pennsylvania around Pittsburgh, where natural fine aggregate sources are limited, so he evaluated the steel slag as fine aggregate in hot mix asphalt and recommended it for the use of steel slag fine aggregate in HMA mixtures [6]. Gordon et.al. have investigated the mechanical performance of asphalt mixtures incorporating slag and glass secondary aggregates. The Mechanical properties of the asphalt mixtures have been measured using the suite of tests (stiffness modulus, resistance to permanent deformation and resistance to fatigue cracking) possible with the Nottingham Asphalt Tester (NAT). The durability of the primary and secondary mixtures has been assessed by subjecting the materials to simulative long-term laboratory ageing and moisture susceptibility conditioning using recognized testing (conditioning) procedures and protocols. The results showed that using basic oxygen steel slag and blast furnace slag secondary aggregates have significantly increased the mixture density and stiffness modulus compared to primary aggregate mixtures. The moisture susceptibility of these secondary aggregate mixtures have also been found to be similar to that of the control mixtures, although the slag mixtures have not shown an increased susceptibility to age hardening [7]. Bagampadde et.al. have investigated the optimization of steel slag aggregates for bituminous mixes in Saudi Arabia. The mix's properties that have been tested include resilient modulus, split tensile strength, stability, fatigue, and permanent deformation. They also used slag with polymers. The results showed that mixes with slag in the coarse portion and limestone in the sand and filler portions modified with polymer had high resistance to rutting and fatigue failure [8].

Determining the mechanical properties of alternative materials using performance- based specifications indicated that many such materials performed as well as (or even better) than conventional materials. The stiffness and strength properties of the materials and mixtures were dependent on the coarsest particle size of the material and the amount of binder. Coarse materials had a higher stiffness than fine materials and also required less binder to achieve a particular strength, the high strength and stiffness exhibited by many of the treated alternative aggregates (steel slag) may enable the thickness of pavement layers to be reduced and thus the overall consumption of materials to be reduced without any loss in performance [9].

2. PRODUCTS OF STEEL SLAG AND USAGE

Steel slag, a by-product of steel making, is produced during the separation of the molten steel from impurities in steel-making furnaces. The slag occurs as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling. Virtually all steel is now made in integrated steel plants using a version of the basic oxygen process or in specialty steel plants (mini-mills) using an electric arc furnace process. The open hearth furnace process is no longer used. In the basic oxygen process, hot liquid blast furnace metal, scrap, and fluxes, which consist of lime (CaO) and dolomitic lime (CaO.MgO or "dolime"), are charged to a converter (furnace). A lance is lowered into the converter and high-pressure oxygen is injected. The oxygen combines with and removes the impurities in the charge. These impurities consist of carbon as gaseous carbon monoxide, and silicon, manganese, phosphorus and some iron as liquid oxides, which combine with lime and dolime to form the steel slag. At the end of the refining operation, the liquid steel is tapped (poured) into a ladle while the steel slag is retained in the vessel and subsequently tapped into a separate slag pot.

There are several different types of steel slag produced during the steel-making process. These different types are referred to as furnace or tap slag, raker slag, synthetic or ladle slag, and pit or cleanout slag. The basic oxygen steel making furnace (BOS) and the electric arc furnace (EAF) -slag from different sources as characterized by their chemical and mineral compositions plus their technical properties, are generally comparable and independent of their producers. Differences arise from the use of dolomite rather than lime with the effect of a higher MgO-content in the slag BOF- and EAF-slag are calciumsilicatic with a range of CaO between 42 and 55%, and a range of SiO_2 between 12 and 18%. EAF-slag is comprised of CaO between 25 and 40% and 12 to 17% SiO_2. Their MgO-content may be higher due to the reactions with the refractory lining [10].

Slag is often specified for use in bituminous concrete because of its high stability and superior skid resistance. Durability, hardness and bond characteristics of blast furnace and steel furnace slag can be advantageous in producing high quality asphalt.

Heaston explained that, due to slag's high stability and high skid resistance, the pavement can be constructed as thin layers, permanent deformation caused by high temperatures is reduced, and safety of roads increases. Because the surface of slag is angled and slag has good adhesion with asphalt, the mechanical adhesion and the stability of pavement increase. Slag can retain heat for a long time. This property is advantageous for spread and compaction [11].

Steel furnace slag is a valuable, high quality product which is used in construction. In some areas this material is marketed under the name "Furnaston". Crushed and screened to required gradations, steel furnace slag is also used where its unique qualities assure the highest performance: maximum durability, higher strength and extreme hardness. Steel furnace slag is used as an unconfined aggregate base selectively under bituminous concrete paving and all types of binder, wearing courses, and skid resistant overlays, and used on main lines of major railroads and spur track ballast for plant service. Also, steel furnace slag is used in special applications, such as cement manufacture, soil conditioning, and rip-rap protection.

3. MATERIALS AND METHOD

3.1. Materials

In this study the appropriateness and the performance of steel slag, which is used as an aggregate in hot mix asphalt (HMA), were investigated. Three different aggregates were used: the first was steel slag, the second was limestone, and lastly basalt. The slag was obtained from Erdemir. The steel production is done in three basic oxygen steel making furnaces- each with a capacity of 120 tons- in Erdemir. Per year, 3-3.2 million tons of steel are produced and 300-350-thousand tons of slag come into being as a result in Erdemir. This slag is poured into a stock field and cooled with water. After the crushing and elevation process, the magnetic parts are separated. The chemical properties of slag are given on Table 1 [12]. The physical properties of three types of aggregates and the gradation of aggregate are given on Table 2 and Table 3, respectively. Asphalt cement with B 100-150 penetration was used in the experiments. The specifications of asphalt cement are given on Table 4.

Table 1. Chemical properties of Erdemir BOF slag.

CaO (%)	47.0 – 55.0
CaO Free (%)	6.5
SiO_2 (%)	7.5 – 15.0
Al_2O_3 (%)	1.2 – 1.7
MgO (%)	1.3 – 1.5
Total Fe (%)	20.0 – 26.0
Total Mn (%)	3.5 – 5.3
CaO / SiO_2 (%)	3.7 – 6.2

Table 2. Physical properties of three types of aggregates.

Physical properties / Aggregate type	BOF slag	Limestone	Basalt
Strip resistant (%)	80	65	70
Abrasion lost (Los Angeles) (%) (ASTM C 131)	20	30	28
Frost action (with Na_2SO_4) (%) (ASTM C 88)	8.560	9.100	6.160
Specific gravity of course aggregate (gr/cm^3) (ASTM C 127)	3.118	2.620	2.680
Specific gravity of fine aggregate (gr/cm^3) (ASTM C 128)	3.079	2.640	2.730
Specific gravity of filler (gr/cm^3) (ASTM D 854)	2.941	2.660	2.720

Table 3. Gradation of aggregate.

Sieve size (mm)	25	19	12.5	9.5	4.75	2	0.425	0.18	0.075
Passing (%)	100	90	72.5	63	49	36.5	19.5	12	4.5

Table 4. Binder properties.

Material	Specific gravity (gr/cm^3) (ASTM D 70)	Penetration (0,1mm) (ASTM D 5)	Ductility (mm) (ASTM D 113)	Softening point (°C) (ASTM D 36)
AC 100-150	1.015	120	> 100	45

3.2. Method

The Marshall method [13] was used for determining optimum bitumen content for the mixtures. Three identical samples were produced for the mixtures containing steel slag, limestone and basalt. Bitumen range region (4.0%, 4.5%, 5.0%, 5.5%, 6.0%) was regulated according to the bitumen demand for each mixture. Six designs were realized and 45 asphalt briquettes were fabricated. Compacting energy was applied as 75 blows per side. To investigate the effectiveness of steel slag and to compare with the other mixtures containing limestone and basalt at different air void contents, the test specimens were subjected to different numbers of compaction blows between 35 and 75 at optimum bitumen content to maintain different air void content.

In the study, indirect tensile modulus (ITM) and creep modulus (S) tests were applied in order to investigate the effects of the steel slag usage on the pavement. The tests were carried out with the UMATTA testing machine seen in Figure 1.

Figure 1. UMATTA testing device.

Indirect tensile modulus is considered to be a very important performance characteristic of the pavement. It is a measure of the load-spreading ability of the bituminous layers and controls the level of traffic induced tensile strains on the underside of the roadbase, which are responsible for fatigue cracking together with the compressive strains induced in the subgrade that can lead to permanent deformation [14]. This test also provides an important input for the structural design of a pavement system using a multi layer elastic theory for design. The indirect tensile modulus test defined by BS DD 213 [15] is a non-destructive test and has been identified as a potential means of measuring this property. The ITM in MPa is defined as

$$ITM = F(R + 0{,}27) / LH \tag{1}$$

Where F is the peak value of the applied vertical load (repeated load) (N), H is the mean amplitude of the horizontal deformation obtained from 5 applications of the load pulse (mm), L is the mean thickness of the test specimen (mm), and R is the Poisson's ratio (assumed 0.35). The test was done deformation controlled. The magnitude of the applied force is adjusted by the system during the first five conditioning pulses such that the specified target peak transient diametral deformation is achieved. A value is chosen to ensure that sufficient signal amplitudes are obtained from the transducers in order to produce consistent and accurate results. The value selected was 7 micrometers in this test. During testing, the rise time, which is measured from when the load pulse commences and is the time taken for the applied load to increase from zero to a maximum value, was set at 124 ms. The load pulse application is equated to 3.0 s. The test is normally performed at 20 ^{o}C.

The creep test is carried out in the static mode of loading. This test gives results which allow the characterizations of the mixes in terms of their long-term deformation behavior [16]. Creep modulus (S) is important shed light to asses rutting. The creep modulus was calculated from the following equations:

$$\varepsilon c_t = (L2_t - L1) / G \tag{2}$$

$$\sigma = F / A \tag{3}$$

$$S = \sigma / \varepsilon c \tag{4}$$

Where εc_t is the accumulated axial strain (creep) at time t, $L2_t$ is the displacement level of the transducers at time t, L1 is the initial zero reference displacement of the transducer before the full loading stress is applied, G is the initial specimen length, σ is the vertical stress, F is the vertical force, A is the cross-sectional area of the specimen, and S is the creep modulus at time t. The test was performed at 40 ^{o}C, and the specimens preloading for 2 min. at 0.01 Mpa as a conditioning stress and constant loading stress during the test was equal to 0.1 Mpa in 3600 s.

4. EXPERIMENTAL RESULTS

Firstly the Marshall mix design was carried out and the optimum binder content obtained for the mixes containing steel slag, limestone and basalt as 5.0, 4.9, 5.1 respectively. Three identical specimens were prepared at optimum bitumen content (OBC) in 63.5 □ 2 mm height and 101,6 mm diameter using 75 blows according to the Marshall procedure for all aggregate types. The fundamental properties of specimens as air void (VA), voids filled with asphalt (VFA), voids in mineral aggregates (VMA), were determined for all the specimens. Afterwards indirect tensile modulus and creep modulus of the specimens were determined. The properties of specimens prepared at optimum bitumen content (with 75 blows) were given in Table 5.

Table 5. The fundamental properties of specimens prepared at OBC.

Aggregate type	Steel slag			Limestone			Basalt		
OBC (%)	5.0			4.9			5.1		
Specimen no.	1	2	3	1	2	3	1	2	3
VA (%)	3.730	3.930	3.802	3.895	3.777	3.791	3.987	3.833	3.756
VFA (%)	77.302	76.334	16.607	73.559	74.179	74.106	74.249	75.024	75.417
VMA (%)	16.433	16.607	16.496	14.732	14.627	14.639	15.483	15.348	15.280
ITM (MPa)	2978	2790	2813	1196	1239	1221	1276	1315	1422
S (MPa)	44.23	42.31	46.70	36.71	38.87	35.64	54.10	53.28	56.34

The strain values of three types of specimens prepared at OBC at indirect tensile modulus test are given in Figures 2, 3 and 4.

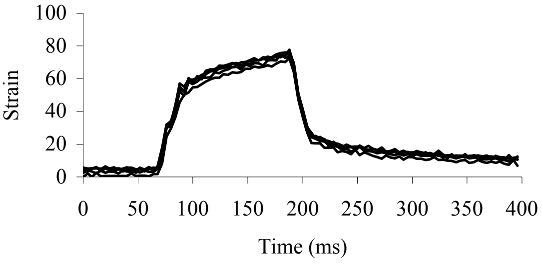

Figure 2. Strain values of steel slag specimen at 5-pulse indirect tensile modulus test.

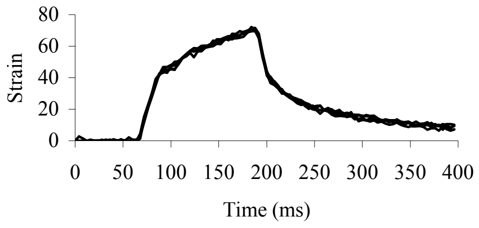

Figure 3. Strain values of limestone specimen at 5-pulse indirect tensile modulus test.

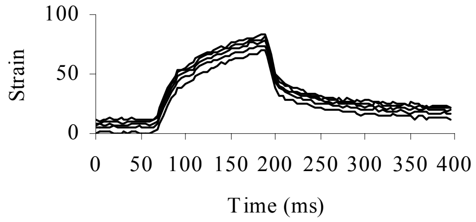

Figure 4. Strain values of basalt specimen 5-pulse indirect tensile modulus test.

It is seen from the figures that the recoverable strain is higher for the steel slag mixture than the others at 200 ms. It has been determined that the steel slag specimens had the highest indirect tensile modulus value and the value of limestone specimen have got behind the value of basalt specimen. The strain values of three types of specimens prepared at OBC at creep modulus test are given in Figure 5.

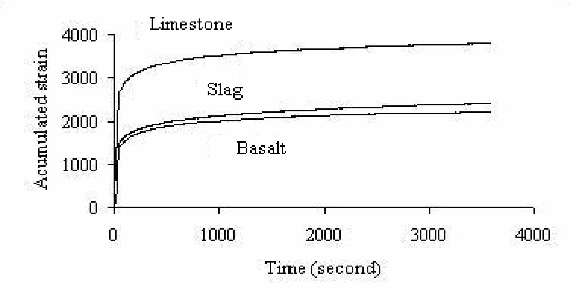

Figure 5. Relationship between time and accumulated strain for three types of specimens at creep modulus test.

The limestone specimens showed the highest accumulated strain and therefore the lowest creep modulus. Basalt specimens performed better than slag specimens in the creep test. The indirect tensile modulus and creep modulus of specimens prepared at OBC were given in Figures 6 and 7. It was determined that the indirect tensile modulus of the steel slag specimen is 2.3 times higher than the limestone specimen, and 2.2 times higher than the basalt specimen.

Figure 6. ITM values of specimens prepared at OBC.

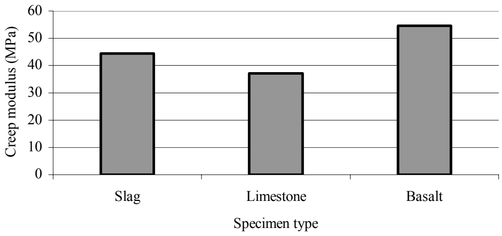

Figure 7. Creep modulus of specimens prepared at OBC.

To investigate the effectiveness of air void versus indirect tensile and creep modulus of specimens, the specimens prepared at optimum bitumen content however subjected to different numbers of compaction blows between 35 and 75. For experimental studies 12 specimens prepared with steel slag, 9 specimens prepared with limestone and 9 specimens prepared with basalt were used. The properties of specimens prepared with steel slag, limestone and basalt are given on Tables 6, 7 and 8 respectively.

Table 6. The fundamental properties of steel slag specimens.

	1	2	3	4	5	6	7	8	9	10	11	12
VA (%)	4.53	4.93	6.60	2.48	8.89	7.71	2.97	5.75	8.60	6.39	7.30	6.81
VFA (%)	72.32	70.54	63.73	82.96	55.98	61.64	80.20	67.02	58.80	64.50	61.18	62.92
VMA(%)	16.39	16.74	18.20	14.59	20.21	18.70	15.02	17.46	19.43	18.02	18.81	18.39
ITM (Mpa)	2899	1943	1746	3558	1456	1689	3184	1874	1612	1786	1635	1702
S (Mpa)	43.05	41.65	27.49	49.10	15.06	21.87	46.02	34.00	15.56	33.28	20.42	23.16

Table 7. The fundamental properties of limestone specimens.

	1	2	3	4	5	6	7	8	9
VA (%)	4.63	6.98	2.56	5.04	4.33	4.76	6.01	4.63	4.97
VFA (%)	71.55	62.07	82.45	69.71	72.93	70.92	65.36	71.52	70.00
VMA (%)	16.28	18.31	14.44	16.64	16.02	16.40	17.55	16.29	16.58
ITM (Mpa)	842	522	1180	545	843	835	534	839	774
S (Mpa)	34.30	18.24	40.12	26.15	37.98	31.25	23.83	32.45	29.46

Table 8. The fundamental properties of basalt specimens.

	1	2	3	4	5	6	7	8	9
VA (%)	6.12	4.97	5.06	2.58	7.24	6.51	3.87	4.98	5.31
VFA (%)	64.92	69.37	68.96	81.67	60.25	70.92	74.60	69.31	67.86
VMA (%)	17.16	16.24	16.32	14.14	18.24	16.40	15.27	16.25	16.54
ITM(Mpa)	897	1239	1153	1289	654	850	1251	1213	1096
S (Mpa)	42.9	49.22	45.1	54.94	35.33	41.49	53.17	48.01	43.33

The relation between air voids and indirect tensile modulus and creep modulus for three different specimens are given in Figures 8 and 9 respectively.

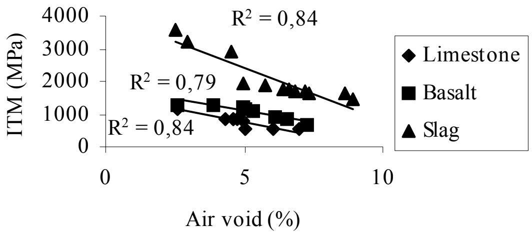

Figure 8. Relationship between air void and indirect tensile modulus for all specimens.

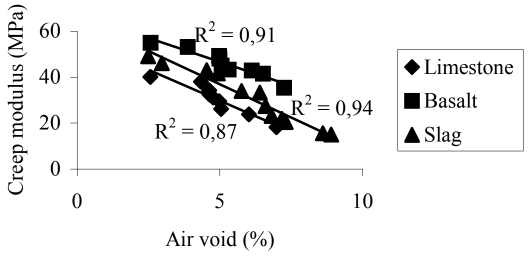

Figure 9. Relationship between air voids and creep modulus for all specimens.

The figures provide to compare the properties according to air void contents. In Figures 8 and 9 the slag specimens exhibit the highest values at all air voids. In Figure 9 the basalt specimens exhibit the highest value and slag specimens have the second highest value. It is also seen from the figures that all the specimens have a linear relation between air void at both indirect tensile and creep modulus test.

5. CONCLUSION

The indirect tensile and creep modulusof the mixtures containing steel slag, limestone and basalt were investigated in two steps. In the first step, the specimens were prepared at optimum bitumen content using 75 blows per side of the specimens according to the Marshall procedure. The indirect tensile and creep modulus of these mixtures were compared. It is found that the indirect tensile modulus of the mixtures prepared with steel slag had the highest value.The steel slag mixes have much higher ITM- approximately 2.3 times that of the limestone mixes and 2.2 times that of the basalt mixes. The improved ITM value should lead to increased resistance to asphalt cracking in practice. In terms of creep modulus, the basalt mixes were found to have higher values than the others. However, the steel slag mixes provide a remarkable value as basalt mixes. In the second step of the study the mixtures were prepared at different air void content using different compaction numbers between 35-75. Then the indirect tensile and creep modulus of these mixtures were also compared. At 5 percent air void, the steel slag mixes have a much higher ITM- approximately 4 times that of the limestone mixes and 1.7 times that of the basalt mixes. It was found that certain correlations exist between air voids and indirect tensile modulus and creep modulus and provide to compare these properties according to air void contents. Consequently, the usage of steel slag in HMA improved the indirect tensile modulus and also improved the value of creep modulus than that of the limestone mixtures. Using steel slag in HMA facilitates the prevention environmental pollution. It is considered that the HMA containing steel slag can be used especially in intersections due to its high stiffness to overcome ondulation problems induced by a vehicle's wheels when decreasing its speed.

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