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The Opportunities for the Development of Low-Cost and Environmental-Friendly Concrete Paving Blocks Using Different Types of Weathered Iron and Steel Slag

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Abstract-This research aims at investigating the possibility of using different types of weathered iron and steel slag in the production of concrete paving blocks. Three types of slag (i.e., blast furnace slag (BFS), basic oxygen furnace slag (BOS) and electric arc slag (EAS)) were used as replacement of coarse aggregate, fine aggregate or coarse and fine aggregates simultaneously. Unit weight, compressive strength, tensile splitting strength, abrasion resistance, slip/skid resistance and water absorption of paving blocks were determined and compared with the relevant standards. Results indicated the feasibility of using weathered iron and steel slag as alternative aggregates in the production of low-cost and environmental-friendly paving blocks satisfying the requirements of standard specifications. The characteristics of paving blocks depend on the type, size and percentage of slag in the mix. Paving blocks containing BOS or EAS could be used in heavy-duty applications, whereas the applications of paving blocks containing even 50% coarse BFS should be limited to medium-traffic applications such as public pavements and roads.

Keywords- *Iron and Steel Slag, Concrete Paving Blocks, Recycling*

I. INTRODUCTION

Slag is by-product formed during smelting, and other metallurgical processes from impurities in the metals or ores being treated. During smelting or refining slag floats on the surface of the molten metal, protecting it from oxidation or reduction by the atmosphere and keeping it clean [1]. Slag is broadly divided into two categories, ferrous slag and non-ferrous slag [2], [3]. Non-ferrous slag is generated during the recovery and processing of non-ferrous metal from natural ore such as copper, tin, nickel, lead, zinc and phosphor. Ferrous slag is generated during the refining of ferrous metal such as iron and steel [3], [4]. Various types of slag products have different properties and characteristics depending on the proces0 [3]. Slags are named based on the furnaces from which they are generated. The main types of slags that are generated from iron and steelmaking industries are blast furnace slag (BFS) and steel slag [5].

Blast furnace slag is a non-metallic by-product arising during the production of pig iron in the blast furnace as follows: the vertical shaft blast furnace is used to smelt iron from iron ore (containing iron oxide, silica and alumina) and a fluxing agent (usually limestone, dolomite, or both). The primary fuel is coke, which is subjected to a continuous blast of air, resulting in a high rate of combustion. The fuel, ore and fluxing agent are supplied continuously through the top of the furnace, whereas air is blown into the bottom of the furnace. The smelting process, in which the ore containing iron oxide is converted to metallic iron through a reduction process, occurs as the material moves downward. The end products are liquid pig iron and molten slag which is tapped from the top of pig iron [3], [4], [6]. The temperature of molten slag is close to that of the iron, which is between 1400 and 1600 °C. Blast furnace slag consists essentially of silicates and aluminosilicates of calcium [4]. It is categorized based on the treatment method applied once it is removed from the furnace. The primary types of blast furnace slag are air-cooled slag, granulated slag, and expanded (foamed) slag [3], [4]. About 70% of the generated blast furnace slag is air-cooled slag, whereas 25% is granulated slag and the rest is foamed slag [3]. If the molten slag is allowed to cool slowly under ambient conditions in an open pit, it solidifies to a gray, crystalline, stone-like material, known as "*air-cooled slag*". After crushing and screening, it could be used as aggregate for asphalt pavement, road bases, concrete, railway ballast, embankment, and mineral wool [3], [7], [8]. The asphalt mixtures containing air cooled blast furnace slag aggregate have good binding property, impermeability to humidity, high resistance to stripping, high skid resistance, and increased rutting resistance [9]. On the other hand, if the molten slag is cooled by rapid water quenching, a granular, glassy, and sand-sized particles is generated (i.e., *granulated blast furnace slag*). When crushed, milled and screened to very fine cement-sized particles, ground granulated blast furnace slag has latent hydraulic properties which make a suitable partial replacement for, or additives to, Portland cement [3]. Slag cement has low heat of hydration, low alkali-aggregate reaction and high resistance to chlorides and sulfate [10]. *Expanded (or foamed) blast furnace slag* results from the treatment of molten slag with controlled quantities of water but less than that required for granulation. This process results in the formation of lightweight, cellular, and pumice-like product.

After crushing and screening, it could be used as lightweight aggregate in lightweight concrete, insulating concrete and roof screeds, and the heavier ones for structural concrete [4], [11].

Steel slag is a by-product obtained either from the conversion of iron to steel in basic oxygen furnace or by the melting of scrap to make steel in electric arc furnace. Steel slag is defined by the American Society for Testing and Materials (ASTM) as a non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium, and magnesium that are developed simultaneously with steel in basic oxygen, electric arc, or open hearth furnaces. The chemical composition and cooling of molten steel slag have a great effect on the physical and chemical properties of solidified steel slag. *Basic oxygen furnaces* are located at the integrated steel mills in association with a blast furnace. In the basic oxygen furnace, the hot liquid metal from the blast furnace, scrap and fluxes, which contain lime and dolomitic lime, are charged to the furnace. A lance is lowered into the converter and then oxygen in injected with high pressure to remove the impurities. These impurities consist mainly of carbon in the form of gaseous carbon monoxide, silicon, manganese, phosphorous, and some iron as liquid oxides, which combine with lime and dolomitic lime to form steel slag. At the end of the refining stage, steel in the liquid form is poured into the ladle whereas slag is retained at the top in the vessel and is then subsequently removed in separate slag pot. This slag is in molten state and is then processed to remove all free metallic impurities with help of magnetic separation and then sized into construction aggregates. Unlike basic oxygen furnace process, *electric arc furnace* does not use hot metal, but uses cold steel scraps. Charged material is heated to a liquid state by means of an electric current. The electricity has no electrochemical effect on the metal, making it perfectly suited for melting scrap. During the melting process, other metals are added to steel to give the required chemical composition. Meanwhereas oxygen is blown into the furnace to purify the steel. This slag which floats on the surface of molten steel is then poured off [5], [12]. After slow cooling of molten slag in air, it forms an artificial crystalline rock comparable to that of natural magmatic rocks like basalt or granite [13]. Steel slag particles are angular in shape and have a rough surface texture. Steel slag has higher values for specific gravity, bulk density, and polished stone value with lower values low values for aggregate crushing value, impact, and abrasion than natural aggregates [3]. Some researches were carried out to investigate the possibility of using steel slag in civil engineering applications. Results of researches for using electric arc furnace slag in blended cement production showed that electric arc furnace slag (EAS) contains low percentage of amorphous silica and high content of ferric oxides and consequently it has low or no pozzolanic activities in comparison with BFS. Thus, it is not appropriate to be used in the production of blended cement [14]. Moreover, recent researches indicated the possibility of using steel slag as aggregate in road construction such as stone mastic asphalt and asphalt pavement [15] – [17]. Wu et al (2007) found that steel slag improved the resistance of stone mastic asphalt to low temperature cracking compared with basalt. Mastic asphalt pavement with steel slag showed excellent performance after 2-years service [15]. Shen et al (2009) reported that the inherent properties of basic oxygen furnace slag (BOS) produce asphalt mixes with enhanced skid resistance, moisture susceptibility, rutting resistance, and sound absorption [16]. Although many studies have been conducted on the use of steel slag in road construction and blast furnace slag in concrete, few researches have been performed regarding the utilization of steel slag in mortar and concrete, regardless of its superior/comparable effect compared with natural aggregates [14], [18] – [20]. This is because of the existence of unstable compounds, mainly in the form of free lime and periclase, in steel slag. In the presence of moisture, these compounds transform into $Ca(OH)_2$ and/or $Mg(OH)_2$, which occupy a larger volume than the primary components. The result is swelling of the composite into which slag has been placed [21]. However, recent researches recommended the implementation of aging treatment before using steel slag to ensure the hydration reaction of CaO and MgO to overcome expansion problem. Results of these researches indicated that the implementation of suitable processing technology and long aging time significantly enhances the stability of steel slag [15], [18], [20]. Practical methods of slag aging treatment include atmospheric aging in open spaces, steam aging treatment to below high-temperature steam into stored slag to accelerate the stabilization, warm water aging by immersing the slag in warm water, and finally pressurized aging treatment in autoclave to accelerate the hydration with high pressure steam [22].

World iron and steel production is rising steeply. In accordance with the statistical data reported by World Steel Association that the annual world production of pig iron in 2016 was 1.16 billion metric tons and steel production in the same year was 1.63 billion metric tons. Based on the typical ratios of slag to crude iron and steel production that 1 ton of pig iron generates about 300 kg of blast furnace slag and 1 ton of steel generates 100-150 kg of steel slag [22]. Thus, the world output of blast furnace slag in 2016 was approximately 348 million metric tons and steel slag quantity was on the order of 163-245 million metric tons. With rapid development of steel industry, the amount of iron and steel slag sharply increases. Due to the increased environmental awareness, recycling of industrial by-products and wastes has become an attractive alternative to disposal. Although extensive researches are being carried out for finding suitable recycling fields for iron and steel slag, the utilization rate of slag in Egypt are rather limited and most of slag is disposed off causing serious environment problems. On the other hand, there is a great demand for aggregate in the construction sector. Therefore, this research was carried out to investigate the feasibility of using slag as alternative aggregates in the production of non-structural concrete products such as paving blocks. Two key benefits associated with such recycling of slag are the conservation of natural aggregates to be used in structural concrete and the reduction of solid waste disposal problems.

II. MATERIALS AND METHODS

A. Materials

Paving blocks are composed mainly of cement aggreagte and water. The cement used was Portland cement (CEM I 42.5 N) produced by El-Suez cement Company, Egypt and conforming to BS EN 197-1 (2011). The chemical composition of cement is shown in Table 1. The specific gravity and specific surface area of the used cement were 3.15 and 3672 cm^2/g, respectively, whereas its 2 and 28-days compressive strength were 25.7 and 48.7 MPa, respectively. Crushed dolomite and natural sand were used as natural coarse and fine aggregates, respectively.

Three types of slag (i.e., air-cooled blast furnace slag, electric arc furnace slag and basic oxygen furnace slag) generated as industrial by-products from iron and steel industry were used as alternative coarse and fine aggregates. Blast furnace slag and basic oxygen furnace slag were obtained from Iron and Steel Company, whereas electric arc furnace slag was obtained from Ezzsteel Company, Egypt. The obtained slag was weathered before being prepared for use as an aggregate. There was no need for weathering BFS as the amount of Fe_2O_3 and SO_3 in the used BFS is less than 3% and 2%, respectively as shown in Table 1. Thus, there is no potential for iron unsoundness or calcium sulfide dissolution [4]. On the other hand, BOS and EAS were weathered to transform CaO and MgO into stable forms. This process consists of storing slag stockpiles in outdoor environment with regular sprinkling of water for six months so that the reaction between free lime (CaO) or free magnesia (MgO) and water takes place to achieve the chemical/physical stabilization necessary for safe use as an aggregate. This duration for weathering steel slag was selected based on the previous researches [17], [20], [23]. Manso et al (2006) reported that the stabilization of EAS slag by permanent wetting and exposure to weathering for at least 90 days reduces the expansion ability of slag from 2.5% to 0.4% [20]. Faraone et al (2009) also reported that no free CaO, MgO, $Mg(OH)_2$ or $MgCO_3$ was detected in steel slag weathered outdoor for 5 months and then kept wet for 15 days in the laboratory [23].

After weathering, each slag type was sieved on 14 mm and 4.75 mm sieves. Coarse aggregate was that passed from 14 mm sieve and retained in 4.75 mm sieve, whereas fine aggregate was that passed from sieve 4.75 mm sieve. As shown in Table 1 that the chemical composition of steel slag (i.e., BOS and EAS) is different from that found for iron slag (i.e., BFS). BFS primarily consists of SiO2, CaO, and Al_2O_3 with summation more than 80%; BOS consists mainly of CaO accompanied with significant amounts of Fe_2O_3 and SiO_2 (summation is more than 75%), whereas EAS contains Fe_2O_3, CaO, and SiO_2 as the major components with summation is more than 80%.

Table 2 shows the characteristics of the used aggregates, whereas Fig. 1 shows their grading curves. Visual examination of the surfaces of slag aggregates revealed that slag particles are cubical, angular with rough texture. It is clear from Table 1 that the specific gravity of slag aggregates is higher than that of natural aggregates, regardless of slag type or size. Furthermore, the water absorption of coarse slag aggregates is ~ 3.5-8.5 times that of crushed dolomite indicating the vesicular and porous nature of coarse slag aggregates. Among slag types, EAS showed the highest specific gravity and lowest water absorption, whereas BFS had the lowest values, indicating the higher porosity of BFS compared to other slag types. This result was confirmed by visual examination of slag grains. Impact index for coarse EAS is significantly lower than that of crushed dolomite, whereas the impact index for coarse BFS was comparable to that of crushed dolomite. The higher resistance to impact of coarse aggregate could be beneficial in increasing the resistance of paving blocks to mechanical wear. Coarse slag aggregates had almost similar grading curves. In case of fine slag aggregates it is clear that fine EAS is rougher than other slag types whereas fine BOS had the finest grading curve.

TABLE I. CHEMICAL COMPOSITION OF CEMENT AND SLAG

Component (%)	Cement	BFS	BOS	EAS
SiO_2	21.1	35.70	15.60	16.90
Al_2O_3	6.1	10.72	4.29	5.66
Fe_2O_3	3.0	1.89	21.80	37.85
CaO	61.5	33.8	37.7	27.7
MgO	2.1	7.20	6.30	2.50
SO_3	2.3	1.74	0.92	0.84
Na_2O	0.12	0.45	0.24	0.77
K_2O	0.31	0.39	0.11	0.15
Cl^-	—	0.12	0.20	0.58
MnO	—	2.10	4.43	3.58
TiO2	—	0.61	0.54	0.50
P2O5	—	0.61	1.15	0.47
Cr2O3	—	0.12	0.22	1.20
LOI	2.4	2.13	6.05	0.15

TABLE II. PROPERTIES OF AGGREGATES

Property	Natural aggregates		Slag aggregates					
	Crushed dolomite	Sand	BFS		BOS		EAS	
			Coarse	Fine	Coarse	Fine	Coarse	Fine
Specific gravity (SSD)	2.64	2.51	2.71	2.79	2.85	3.10	3.33	3.49
Absorption (%)	0.82	—	6.96	—	4.32	—	2.87	—
Clay and fine materials (%)	1.02	1.12	—	7.92	—	13.37	—	6.51
Fineness modulus	—	2.33	—	2.25	—	1.89	—	2.77
Impact index (%)	17.01	—	21.8	—	14.3	—	8.6	—
Los Angeles coefficient (%)	22.4	—	28.3	—	16.4	—	12.5	—

B. Methods

A total of sixteen mixes were cast as follows: the first mix was the control mix made with natural aggreagtes. The remaining fifteen mixes were divided into three groups based on slag type: group (I) included BFS partially/totally replacing coarse and/or fine aggregate, group (II) included BOS partially/totally replacing coarse and/or fine aggregate, and group (III) included EAS partially/totally replacing coarse and/or fine aggregate. In each group, five mixes were cast to investigate the influence of incorporating coarse and/or fine iron and steel slag in the production of paving blocks. Each mix was identified with the designation "A-(BC)", where "A" indicates slag type, "B" indicates the replacement percentage of aggregate with slag and "C" indicates the size of replaced aggregate (i.e., coarse aggregate or fine aggregate). For example, designation "BFS-(50%CA)" is for mix including BFS replacing 50% of coarse aggregate, whereas designation "BFS-(50%FA)" is for mix including BFS replacing 50% of fine aggregate and designation "BFS-(50%CA&FA)" is for mix including BFS replacing 50% of coarse aggregate and fine aggregate simultaneously.

The control mix was designed using the absolute volume method with 600 kg/m^3 cement content and fine to coarse aggregate ratio of 1.67 according to the factory's recommendations. Mixes' proportions are presented in Table 3. Iron and steel slag was used to replace 0, 50, and 100% (by volume) of natural aggregate. It should be noted that zero-slump concrete was designed for the production of paving blocks, as the blocks are required to be self-supporting from the moment they are extruded from the mold. If the mix is wet, the blocks sag after the removal of the mold, whereas too dry mix results in incomplete compaction. The amount of added water to the mix is approximately right when ripple marks form on the back of a shovel when it is rubbed against the mix [24], [25].

Paving blocks were manufactured in a local factory in Egypt. Mixing procedure was as follows: First, coarse and fine aggregates were mixed in the mixer for 1 min. Afterward; cement was added to the mixer and dry-mixed with the aggregates for another 1 min. Finally, water was added the mix and mixing was continued for 3 minutes. The total mixing time was about 5 minutes.

For each mix, the amount of added water was adjusted to keep the workability of all mixes suitable for demolding paving blocks immediately after pressing. As shown in Table 3, water demand increases by using iron and steel slag as a partial/total replacement of natural aggregate, regardless of slag type or size. Moreover, water demand for mixes containing fine slag is more than that for mixes containing coarse slag at the same replacement percentage. Among slag types, the replacement of natural aggregate by EAS showed the lowest increase in water demand, whereas the replacement by BFS significantly increased water demand compared with the control mix made with natural aggregate. This increase in water demand is due to the angular shape with vesicular and porous nature of slag aggregates in addition to the fine grading of fine BOS aggregate compared with natural aggregate. Thus, the use of slag especially BFS as fine aggregate has an adverse effect on the water demand of the mixes. Similar finding were reported by Sadek (2014) that the use of BFS as fine aggregate substantially increases the amount of water required for the production of solid cement bricks compared with natural sand [26].

Hexagonal-shaped metallic molds with approximately 34000-mm^2 area and 80 mm thickness were used for the production of paving blocks. From each mix, twenty-four specimens were cast for the determination of the physico-mechanical properties of the blocks. Fresh concrete was filled in the press molds, vibrated and compacted under pressure of 20 MPa [27]. The blocks were left covered with plastic sheet for one day to prevent the evaporation of water. After that, the blocks were cured by sprinkling water twice per day for 27 days. Fig. 2 shows the blocks just after pressing. In this paper, paving blocks with natural aggregate were referred as the control blocks.

The properties of paving blocks (i.e., unit weight, compressive strength, tensile splitting strength, water absorption, abrasion resistance, and slip/skid resistance) were determined at the age of 28 days. The number of specimens required for each test was determined according to the used standard specifications as follows: 5 specimens for compression test, 8 specimens for tensile splitting test, 3 specimens for unit weight and water absorption tests, 3 specimens for abrasion test, and 5 specimens for slip/skid resistance test. Unit weight test was carried out by drying the specimens in an oven at 110 °C for 24 h to obtain constant mass, then weighting the specimens after cooling. Unit weight was calculated by dividing the dry mass of each specimen by its overall volume. Compression test was carried out according to ASTM C140/C140M-15 using 2000 kN universal testing machine. The load was applied normal to the bed area of the block. Compressive strength was calculated by dividing the failure load by the loading area of the specimen. Tension splitting test was conducted in accordance with BS EN 1338-2003 annex F by immersing the specimens in water at 20 ºC for 24 h, then placing the tested block in the testing machine and applying the load along the longest splitting section of the block. Failure load was recorded and tensile splitting strength was the average of eight specimens. Abrasion resistance was determined according to BS EN 1338-2003 annex G. The upper face of the tested block was abraded using corundum with a grit size of F80. After 75 revolutions of the abrasion wheel, the groove generated on the tested surface was measured. A smaller groove indicates a higher abrasion resistance. Slip/skid resistance test was conducted in accordance with BS EN 1338-2003 annex I to evaluate the frictional properties of the upper surface of paving blocks. Immediately before testing, the specimens were submerged in water at 20 °C for 30 min. After locating the specimen and wetting its surface with water, the pendulum was released and pendulum test value was recorded. This operation was performed five times for each specimen. The specimen was then relocated after rotating through 180 ° and the above procedure was repeated. Unpolished slip resistance value (USRV), which is the mean of pendulum test value obtained on the five specimens, represents the slip/skid resistance of paving blocks. The higher USRV indicates higher slip/skid resistance. Water absorption test was carried out in accordance to ASTM C140/C140M-15. The specimens were submerged in water at a temperature of about 22 °C for 24 h and their saturated mass was recorded. Afterward, the specimens were dried in an oven at 110 °C for 24 h and reweighed to get their dry mass. Water absorption was expressed as a ratio of the mass of absorbed water of the immersed specimen to the oven-dried mass of the specimen.

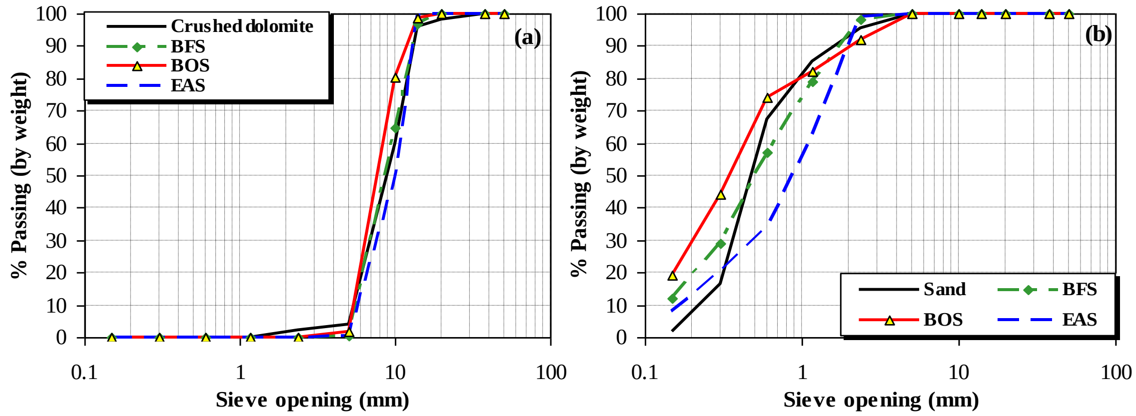

Figure 1. Sieve analysis of aggregates, (a) Coarse aggregate and (b) Fine aggregate

TABLE III. PROPORTIONS OF MIXES (KG/M3)

Mix No.	Identification of the mix	Cement	Coarse aggregate				Fine aggregate				Water
			Crushed dolomite	*BFS*	*BOS*	*EAS*	*Sand*	*BFS*	*BOS*	*EAS*	
1	Control	600	636	—	—	—	1064	—	—	—	145
2	BFS-(50%CA)	600	318	326	—	—	1064	—	—	—	167
3	BFS-(100%CA)	600	—	653	—	—	1064	—	—	—	189
4	BFS-(50%FA)	600	636	—	—	—	532	591	—	—	182
5	BFS-(100%FA)	600	636	—	—	—	—	1183	—	—	222
6	BFS-(50%CA&FA)	600	318	326	—	—	532	591	—	—	201
7	BOS-(50%CA)	600	318	—	343	—	1064	—	—	—	159
8	BOS-(100%CA)	600	—	—	687	—	1064	—	—	—	172
9	BOS-(50%FA)	600	636	—	—	—	532	—	657	—	180
10	BOS-(100%FA)	600	636	—	—	—	—	—	1314	—	219
11	BOS-(50%CA&FA)	600	318	—	343	—	532	—	657	—	194
12	EAS-(50%CA)	600	318	—	—	401	1064	—	—	—	153
13	EAS-(100%CA)	600	—	—	—	802	1064	—	—	—	165
14	EAS-(50%FA)	600	636	—	—	—	532	—	—	740	167
15	EAS-(100%FA)	600	636	—	—	—	—	—	—	1479	194
16	EAS-(50%CA&FA)	600	318	—	—	401	532	—	—	740	179

III. RESULTS AND DISCUSSION

A. *Unit weight*

Fig. 2 shows the effect of using different types of iron and steel slag as a substitution of natural coarse or fine aggregate on the unit weight of paving blocks. As expected, using of slag as alternative aggregate increased the unit weight of paving blocks, regardless of slag type or size. The unit weight of paving blocks containing coarse or fine iron and steel slag varied from 2.32 to 2.61 t/m^3, increasing with the proportion of slag aggregate, whereas the unit weight of the control paving blocks was 2.31 t/m^3. This increase in unit weight is due to the higher specific gravity of iron and steel slag compared with natural aggregates as illustrated previously in section 2. The use EAS showed the highest increase in the unit weight followed by BOS and finally BFS, regardless of slag size. However, the use of coarse BFS did not cause substantial increase in the unit weight of the manufactured blocks even at high replacement levels. At 50% replacement parentage of crushed dolomite with coarse BFS, the unit weight was similar to that of the control blocks, whereas at 100% replacement, an increase of only 1.7% occurred. This is due to the significant higher porosity and lower specific gravity of coarse BFS compared to other slag types. Etxeberria et al (2010) found that the unit weight of concrete containing coarse BFS to be in the range of 2.28-2.37 t/m^3, whereas it was 2.49-2.73 t/m^3 for concrete containing coarse EAS aggregate [28].

By comparing Fig. 2a with Fig. 2b, it can be found that the unit weight of paving blocks containing either coarse BFS or coarse BOS is lower than that for those containing the same percentages of fine slag, whereas in case of EAS, the opposite occurred. Whereas the unit weight of paving blocks containing coarse BFS varied from 2.32 to 2.35 t/m^3, it varied from 2.36 to 2.39 t/m^3 for paving blocks containing the same percentages of fine BFS. Also, whereas the unit weight of paving blocks containing coarse BOS varied from 2.37 to 2.41 t/m^3, it varied from 2.39 to 2.46 t/m^3 for paving blocks containing the same percentages of fine BOS. On the other hand, whereas the unit weight of paving blocks containing coarse EAS varied from 2.50 to 2.61 t/m^3, it varied from 2.49 to 2.55 t/m^3 for paving blocks containing the same percentages of fine EAS. This is may be attributed to the following reasons:

- In case of BFS and BOS, higher specific gravity of fine slag compared with coarse slag is the main reason for the difference in the unit weight of paving blocks. In addition, fine BOS has finer grading compared with other fine aggregates as shown in Fig. 1b. The fine fractions in BOS fills capillary pores and interfacial transition zone leading to densification of the microstructure of paving blocks and consequently increased unit weight.

- In case of EAS, although the specific gravity of fine EAS is higher than that of coarse EAS aggregate, coarser grading of fine EAS aggregate compared with natural sand as shown in Fig. 2b increases the porosity of paving blocks and consequently lightens the weight of paving blocks. Papayianni and Anastasiou (2010) recommended the use of finer sand in order to improve overall aggregate gradation when EAS slag aggregate is used as fine aggregate in concrete [29].

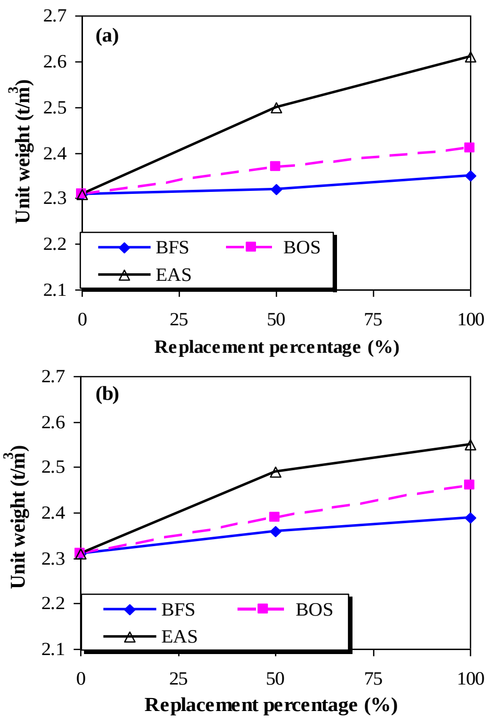

Figure 2. Unit weight of paving blocks containing, (a) Coarse slag and (b) Fine slag

Fig. 3 shows the effect of using iron and steel slag to replace 50% of crushed dolomite and 50% of sand simultaneously on the unit weight of paving blocks. Again, the unit weight of paving blocks containing both coarse and fine iron and steel slag is higher than that of the control blocks made with natural aggregates, regardless of slag type. BFS showed marginal increase in the unit weight, whereas EAS increased the unit weight considerably (i.e., 2.6% increase in the unit weight for BFS compared with 14.7% increase for EAS).

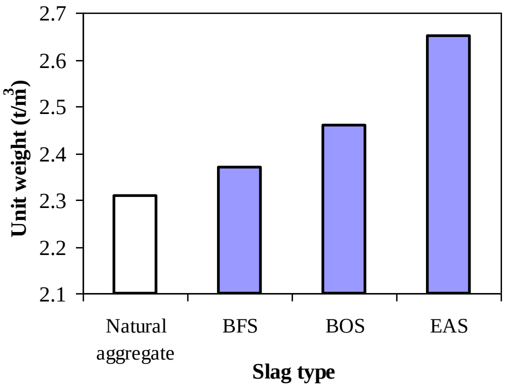

Figure 3. Unit weight of paving blocks containing coarse and fine slag simultaneously

B. *Compressive and tensile splitting strengths*

The compressive and tensile splitting strengths of paving blocks as a function of the substitution percentage of natural aggregates are shown in Figs. 4 and 5, respectively. It is clear that the strengths of paving blocks are strongly influenced by the type of coarse and fine aggregates. A systematic increase in the compressive and splitting tensile strengths can be observed by increasing the substitution percentage of natural aggregates by iron and steel slag, except coarse BFS which decreases the strengths of paving blocks. Among the used slag types, the use of EAS as a substitution of natural aggregates in paving blocks significantly increases its compressive and tensile splitting strengths, whereas paving blocks containing BFS aggregate have the lowest strength values, regardless of slag size. With regard to the control blocks made with natural aggregates, using of 50% and 100% coarse BFS decreased the compressive strength of paving blocks by 8.1% and 24.9%, respectively, whereas the use of the same percentages of fine BFS increased the compressive strength of paving blocks by 4.4% and 9.4%, respectively. On the other hand, using of 50% and 100% coarse BOS increased the compressive strength of paving blocks by 14.0% and 22.7%, respectively, and the use of the same percentages of fine BOS increased the compressive strength of paving blocks by 12.7% and 20.5%, respectively. Moreover, using of 50% and 100% coarse EAS increased the compressive strength of paving blocks by 30.4% and 56.3%, respectively, and the use of the same percentages of fine EAS increased the compressive strength of paving blocks by 25.9% and 51.1%, respectively. Similar trend could be observed for splitting tensile strength. Hence, using BFS to substitute coarse aggregate worsens the mechanical properties of paving blocks in terms of compressive and tensile splitting strengths on contrary to the case of being used as an alternative aggregate to natural sand, whereas the use of either BOS or EAS as coarse or fine aggregate enhances the mechanical properties of paving blocks. This is may be ascribed to the following reasons:

- In case of using iron and steel slag as coarse aggregate, the high roughness and angularity of slag particles increases the bond between cement paste and slag surface leading to the increased strength [16], [30]. However, the considerable vesicular and porous nature of coarse BFS decreases its hardness leading to inferior strengths. This trend is evidenced by the impact index of the used coarse aggregates (Table 2). Coarse BFS aggregate has the highest impact index on contrary to coarse EAS aggregate that has the lowest value which infers its high hardness. Etxeberria et al (2010) found that the compressive strength of concrete containing 25-100% BFS as a replacement of coarse aggregate to be in the range of 41-47.8 MPa, whereas the replacement of coarse aggregate by EAS resulted in concrete with compressive strength in the range of 47.1-54.1 MPa, indicating its higher hardness [28].

- In case of using iron and steel slag as fine aggregate, also the high angularity of slag particles is the main reason for increasing the strengths of paving blocks [14], [26] in addition to the densification of microstructure in case of using fine BOS as illustrated previously in section 4.1. Sadek (2014) reported 29-53% increase in the compressive strength of solid cement bricks by replacing 50-100% of sand by fine BFS [26]. Qasrawi et al (2009) found that using unprocessed steel slag as fine aggregate improved the compressive strength of concrete by 1.1–1.3 times the strength of control concrete depending on the replacement percentage and the grade of concrete [14].

By comparing Figs. (4a with 4b) and (5a with 5b), it can be found that the compressive and tensile splitting strengths of paving blocks containing coarse BFS is lower than that for those containing the same percentages of fine BFS. This is due to the considerable vesicular and porous nature of coarse BFS, whereas in case of fine BFS most of this vesicular nature is eliminated by crushing BFS to obtain fine aggregate. On the other hand, the compressive and tensile splitting strengths of paving blocks containing coarse EAS is higher than that for those containing fine EAS at the same replacement percentage. This may be to the coarse grading of fine EAS which increases the porosity of paving blocks, thus decreasing the strength in case of using fine EAS. For paving blocks containing BOS, there is no significant difference was found between the strengths of the blocks containing coarse EAS and fine BOS.

Fig. 6 shows the effect of using iron and steel slag to replace 50% of crushed dolomite and 50% of sand simultaneously on the compressive and tensile splitting strengths of paving blocks. It is clear from the figure that whereas the strengths of paving blocks containing both coarse and fine iron slag are comparable to that of the control blocks, using of steel slag as fine and coarse aggregates simultaneously significantly increases the strength values of paving blocks, indicating the adverse effect of coarse BFS on the mechanical properties of paving blocks.

According to ASTM C936/C936M-15, paving blocks should have at least 55 MPa compressive strength, whereas in the Indian Standard IS 15658:2006, paving blocks are divided into five classes based on traffic category (i.e., non-traffic, light traffic, medium traffic, heavy traffic, and very-heavy traffic). The average 28-days compressive strength of paving blocks should not be less than 30 MPa, 35 MPa, 40 MPa, 50 MPa, and 55 MPa for non-traffic, light traffic, medium traffic, heavy traffic, and very-heavy traffic applications, respectively. Accordingly, all the manufactured paving blocks (except blocks containing 100% coarse BFS) could be used in very heavy traffic applications as their compressive strength is higher than 55 MPa according to ASTM C936/C936M-15 and IS 15658:2006. Paving blocks containing 100% coarse BFS satisfied the requirements prescribed by IS 15658:2006 for medium traffic applications. On the other hand, BS EN 1338-2003 requires a minimum tensile splitting strength of not less than 3.6 MPa. It is clear that all mixes, even those containing coarse BFS aggregate satisfy the tensile splitting strength requirement of 3.6 MPa imposed by BS EN 1338-2003.

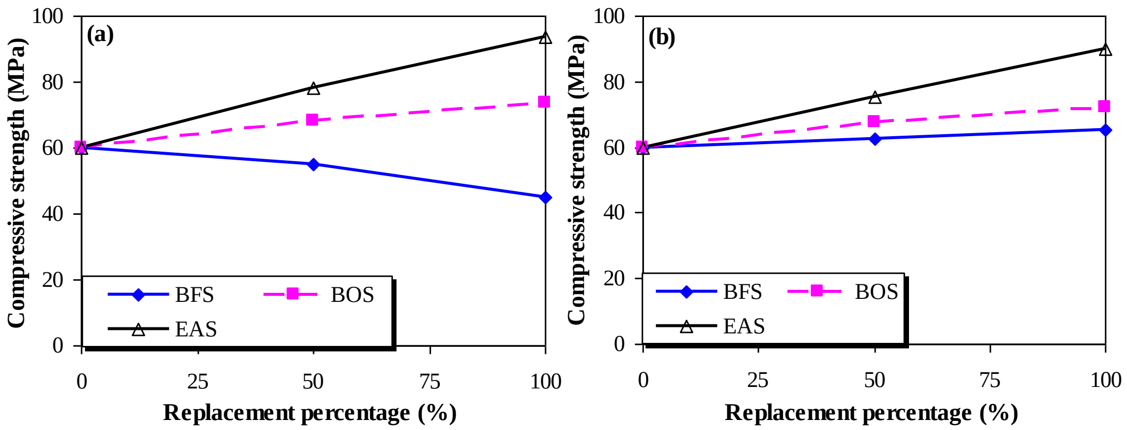

Figure 4. Compressive strength of paving blocks containing, (a) Coarse slag and (b) Fine slag

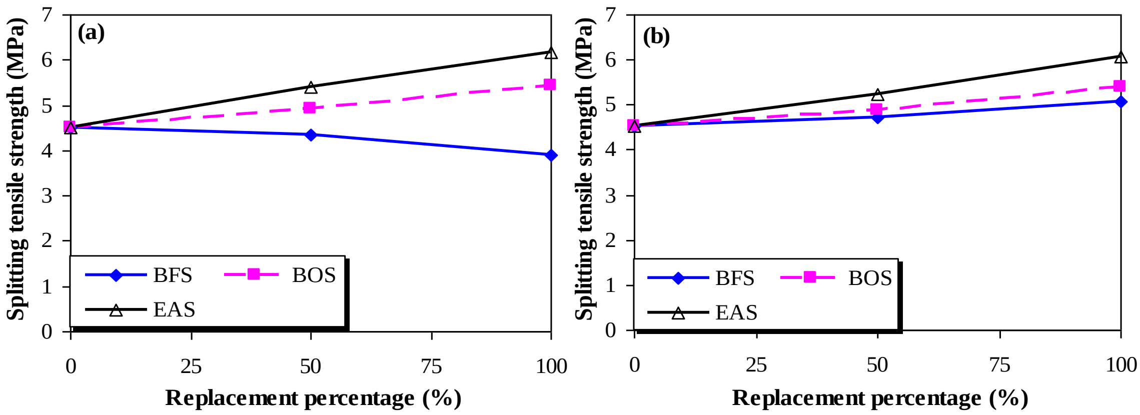

Figure 5. Tensile splitting strength of paving blocks containing, (a) Coarse slag and (b) Fine slag

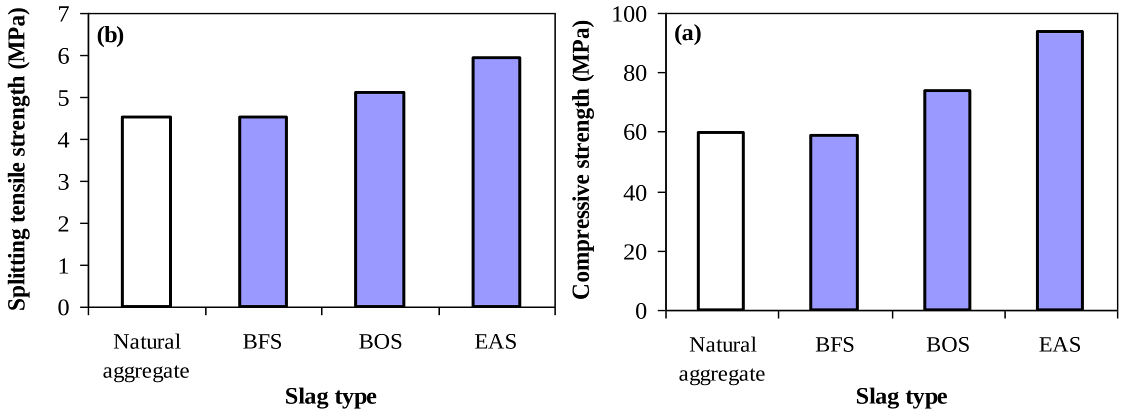

Figure 6. Strengths of paving blocks containing coarse and fine slag simultaneously, (a) Compressive strength and (b) Tensile splitting strength

C. Abrasion resistance

It is well known that the abrasive wear occurs on all surfaces subjected to abrasive forces between the surface and moving objects during service such as pavements, floors, and concrete highways. The abrasion process occurs due to the penetration of abrasive particles in the specimen surface with the effect of normal load followed by the formation of grooves and scratches on the surface with shear force [31]. For concrete, its abrasion resistance has been defined in terms of its ability to resist being worn away by rubbing and friction [32]. Thus, abrasion resistance of paving blocks is very important for their service life.

Fig. 7 shows the relationship between groove length due to abrasion and replacement percentage of coarse or fine aggregate with iron and steel slag. As mentioned previously that groove length due to abrasion was measured and smaller groove length indicates higher abrasion resistance. It is clear from the figure that the values of groove length decrease almost linearly by using iron and steel slag as alternative aggregates, except coarse BFS which causes a considerable increase in the groove length especially at higher replacement percentages, indicating the low abrasion resistance of coarse BFS particles and consequently its detrimental effect on the abrasion resistance of paving blocks. Among the investigated slag types, it can be found that at the same replacement percentage of natural aggregates, paving blocks containing EAS aggregate had the lowest groove length on contrary to paving blocks containing BFS aggregate, regardless of slag size. This inferior behavior of BFS is due to its vesicular and porous nature leading to the formation of friable and weak surface that couldn't withstand the abrasion. This result is consistent with the results of abrasion test (Table 2) carried out on the used coarse aggregates. Coarse BFS had the highest Los Angeles coefficient, whereas coarse EAS and BOS aggregates had lower values for Los Angeles coefficient than crushed dolomite, indicating high abrasion resistance of EAS and BOS particles compared with BFS.

On the other hand, the groove length in case of paving blocks containing coarse BFS is higher than that for those containing the same percentages of fine BFS indicating the effectiveness of using BFS as fine aggregate than being used as coarse aggregate for withstanding the abrasion, whereas the opposite is true in case of using BOS or EAS as alternative aggregates. It is well known that abrasion resistance of cement-based materials depends on compressive strength, aggregate content and especially the volume of coarse aggregates, aggregate resistance to fragmentation, concrete surface finishing and early age curing of concrete [29]. Thus, the ability of paving blocks to withstand abrasion is improved by increasing the compressive strength and this is the case in this research as the use of coarse steel slag (i.e., BOS and EAS) is more effective in enhancing the compressive strength of paving blocks than the use of their fine fractions and consequently the abrasion resistance is also enhanced by using coarse steel slag than fine steel slag. Papayianni and Anastasiou (2010) found 73.9% improvement in the abrasion resistance of concrete by replacing crushed limestone with EAS and only 77.4% improvement by replacing both coarse and fine aggregate. Thus, the authors found that coarse EAS contributes greatly to the increased abrasion resistance [29].

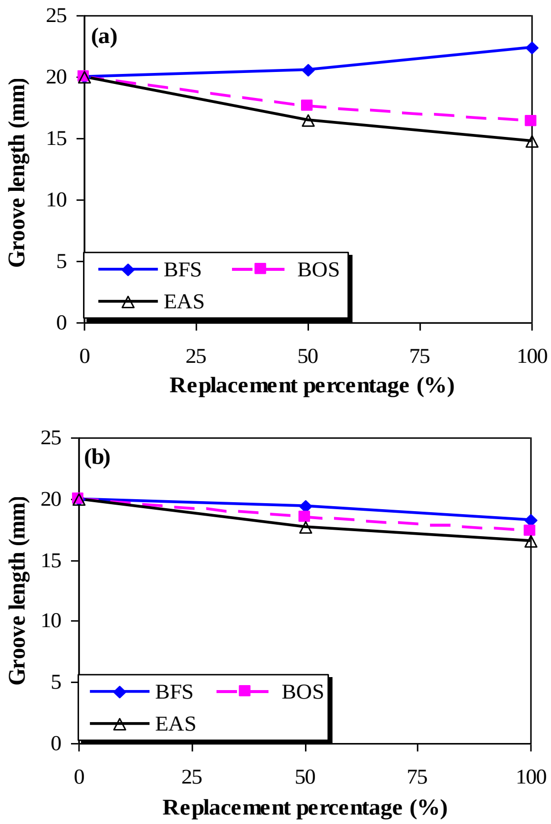

Figure 7. Groove length of paving blocks containing, (a) Coarse slag and (b) Fine slag

Fig. 8 shows the effect of using iron and steel slag to replace 50% of crushed dolomite and sand simultaneously on the abrasion resistance of paving blocks. It is clear that the abrasion resistance of paving blocks is enhanced by using iron and steel slag to replace 50% of coarse and fine aggregate simultaneously. The groove length decreased by 1.1%, 19.5% and 28.0% by using BFS, BOS and EAS aggregates, respectively compared with the control blocks made with natural aggregates. This is due to the existence of high abrasion-resistant material near the surface of paving blocks which takes longer time to abrade than natural aggregates. It should be noted that the groove length of paving blocks containing BOS or EAS replacing 50% of coarse and fine aggregate simultaneously is lower than those containing up to 100% of BOS or EAS replacing coarse or fine aggregate individually, indicating the beneficial effect of using steel slag to replace 50% coarse and fine simultaneously.

According to BS EN 1338-2003, paving blocks are categorized into three classes based on the groove length. In areas subjected to very heavy pedestrian and vehicular traffic, Class 4 paving blocks with groove length ≤ 20mm should be used. In areas subjected to normal pedestrian and vehicle use (e.g., public pavements and roads), at least Class 3 paving blocks with groove length ≤ 23mm should be used. In areas subjected to light pedestrian and vehicular use (e.g., garden, drives), at least Class 1 paving blocks with no performance measured should be used. Accordingly, all paving blocks (except those containing coarse BFS) could be used in areas subjected to very heavy pedestrian and vehicular traffic as it met the requirements of Class 4 with groove length ≤ 20mm. On the other hand, paving blocks containing coarse BFS as a partial/total replacement of coarse aggregate could be used in areas subjected to normal pedestrian and vehicle use such as public pavements and roads as their groove lengths were in the range of 20-23 mm, which satisfy the condition for Class 3.

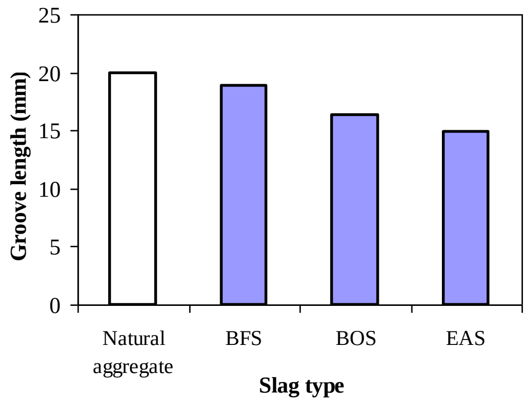

Figure 8. Groove length of paving blocks containing coarse and fine slag simultaneously

D. Slip/skid resistance

Fig. 9 shows the effect of using different slag types on the slip/skid resistance of paving blocks. It is clear that the slip/skid resistance of paving blocks depends on the type and size of aggregate. Using of coarse BFS decreases the slip/skid resistance of paving blocks, whereas the use of fine BFS slightly increases the slip/skid resistance. The opposite occurred in case of using BOS as alternative aggregate to natural aggregates. Compared with the control paving blocks made with natural aggregates, the reduction in the slip/skid resistance by replacing 100% of coarse aggregate by coarse BFS was found to be 9.7%, whereas the increase in the slip/skid resistance by using 100% fine BFS was 3.2%. The increase in the slip/skid resistance by using 100% coarse BOS was 10.5%, whereas the reduction in the slip/skid resistance by using 100% fine BOS was 11.3%. On the other hand, the slip/skid resistance of paving blocks increases systematically by using EAS, regardless of its size. Moreover, paving blocks made with fine EAS performed better than blocks containing coarse EAS. The full replacement of crushed dolomite with coarse EAS increased the slip/skid resistance by 12.9%, whereas the full replacement of sand with fine EAS increased the slip/skid resistance by 21%.

By comparing the effect of using coarse iron and steel slag on the slip/skid resistance of paving blocks (Fig. 9a), it can be found that EAS and BOS blocks showed the highest values of slip/skid resistance followed by BFS blocks. The increase in slip/skid resistance by using slag is generally due to the angular and roughly texture of slag compared with crushed dolomite. However, the vesicular and porous nature of coarse BFS hindered this effect. On the other hand, by comparing the effect of using fine iron and steel slag on the slip/skid resistance of paving blocks (Fig. 9b), it can be found that EAS blocks showed the highest values of slip/skid resistance followed by BFS blocks and finally BOS blocks. This may be due to the coarse grading of EAS compared to other fine aggregates as shown in Fig. 1b, leading to the formation of rough surface of the block thus increasing the friction when the pendulum passing over it. The opposite occurred by using fine BOS because of its finer grading compared to other fine aggregates Fig. 1b.

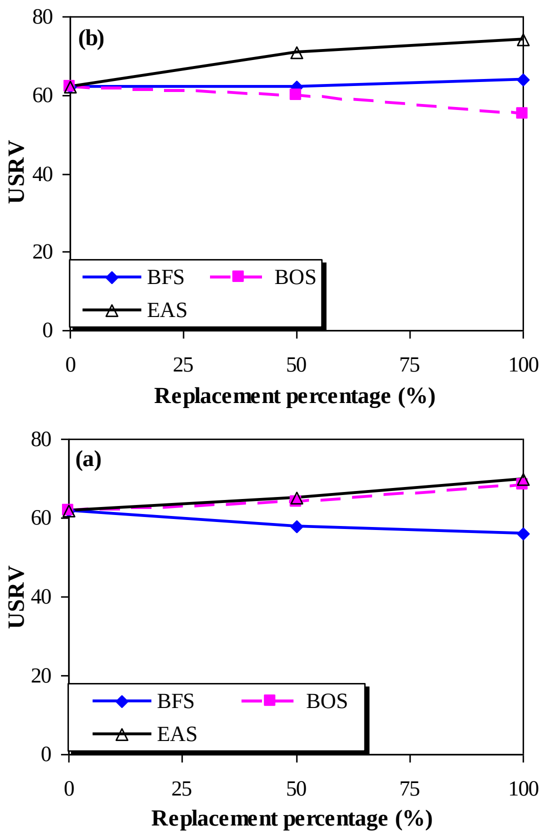

Figure 9. Slip/skid resistance of paving blocks containing, (a) Coarse slag and (b) Fine slag

Fig. 10 shows the effect of using iron and steel slag to replace 50% of crushed dolomite and sand simultaneously on the slip/skid of paving blocks. It is clear from the figure that whereas the slip/skid resistance of paving blocks containing either BFS or BOS replacing 50% of coarse and fine aggregates simultaneously is comparable to that of the control blocks, using of EAS to replace 50% of fine and coarse aggregates simultaneously significantly increases the slip/skid resistance of paving blocks, indicating the beneficial effect of using iron and steel slag, especially EAS to replace coarse and fine aggregate simultaneously for enhancing the slip/skid resistance of paving blocks.

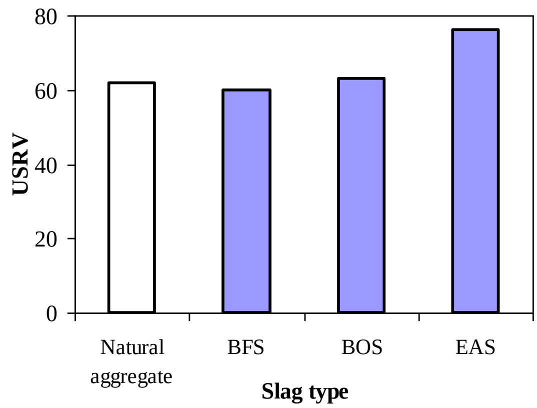

Figure 10. Slip/skid resistance of paving blocks containing coarse and fine slag simultaneously

BS EN 1338-2003 classifies paving blocks into four categories based on their potential for slip. If USRV is below 19 the potential for slip is high, whereas if it is between 20 and 39 the potential for slip is moderate, and if it is between 40 and 74 the potential for slip is low, and finally the potential for slip is extremely low when USRV is above 75. Accordingly, the potential of slip for all the manufactured blocks (except those containing EAS replacing 50% of coarse and fine aggregate simultaneously) is low as their USRV ranged from 55 to 74. The potential of slip for paving blocks containing EAS replacing 50% of coarse and fine aggregate simultaneously is extremely low as its USRV is more than 75.

E. Water absorption

The weathering resistance of concrete paving blocks is believed to be related to the water absorption. The main agents of deterioration require the presence and movement of water within the material itself. The presence of water can cause freeze-thaw damage to the product. Furthermore, water can carry chlorides and sulfates as well as other harmful ions [33]. Hence, the absorption of paving blocks has a great effect on its durability. Fig. 11 demonstrates the water absorption of paving blocks as a function of replacement percentage of natural aggregates by iron and steel slag. It is clear from the figure that water absorption highly depends on type and size of slag. In case of using slag as coarse aggregate, water absorption was found to increase systematically by increasing slag content. Coarse BFS significantly increases the water absorption of paving blocks followed by coarse BOS, and finally coarse EAS. The increase in water absorption by replacing 100% of coarse aggregate by coarse BFS, BOS, and EAS was 120.4%, 41.2%, and 22.6%, respectively. On the other hand, in case of using slag as fine aggregate, water absorption increases systematically by increasing the content of BFS and EAS, whereas it decreases by using BOS. The increase in water absorption by replacing 100% of fine aggregate by fine BFS and EAS was 88.2% and 33.9%, respectively, whereas the reduction in water absorption by using 100% of BOS as fine aggregate was 29.1%. It is clear from the above values that fine BFS and BOS aggregates have better effect on the water absorption than coarse BFS and BOS aggregates, whereas the opposite occurred in case of EAS aggregate. The increase in water absorption of paving blocks is mainly due to the higher water absorption capacity of the used slag compared with natural aggregates (Table 2). However, in case of using BOS as fine aggregate, it's very fine fractions fills capillary pores and interfacial transition zone leading to densification of the pore structure and microstructure of paving blocks leading to decreased porosity and consequently decreased water absorption.

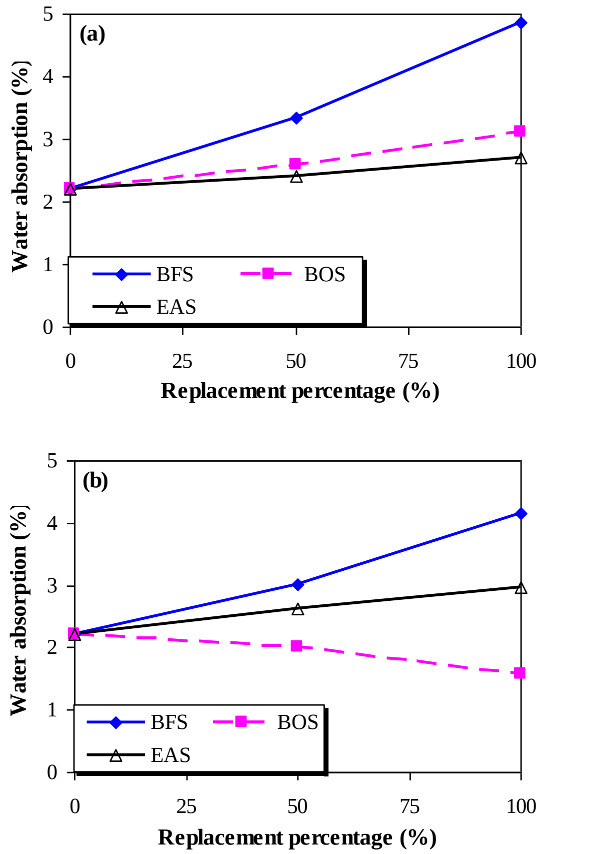

Figure 11. Water absorption of paving blocks containing, (a) Coarse slag and (b) Fine slag

Fig. 12 shows the effect of using iron and steel slag replacing 50% of crushed dolomite and sand simultaneously on the water absorption of paving blocks. It is clear from the figure that the water absorption of paving blocks containing BFS is significantly higher that of the control blocks, whereas using of either BOS or EAS to replace 50% of coarse and fine aggregate simultaneously decreases the water absorption of paving blocks. With regard to the control blocks made with natural aggregates, it can be found that water absorption is almost doubled by using BFS, whereas it decreased by 22.6% and 21.3% by using BOS and EAS aggregates, respectively.

BS EN 1338-2003 and IS 15658:2006 require paving blocks to have less than 6% water absorption, whereas the maximum limit of water absorption in ASTM C936/C936M-15 is 5%. It is clear that all mixes satisfied the maximum limit for water absorption, regardless of type, size or content of slag aggregates.

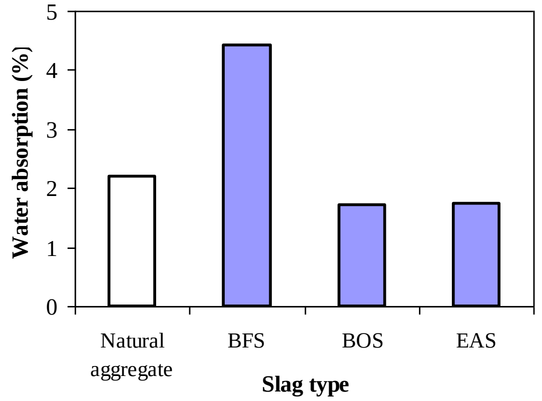

Figure 12. Water absorption of paving blocks containing coarse and fine slag simultaneously

It is clear from the above discussion that the overall performance of the manufactured blocks is satisfactory and satisfies the requirements of standard specifications. As illustrated previously that the characteristics of paving blocks depend on the used aggregates. Using of iron and steel slag has the following effects on the manufactured blocks:

- All the manufactured paving blocks (except those containing 50% or 100% coarse BFS aggregates) met the requirements of specifications for being used in heavy-duty applications.

- The applications of paving blocks containing even 50% coarse BFS should be limited to medium-traffic applications such as public pavements and roads as these blocks are not allowed to be used in heavy-duty applications.

- Paving blocks containing EAS replacing 50% coarse and fine aggregates simultaneously showed the best performance among all the manufactured blocks. However, its heavy weight should be taken into account during the design stage.

IV. ENVIRONMNENTAL AND ECONOMIC CONSIDERATIONS

It should be mentioned that the recycling of iron and steel slag in the production of paving blocks is beneficial from different points of view. It helps in the conservation of natural aggregates from one side and from another side it helps in the recycling of significant amounts of slag in an environmental-friendly manner rather than being disposed-off, consequently solving the environmental problems arising from the disposal of these slags. Moreover, such recycling of slag also gives an economic approach to the construction industry. The cost of paving blocks is divided into the cost of raw materials (i.e., cement, natural aggregates and water), transportation cost of raw materials and manufacturing cost of paving blocks. Iron and steel slags are by-products generated during the manufacturing of iron and steel products. Thus, the cost of paving blocks will be reduced by using iron and steel slag as alternative aggregates to natural aggregates. The recycling of slag will not bring additional cost to producers as it is available for free. Thus, the environmental and technical benefits resulted from the recycling of iron and steel slag associated with the satisfactory performance of the produced paving blocks could change the vision to slag from being an industrial waste to be modern industrial product that could be used as secondary aggregate

V. CONCLUSION

It is feasible to recycle weathered iron and steel slag as alternative aggregates in the production of low-cost and environmental-friendly paving blocks satisfying the requirements of standard specifications. The characteristics of paving blocks depend on the type, size and percentage of slag in the mix. At the same size and percentage of slag, EAS aggregate has the best effect on the characteristics of paving blocks followed by BOS and finally BFS aggregate. Paving blocks containing EAS replacing 50% coarse and fine aggregates simultaneously showed the best performance among all the manufactured blocks. Using of BFS as a replacement of coarse aggregate worsens the quality of the blocks in terms of compressive strength, tensile splitting strength, abrasion resistance, slip/skid resistance and water absorption, whereas its use as fine aggregate enhances the overall characteristics of paving blocks except water absorption. However, paving blocks containing BFS replacing 50% of coarse and fine aggregates simultaneously has comparable characteristics to the control paving blocks as fine BFS hinders the negative effects of coarse BFS. Thus, it is recommended to use a blend of coarse and fine BFS than using coarse BFS alone in the production of paving blocks. On the other hand, using of BOS either as coarse or fine aggregate enhances the characteristics of paving blocks compared with the effect of natural aggregates, except water absorption in case of being used as coarse aggregate and slip/skid resistance in case of being used as fine aggregate. Using of EAS either as coarse or fine aggregate enhances the characteristics of paving blocks compared with the effect of natural aggregates. However, its heavy weight should be taken into account during the design stage. Moreover, at the same replacement percentage of natural aggregates, using of EAS as coarse aggregate is better than being used as fine aggregate for enhancing the compressive strength, tensile splitting strength, abrasion resistance and water absorption of paving blocks.

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