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Research/Technical Note

The Impact of Incorporating Slag Aggregates on the Abrasion Behavior of Concrete Paver Blocks

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Abstract: Recently, the interlocking concrete block pavement has been extensively used in many countries as an alternative to concrete and asphalt pavements. It has become a good choice for paving of parking areas, pedestrian walks, traffic intersections, and roads. The abrasion resistance of concrete pavement is defined by its ability to resist being worn away by friction and rubbing. The compressive strength and the aggregate type are two important factors that affect the abrasive behavior of concrete. In this study, the natural coarse aggregate was replaced by Electrical Arc Furnace Slag (EAFS) in order to improve mechanical properties of concrete pavement blocks. The effect of different mixing ratios of EAFS on abrasion resistance, compressive strength, and water absorption is evaluated. Abrasion and other requirements for interlocking concrete pavers are evaluated according to ASTM standards. Results suggested that EAFS is a good alternative to the normal available aggregates.

Keywords: Slag Aggregate, Paver Block, Abrasion Resistance

1. Introduction

Concrete pavement was firstly introduced in the fifties as replacement for the paver bricks. The shape of the block has steadily developed from non-interlocking to partially interlocking to fully interlocking to multiply interlocking shapes. It has become a perfect solution for almost any application because of their high quality, and lower life cycle cost in contrast to asphalt or concrete.

Most concrete is composed mainly of Portland cement, coarse and fine aggregate and water. This concrete is molded in, specialized manufacturing equipment under pressure or vibration. Thus, concrete paver is regarded as a particulate composite material because it is composed of a number of materials that combine to form this versatile material.

Deterioration of paver surfaces occurs due to various forms of wear, such as erosion, cavitation and simple abrasion due to various exposures [1]. The definition of wear in terms of the weight of debris formed is not applicable in situations when there is deformation but little or no debris; therefore, a definition of wear in terms of the results of sliding wear tests has been proposed [2]. Specifically for concrete, its abrasion resistance has been defined in terms of its ability to resist being worn away by rubbing and friction [3].

Abrasion resistance of concrete pavements is a surface property that is mainly dependent on the quality of the surface layer characteristics. Abrasion of concrete is primarily dependent upon its compressive strength, cement content, water-cement ratio (w/c), cement type, aggregate type and many other factors [4]. For concrete with high abrasion resistance, it is desirable to use a hard surface material, aggregate and cement with low porosity and high strength [5]. Hardness of coarse aggregate is important here. It was reported that the service life of concrete blocks can be extended by using harder aggregate types for most modes of wear [6].

Waste management has become one of the most complex and challenging problem affecting the environment of the world. It is demonstrated that concrete which contains at least 20% of waste products as aggregates is called ‘‘Green Concrete’’ [7]. From this viewpoint, several research studies have been conducted to study the viability of replacing limestone aggregate with alternative coarse aggregate on the production of concrete pavement blocks. As for the replacement of traditional coarse aggregates by ceramic coarse aggregates, the results were promising but underperformed slightly in water absorption, and water permeability [8]. A pioneer work was conducted by [9], in which different slag types are proposed to replace coarse aggregates in producing cement masonry bricks and paving interlock units. Three different slag replacement levels were investigated, namely: 33%, 67%, and 100%. It was demonstrated that all paving interlock groups have higher compressive strength than the reference group. Both Basic Oxygen Furnace Slag (BOFS) and Electrical Arc Furnace Slag (EAFS) groups resulted in compressive strength higher than the specified ASTM value of 55.2 MPa while blast furnace slag groups reached 82% of this limit. All slag types resulted in higher abrasion resistance values than dolomite used for the control group. Nevertheless, at high replacement levels, BOFS and EAFS groups showed abrasion resistance values comparable to those of the typical commercial units. The performance of replacing aggregate (coarse and fine) with slag on various concrete properties was also evaluated [10]. Concrete of M20, M30 and M40 grades were considered for a w/c ratio of 0.55, 0.45 and 0.40 respectively for the replacements of 0, 30, 50, 70 and 100% of aggregates (Coarse and Fine) by slag. It was shown that that compressive strength of concrete improved by 4 to7% at all the replacement levels of normal crushed coarse aggregate with crystallized slag. Furthermore, the replacement of 100% slag aggregate (coarse) increased concrete density by about 5 to 7% compared to control mix. The improvement in density was due to the higher unit weight of slag aggregate which is 9% heavier than natural aggregate.

The present study aims at evaluating the impact of replacing coarse aggregate by steel slag in the production of interlock blocks. The influence of surface irregularity on the abrasion requirement for interlocking concrete pavers will be discussed in the light of the current ASTM C936 [11]. Samples were tested for abrasion resistance, compressive strength, bulk density, water absorption, and macrotexture depth. Tests were carried out at two different slag replacement levels; 50% and 100% and three different mixing ratios.

2. Materials and Methods

2.1. Cement

Ordinary Portland Cement is used in the manufacture of all concrete paving blocks in accordance to ESS 4756-1/2007 [12].

2.2. Sand

Clean natural desert sand free from impurities having a fineness modulus of 1.75 was used as fine aggregate.

2.3. Aggregates

Natural coarse aggregate used in this study was crushed limestone of 12 mm nominal maximum size. On the other hand, Electrical Arc Furnace Slag (EAFS) was adopted as a replacement for natural aggregates. The slag was supplied from Hadid Co. for Industry, Trading & Constructing CONTRASTEEL S.A.E with a maximum particle size of 12.50 mm. Chemical properties of slag used in the study are given in Table 1.

Table 1. *Chemical Analysis of EAF-Slag (%).*

(Fe)	(SiO_2)	(CaO)	(Al_2O_3)	(MgO)	(MnO)
22.78	21.99	37.90	7.90	7.53	2.24

2.4. Samples Preparation and Testing

Five groups of mixes were prepared to evaluate the impact of slag replacement level and Cement/Slag mix ratio. The first mix is the control mix, in which natural aggregates were used. The primary mix proportions of the interlock units were determined and adjusted based on the information available from local producers and previous literatures [9, 13]. In the second and third mixes, slag was used replacing 50% and 100% of natural aggregate, respectively. In the fourth and fifth mixes, 100% slag was used at two different mixes proportions. Fixing the w/c ratio at 0.4, Table 2 shows the mix proportions of the different mixes and the details of the paving interlock groups.

Table 2. *Mix Proportions of Paving Interlock Groups.*

group	Cement (kg)	Sand (kg)	Limestone (kg)	Slag (kg)	Rep.%	Mix ratio (Cement : F.A: C.A)
1	21.6	64.8	32.4	-	--	1 : 3 : 1.5
2	21.6	64.8	16.2	16.2	50	1 : 3 : 1.5
3	21.6	64.8	-	32.4	100	1 : 3 : 1.5
4	21.6	64.8	-	64.8	100	1 : 3 : 3
5	20	40	-	60	100	1 : 2 : 3

F. A fine aggregate, C. A coarse aggregate.

The water contents of the paving units were adjusted based on the aggregate ability [13]. The water to cement (w/c) ratio was adjusted for each mix to maintain an almost zero slump. Each of these groups contains eighteen M-40 hexagonal blocks having the dimensions of 20 x 23 x 8 cm, as shown in Fig. 1. All specimens were air-cured until testing rather than water cured in order to simulate the curing practice followed by the industry.

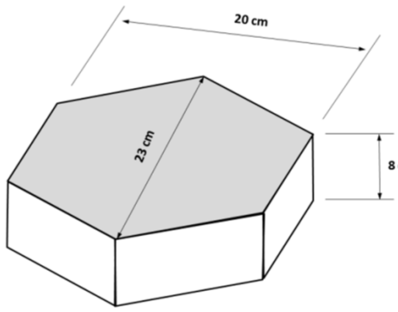

Figure 1. *Typical dimensions of paving interlock specimen.*

Specimens were tested for abrasion resistance according to ASTM C241-90. Compressive strength, water absorption and bulk density were also measured for all test groups, the number of blocks tested for each batch is given in Table 3. Specification covers the requirements for interlocking concrete pavers according to ASTM C 936 [11], IS-15658 [14] and ESS 4382 [15] are summarized in Table 4.

Table 3. *Samples tested as per ASME C936.*

Property	Testing method	Number of paver blocks for each test
Abrasion Resistance	ASTM C241	5
Compressive Strength	ASTM C140	5
Water Absorption	ASTM C936	5
Bulk Density	ASTM C 29/C 29M	1

Table 4. *Recommended requirements for interlocking concrete pavers.*

Test	ASME C 936	IS-15658:2006	ESS 4382—1/2004
Abrasion Resistance	The average thickness loss not exceed 3 mm	The average thickness loss not exceed 6 mm	The average thickness loss not exceed 3 mm
Compressive Strength	55 - 50 MPa	40 MPa	50 MPa Heavy duty 30 Mpa Medium duty 30 MPa Normal duty
Water Absorption	5 %	6 %	5% Heavy duty 6% Medium duty 8% Normal duty

3. Results and Discussion

3.1. Effect of Slag Replacement Level

All experimental results are presented in Tables 5 and 6. It is indicated that test groups (1, 2, and 3) have higher abrasion resistance than the control group. These groups showed much lower abrasion coefficient than the ASTM limit of 15 $cm^3/50cm^2$. Mixes 2 and 3 (containing 50% and 100% of slag aggregate) gave abrasion resistance that was higher by 11% and 58%, respectively, of that for the control mix.

Table 5. *Results of abrasion tests.*

Group	Original wt. (gm)	Final wt. (gm)	Weight loss (gm)	Thickness loss (mm)	Abrasion resistance, H_a	Abrasion coefficient ($cm^3/50cm^2$)
1	412	394	18	1.57	1.50	7.85
2	419	403	16	1.46	1.66	7.30
3	448	436	12	1.07	2.37	5.34
4	444	432	12	1.06	2.51	5.31
5	482	472	10	0.77	3.29	3.86

The average abrasion resistance was estimated based on ASTM C 241[16].

Table 6. *Average of compressive strength, water absorption and bulk density.*

Group	Compressive Strength* (MPa)	Water Absorption (%)	Bulk Density(gm/cm^3)
1	39.4	4.24	2.199
2	46.2	4.01	2.245
3	51.0	3.2	2.328
4	48.1	2.89	2.469
5	42.2	2.92	2.662

* 28 day

There is a direct proportionality between slag replacement level and abrasion behavior of paving units, as shown in Fig. 2. Increasing the slag replacement level resulted in increasing the abrasion resistance.

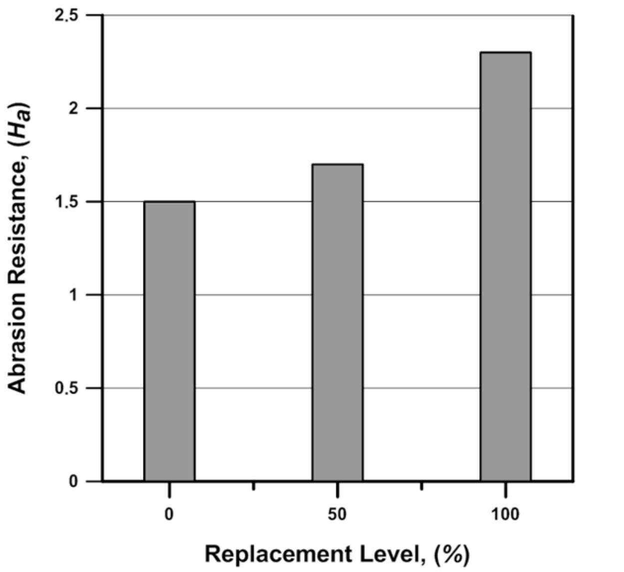

Figure 2. *Effect of slag replacement level on abrasion resistance (for Mix 1:3:1.5).*

This may be related to the hardness that slag imparts to concrete; hardness is believed to be the most important factor that controls the wear of the aggregate in concrete. The hard aggregate should protect the softer paste, provided that there is an adequate aggregate/paste bonding strong enough to hold the aggregate securely in the face of the ‘attacking’ abrasion load [2]. Investigation of the specimen abraded surfaces, Figure 3, indicated that the hard slag aggregates in the matrix prevent abrasive particles from penetrating more into concrete. While on the other hand, abrasion of limestone in the control mix was observed. This finding is agreed with the physical properties of slag aggregates, where the hardness of slag is about 50% compared to the hardness of limestone [17].

The results also indicated that slag replacement resulted in improving compressive strength of the paver blocks, Table 6. The strength improvement was notably observed at 100% replacement level in the average value of 29% compared to the control mix. The improvement was due to good adhesion between slag aggregate and cement paste due to rough surface of slag aggregate. Although all mix groups didn't meet the requirement of ASTM, almost all of them satisfy the limit of SI and ESS (normal and medium duty), as shown in Figure 4.

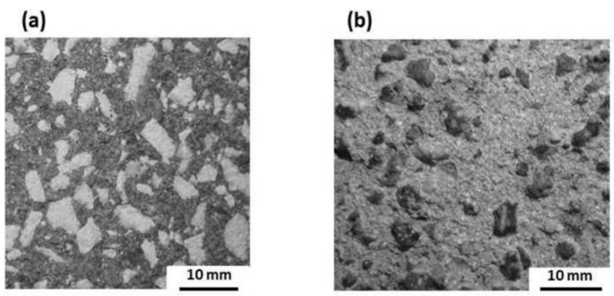

Figure 3. *Photography of abraded surface; (a) limestone specimen (Mix group 1), and (b) slag.*

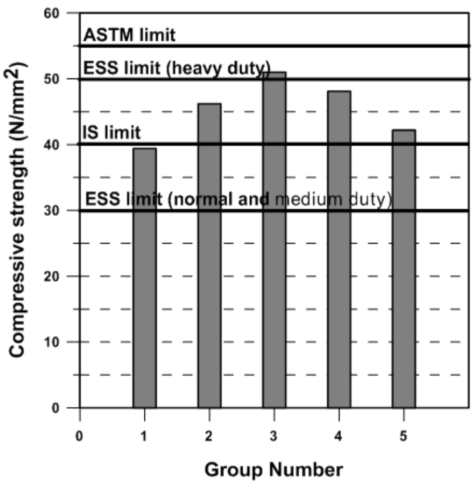

Figure 4. *Compressive strength of interlock groups.*

3.2. Effect of Mix Ratio

It is well recognized that coarse aggregate plays an important role in concrete pavers since it occupies at least one-quarter of the total volume of concrete. Results signified that changes in mixing ratio and slag aggregate content can change the abrasion resistance of paving units, as shown in Table 7.

Table 7. *Abrasion resistance for mix designs.*

Group	Mix ratio	Slag content (%)	Abrasion resistance (H_a)
1	1 : 3 : 1.5	0	1.50
2	1 : 3 : 1.5	0.13	1.66
3	1 : 3 : 1.5	0.27	2.37
4	1 : 3 : 3	0.43	2.51
5	1 : 2 : 3	0.50	3.29

Figure 5 indicates that there is a clear dependency between slag content and abrasion resistance. As in many particulate composite materials, properties and content of filler particles play a control role in determining its wear and abrasion behavior. Thence, it was expected to find highest abrasion resistance at the highest slag content.

The results indicated that compressive strength of groups 4 and 5 were higher by 7 to 22.1 % compared to control mix. This improvement may be due to good adhesion between slag aggregate and cement paste due to rough surface of slag. However, no clear correlation between compressive strength and slag content can be deduced from the results. No available explanation for the disparity of resulted compressive strength for groups 3, 4, and 5.

However, another previous study [13] discussed the effect of aggregate-to-cement (A/C) ratios and types of aggregates on the properties of pre-cast concrete blocks. It was found that the compressive strength of the paving blocks decreased as the A/C ratio increased. The results showed that the strength was directly proportional to the crushing strength of the aggregates. It was also reported that the compressive strength of ceramic waste concrete was found to increase with ceramic waste content and the optimum strength was at 50% substitution percentage by fine ceramic. We suggest that more investigation is required in order to find an optimum slag content (or mixing ratio) to ameliorate strength properties of concrete paving blocks.

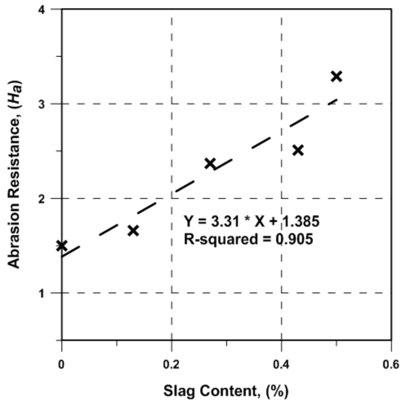

Figure 5. *Variation of abrasion resistance with slag content.*

3.3. Bulk Density and Water Absorption

Table 6 shows the average bulk density and water absorption results for all paving interlock groups and Figure 6 illustrates the effect of slag aggregate on water absorption. All test groups resulted in bulk density values either comparable to or slightly higher than the control group. Group 5 with the highest slag content (50% slag of the total content) showed the highest bulk density value, whilst group 2 (13% slag of the total content) resulted in the lower bulk density. The direct relation between slag content and the bulk density of paving interlock is attributed to the higher bulk density of EAFS over that of natural aggregate. The close bulk density values of group 2 and the control group may be due to the low slag content.

According to ESS 4382, average water absorption for normal duty paving units should not be greater than 8% with no individual block greater than 10%. While ASTM C936 states that the average absorption of test samples shall not be greater than 5% with no individual unit greater than 7% [11, 15].

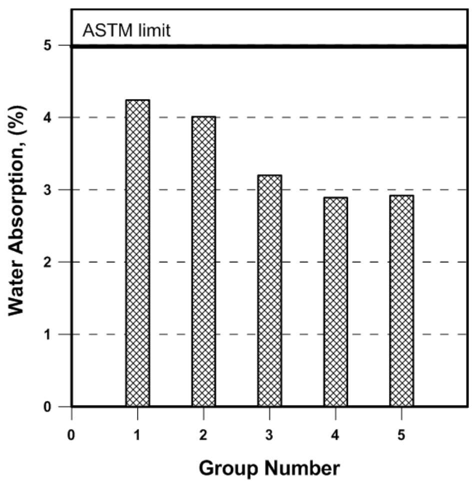

Figure 6. *Effect of slag aggregate on water absorption.*

Accordingly, ASTM does not categorize water absorption of paving units as does the ESS. However, the water absorption percentages for all test groups were found to be lower than ASME and ESS limits, as summarized in Table 4. It should be mentioned that all specimens exhibited lower absorption percentages than the control group. Results indicated that water absorption decrease by increasing slag aggregate content and vice versa. The relatively lower water absorption percentages of slag groups may be directly attributed to the lower porosity of EAFS compared to the limestone. Since the coarse aggregates represent more than 25% of the weight of the constituent materials of concrete pavement blocks, they have substantial influence on its overall porosity.

3.4. Characteristics of Surface Texture

Pavement texture characterizes the pavement surface and it has a direct influence upon friction, skid resistance, tire-pavement noises, tire abrasion, and rolling resistance [18]. The pavement texture is defined as the irregularities on a pavement surface that deviate from an ideal, perfectly flat surface [19]. World Road Association (PIARC) has established standard categories of texture, classified by the wavelength (λ) and peak-to-peak amplitude (A) which includes [20]:

- Micro-texture (λ < 0.5 mm, A = 1 to 500 μm).
- Macro-texture (0.5 mm ≤λ< 50 mm, A = 0.1 to 20 mm).
- Mega-texture (50 mm ≤λ< 500 mm, A = 0.1 to 50 mm).

In particular, the macrotexture of a pavement surface results from the coarse aggregate particles in the mixture and plays a key role in wet weather friction [21]. The basic principle of quantitatively measuring the macrotexture depth of pavement surface is by Sand Patch Test [18, 22]. Sand Patch Test is a volumetric approach of measuring pavement by evenly filling the apertures on the pavement surface with a known volume (V) of sand to form a circle.

The diameter (D) of the circle on which the sand material has been spread is measured and used to calculate mean texture depth MTD using Equation (1) below:

$$MTD = \frac{4V}{\pi D^2} \tag{1}$$

As the resulted pavement texture measurements is limited and also there is not enough measurement data for corresponding analyses in Egypt. Therefore recommendations for use of pavement texture values and establishment of their limit values is based mainly on the foreign experience and available literatures.

Some European countries have specified a minimum desired macrotexture. For example, current British specification requires a minimum 0.65 mm MTD for transversely textured surfaces. Ohio and French specifications recommended a volumetric MTD of ≥0.40 mm to ≥1.00 mm [23]. Likewise it was reported that the recommended value of MTD for pavement should be not less than 0.4 mm and not more than 0.9 mm [19].

Regarding to the present study, at the end of abrasion test, all pavers were measured in accordance with ASTM E965. Table 8 summarizes MTD average values and Figure 7 shows the calculated MTD compared to recommended requirements.

Table 8. *Mean texture depth MTD for mix designs.*

Group	D (mm)	MTD (mm)
1	52.7	0.69
2	46.8	0.87
3	47.9	0.83
4	45.6	0.92
5	45.2	0.93

MTD given in the Table is the mean value of 5 samples, V= 1500 mm^3.

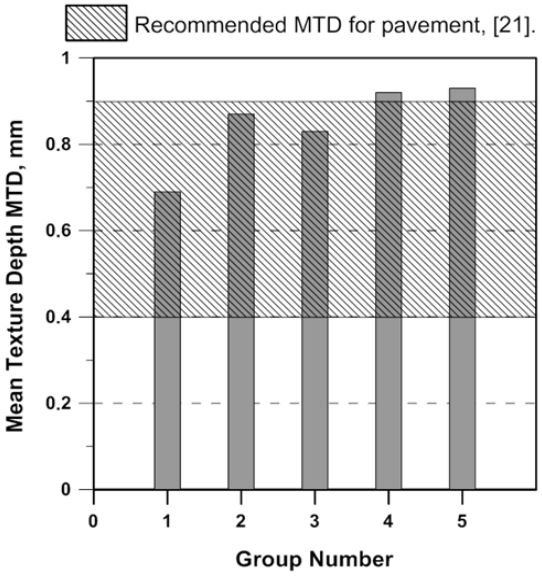

Figure 7. *The calculated MTD values compared to recommended requirements.*

The lowest MTD was found to be 0.69 mm for the group 1, control mix with 100% natural (limestone) aggregate, due to the relatively lower hardness of limestone compared to slag. Inspection of the abraded surface of this group suggested that the coarse aggregates were abraded somewhat in equal manner as the paver matrix. On the other hand, pavers contain 100% slag aggregate showed relatively highest MTD values, 0.92 and 0.93, due to the high abrasion resistance of hard slag.

The contrast in abrasion resistance between slag aggregated and paver matrix resulted in relatively irregular abraded surface, as shown in Figure 3(b). However, all test groups showed MTD in the range from 0.69 mm to 0.93 mm which are comparable to the aforementioned survey.

4. Future Work

The effect of surface irregularities on the abrasion requirement for interlocking concrete pavers will be extensively investigated and discussed in the light of currently ASTM standards.

5. Conclusions

The current study elucidates the use of Electrical Arc Furnace Slag (EAFS) as coarse aggregates in producing paving interlock units. Based on the results presented above, the following conclusions can be drawn:

1. All block pavements samples made from steel slag satisfy most of the ASTM and ESS requirements.
2. Introducing slag aggregate resulted in in higher abrasion resistance values (up to 119%) compared to dolomite used for the control group.
3. All slag mixes showed (7 to 29%) higher compressive strength than the reference group.
4. Slag interlock samples shown an acceptable MTD values. However,
5. Laboratory tests showed an acceptable MTD values in all slag interlock samples. However, the lowest MTD value was found in control mix due to the relatively lower hardness of limestone compared to slag.

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