Solid waste management in developing countries: Reusing of steel slag aggregate in eco-friendly interlocking concrete paving blocks production

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Abstract
The needs to meet the global demand for the conservation of non-renewable resources has necessitated the efforts of finding alternative materials. This current study investigates the beneficial utilization of the crushed waste furnace steel slag as a replacement for natural sand in concrete interlocking paving block units' production for pedestrian and non-traffic applications. A total number of 144 paver samples were cast at replacement percentages of 0, 20, 40, 60, 80 and 100% by weight of sand using a mix proportion ratio of 1:1.5:3 (cement: sand: granite) at a constant water-cement ratio of 0.5, targeting a strength of 20 MPa at 28 days. Tests carried out include physical characterization of the constituent materials, compressive strength, split tensile strength and water absorption tendency of the hardened H-shaped interlocking pavers. Results showed a significant 15% increase in the compressive strength at 28-day up to 40% sand replacement while the tensile strength also increases by 10% at 28-day up to 20% sand replacement compared to the control samples before a gradual strength reduction as the percentage replacement increases. The results indicate the possibility of using waste furnace slag for the production of interlocking pavers to promote an eco-friendly and sustainable pavement infrastructure in line with the UN Sustainable Development Goals.

Keywords: Waste furnace slag, Interlocking paving block unit, Compressive strength, Split tensile strength, Waste recycling

Introduction

Many developing countries are now experiencing a rise in pollution and environmental problems due to increased urbanization, industrialization and infrastructural development (Karak *et al*, 2012; Wilson and Webster, 2018). This increase has led to different kinds of hazardous and non-biodegradable solid wastes being generated and released into the environment (Olofinnade *et al.*, 2020; Abraham and Chakraborty, 2019). According to Sharba (2019) that managing the environmental pollution from both industrial and construction wastes is one of the persisting issues presently facing many developed and developing countries. A study by Pappua *et al* (2007) reported that as at 2002 the volume of solid wastes generated globally as industrial and municipal wastes was about 12 billion tonnes, and it was projected that an estimated 19 billion tonnes of solid wastes from both the industry and domestic are expected to be generated yearly by 2025. Meanwhile, report by Beede and Bloom (1995) estimated the total solid waste will be increased to 27 billion tonnes in 2050. Murari *et al* (2015) opined that the increase was as a results of enhanced technological innovations and industrialization in the various sectors, thus contributing to an increment both in the volume and variety of generated wastes from domestic, industrial, agricultural and mining activities. The steel industry is one of such sectors that is a source of industrial waste to the environment through its activities (Qasrawi *et al*., 2009; Johnpaul *et al*., 2019). The waste from the steel industry referred to as steel slag is often time discarded as waste in open spaces and landfill causing a major source of land and water pollution (Yu *et al.,* 2016; Johnpaul *et al*., 2019).

In the process of steel production, one of the by-products that emerges is the steel furnace slag, and it was reported that the poor disposal of the slag materials constitute menace to the environment and society health (Awoyera *et al*. 2016; Sharba 2019). Generally, based on the method and raw materials for the steel production, slag are classified into basic oxygen furnace (BOF) slag and electric arc furnace (EAF) slag. A study by Akinwumi *et al.* (2012) mentioned that about 96 to 145 million metric tonnes of slags are produced annually from the steel industry, and most often, these steel slags are indiscriminately discarded openly posing environmental threats to the society. The United States geological survey (USGS), also estimated in 2015 the amount of steel slag produce yearly will be about 170 to 250 million metric tonnes. Beside the threats to the environment and associated menace to human health, there is also the issue of availability of land spaces as dumping sites for the disposed slags (Olonade *et al*., 2015; Yu *et al*., 2016).

Consequently, there is an urgent need for an alternative approach of managing the steel slag instead of landfilling. Furthermore, the need for infrastructural development and industrialization in developing countries has also led to an increase in the demand for construction materials such as concrete due to rapid increasing construction activities (Olofinnade *et al*., 2019). This increase in demand for traditional materials used in the making of concrete has led to many negative environmental burdens leading to depletion of natural raw materials, scarcity and high cost of these resources (Yong and Teo, 2009). As also echoed by Calkins (2009) and Kline and Barcelo, (2012) that the industry relied more on traditional materials that are non-renewable while it's also contributed more greenhouse gases (GHG) into the atmosphere through its activities compare to other industries. Meanwhile, it was stated by Meyer (2004) that over 10 billion tonnes of concrete are produced yearly all over world, however, a recent report on global high-strength concrete market (2020 to 2025) forecast a growth in the demand for concrete. Such volume of demand without thought will require vast amount of cement and raw resources, with huge impact on the environment. Therefore, there is a need by the construction industry to find alternative ways to limit these negative environmental stresses, thus reducing material cost and energy consumption, raw resources depletion and GHG emission, thus making construction activities more sustainable.

One of the strategies that can be adopted to make construction activities sustainable is utilizing minimal natural resources, by recycling of waste materials that may constitute nuisance to the environment as alternative material in concrete and mortar composites (Akinwumi *et al*. 2016). Reuse of waste materials in concrete provides an efficient means of removing the burden of non-biodegradable wastes from the environment (Calkins 2009; Olofinnade *et al*. 2017). More importantly is when such materials are locally available and can be used to replace the traditional materials in concrete production. Many studies have been carried out by different researches to find ways to utilize wastes in the production of concrete, such wastes include furnace slag, plastic PET, ceramic, glass, agro-wastes, and shells. For instance, a study by Kumar *et al*. (2016) shows that using agro-wastes as a replacement for fine aggregate increases the strength of the concrete, while Vanitha *et al*. (2016) shows that waste plastic can be used in concrete mix in the production of paver blocks, replacing coarse aggregate at 4% without compromising its strength.

Slag application in concrete

Recycling of slag reduces cost and increases material conservation, thus reducing pollution caused by these non-biodegradable slag wastes (Daware *et al*., 2019). A study by Jiang et al. (2018) highlighted some of the various types and physico-chemical characteristics of the various steel slags. Sharba (2019) also emphasized that slag can be a good surrogate material for natural aggregates thereby protecting the environment and the natural resources. Many studies have been reported on the beneficial application of slag as aggregate in concrete (Maslehuddin *et al*., 2003; Qasrawi *et al*., 2009; Olonade *et al*., 2015; Yu *et al*., 2016, Awoyera *et al*., 2016; Akinwumi et al., 2016; Jiang *et al*., 2018; Sharba 2019; Penteado *et al*., 2019). These studies established that concrete containing slag has compressive, splitting tensile, and flexural strengths as well as modulus of elasticity, which is comparable or slightly higher to concrete produced with traditional aggregates. However, a study by Pellegrino *et al*. (2013) opined that slag due to its angularity in shape was reported to have negative impact on the workability of the concrete, especially at high replacement levels, while Penteado *et al*. (2019) reported that addition of slag in concrete slightly causes a reduction in the water absorption capacity. Liu and Guo (2018) reported that steel slag powder has more continuous hydration activity than cement does at late ages. A study by Mujedu *et al*. (2018) assessed the use of blast furnace slag as a replacement for coarse aggregate in concrete production and revealed that the compressive strength was increased by 61% at 7 days and 78% at 28 days. Also research by Hiraskar and Patil (2017) concluded that using steel slag aggregates in concrete is a concept that yields result which impacted on the strength of concrete more than natural aggregate. It was also mentioned that the compressive strength was noticed to increase up to 50% replacement after which it begin to reduce, while asserting that the use of slag in high strength concrete benefits the construction industry by assuring greater safety, while also achieving sustainable infrastructure. But, Al-Negheimish *et al*. (1997) reported on the risk of using slag in concrete. Coppola et al., (2016) suggested a maximum limit of about 15% as percentage of natural aggregate to be replaced with electric arc furnace slag to limit the amount of superplasticizer required attain same workability as the reference mix. Furthermore, the study opined that increasing the amount of slag increases the density, elastic modulus in compression and compressive strength of concrete. Abdelbary and Mohamed (2018) opined that steel slag can be used as green material in the production of paver units. The study showed that pavers with steel slag exhibit enhanced abrasion resistance. The American Society for Testing and Materials (ASTM) released ASTM D5106 (1992) –Standard Specification for Steel Slag Aggregates for Bituminous Paving Mixtures" on the use of steel slag in pavement construction. Under a high temperature curing conditions, Liu and Guo (2018) concluded in their study that steel slag aggregates will react and form a strong bonding with the hardened cement paste, thus causing the concrete to exhibit a higher compressive strengths. Also, a study by Rubio-Cintas et al. (2021) on the effect on steel slag types on the shrinkage property of concrete reported that slag can be used optimized the performance of concrete through reducing the cracking caused by early age shrinkage of the concrete mix. The dry shrinkage of the concrete increases by increasing the amount of steel slag content in the concrete mixture (Coppola et al., 2016). Palankar *et al*. (2016) investigate the long term performance of alkali activated concrete mixes containing steel slag as coarse aggregates and results showed no strength reversal when tested for long term strength properties up to one year. However, the alkali activated concrete containing steel slag aggregate was reported to have a high water absorption rate compared to regular concrete (Palankar *et al*., 2016).

Slag contain free lime (CaO) and magnesium oxide (MgO) in very small amount that can cause volumetric instability in concrete. However, such risk can be mitigated by stockpiling and sufficiently exposing the slag materials in an open environment to weathered for a long period of time before usage (Al-Negheimish *et al*., 1997; Juckle, 2003). Some of the common chemical oxides composition in steel slag are SiO_2, Fe_2O_3, CaO, MnO and Al_2O_3 (Zhang et al. 2008). Meanwhile, a study by Liu and Guo (2018) presented the x-ray diffraction (XRD) patterns for steel slag material. The XRD patterns as shown in Figure 1 depicts the mineralogical compounds phases present in steel slag materials and the main mineral phases of steel slag are C_3S, C_4AF, C_2S, RO phase and free-CaO (Zhang et al. 2018).

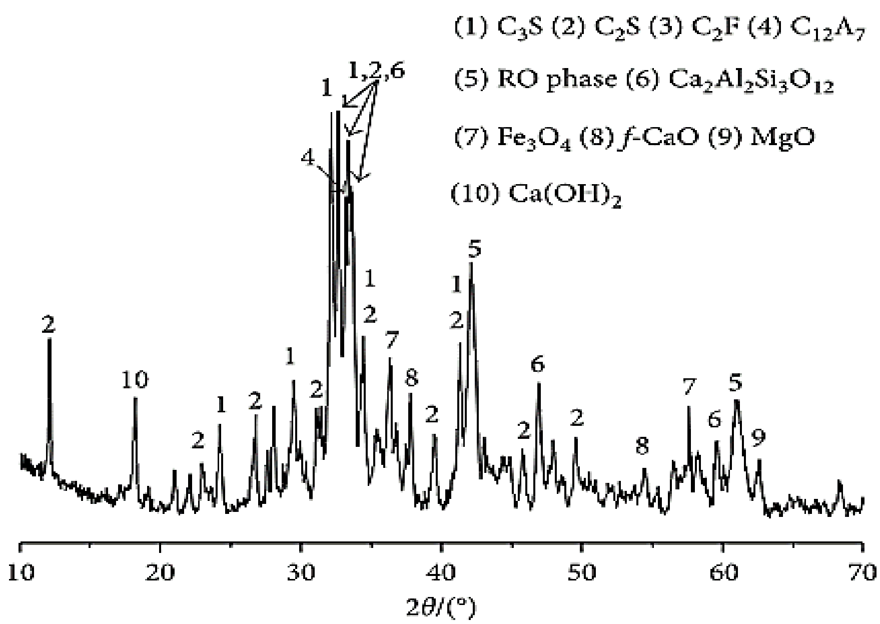


Figure 1. XRD patterns for steel slag material (Liu and Guo, 2018)

In Nigeria, vast volume of furnace slag are generated annually, and this slag are commonly discarded openly in dump sites. An estimated volume of slag generated locally as by-product from steel and iron smelting factories in various parts of Nigeria is shown in Table 1. Occasionally the slag are deployed as makeshift filling materials for potholes in failed section of roads in some parts of the country. But as previously discussed, studies have shown the possibility of using slag as a viable sustainable surrogate for natural aggregate in concrete and also as possible additive material for cement replacement (Tiifekqi et *al*., 1997; Yu *et al*., 2016, Awoyera *et al*., 2016; Sharba 2019), as well as sustainable material for modification of soil and as bituminous pavement admixture (Bagampadde *et al*., 1999; Yildirim and Prezzi, 2009; Ahmedzade and Sengoz, 2009; Sorlini *et al*., 2012; Akinwumi, 2014). Hence, suggest that furnace slag can be effectively manage in an ecofriendly way instead of the routine indiscriminately disposal as mostly noticed in most parts of the country (Egunlae and Oloruntoba, 2002). Consequently, the motivation for this current study is to examine the beneficial utilization of furnace slag in the production interlocking concrete paving blocks for possible deployment in paving sidewalks, walkways, driveways and light traffic street roadways. Thus, the specific objectives include; to evaluate the physical properties of the aggregate materials, mechanical properties compressive and split tensile strengths as well as the water absorption tendency of the produced interlocking concrete paver blocks. There is a high demands for interlocking pavers in Nigeria for both private and public use for building premises, landscapes, driveways and for many due to its many advantages, such as low production cost, easy installation and maintenance, its ability to be adjusted to fit any environmental needs like areas of high water level, preventing flooding by allowing for easy flow of rainwater, and can be used in any weather conditions and geographical terrain.

Table 1. Estimated volume/year of slag generated locally in Nigeria

Source	**Slag type**	**Volume (tonnes/year)**
Iron/Steel complex, Ajaokuta	Ferrous	Above 1.5 million
Nigerian machine tools, Oshogbo	Ferrous/non-ferrous	400,000
Nigerian machine works, Kaduna	Ferrous/non-ferrous	400, 000
Delta steel complex, Aladja	ferrous	800,000
Nigeria foundries	Ferrous/non-ferrous	150,000
DICON Kaduna	Ferrous/non-ferrous	50,000
EMDI Akure	Ferrous	10,000
Tower Aluminium	Non-ferrous	2,000
Nigeria Railway Corporation	Ferrous/non-ferrous	3,000
Adebowale foundry	Ferrous/non-ferrous	4,000
Continental steel	Ferrous	3,000
Nigeria Port Authority, Apapa	Ferrous	2,000
NIGALEX	Non ferrous	7,000
ALSCON Ikot Abasi	Non ferrous	8,000

(Source: Egunlae and Oloruntoba, 2002)

Experimental programme

The Figure 2 depicts a flowchart of summary of the test programme on the concrete paver samples used in this current study.

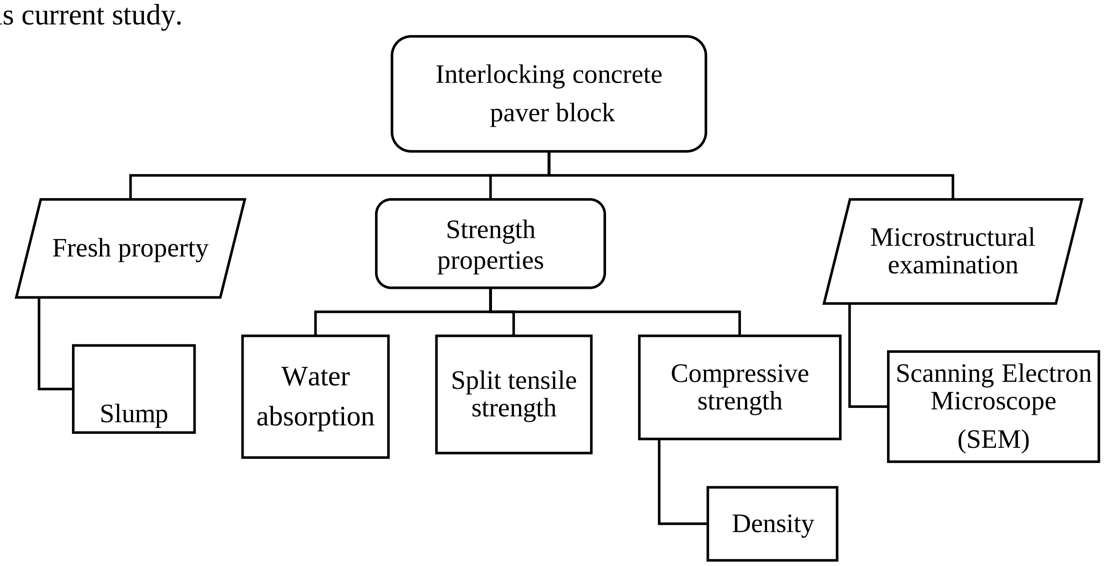


Figure 2. Test programme for concrete paver samples

Materials

The following materials were used in this study; the ordinary Portland cement (OPC) of grade 42.5 which complied with the requirements of BS EN 197-1 (2000) and NIS 444-1(2003) for general construction purpose. River sand as fine aggregate of nominal sizes of not more than 4.75 mm, coarse aggregate (granite) of size ranges of 10 – 12 mm, crushed waste furnace slag (WSF) (Figure 3) and clean water for mixing. No superplasticizer was added into the mixes.

Figure 3. Sand (*left*); WSF (*middle*); and granite (*right*)

The ordinary Portland cement was sourced from a retail store within Ota metropolis, Ogun state, while both the granite (coarse aggregate) and River sand (fine aggregate) was commercially sourced from a quarry site located at the outskirt of Abeokuta, Ogun state, Nigeria. The waste furnace slag (WSF) was sourced as discarded industrial waste from a road side dumpsite located along Idiroko road, Ota, Ogun state. The discarded WSF from the industries are usually stockpiled in boulder sizes in the dumpsite over a long period of time. The WSF was collected in various boulder sizes and moved to the material and concrete testing laboratory of Covenant University where the boulders were sorted, and crushed to the required range of nominal size of about 5 mm. However, before crushing, the collected WSF were stored for about Eight (8) weeks in the laboratory to subdue the free oxides concentration as recommended in the study of Juckles (2003) and Awoyera *et al*. (2016). The concentrations of major oxides in both the Portland cement and WSF material was ascertained through the X-ray fluorescence (XRF) and results are presented in Table 2. In addition, some of the obtained physical properties of the natural aggregates and WSF material are presented in Table 3, while the particle size gradation of the aggregates used are shown in Figure 4. These properties are determined following the procedures of British Standards. Portable water from the Material and Concrete Laboratory; at Covenant University was used for mixing the constituents to produce the interlocking paving samples.

Batching and mixing of constituents materials

The constituent materials were batched by weight using a mixing ratio of 1:1.5:3 (cement: sand: granite) at a constant water-cement ratio (w/c) of 0.50. The targeted strength in this study is 20 MPa at 28-day curing age. The WSF material was introduced into the mixes at varying proportions as a partial and complete replacement for sand at 20, 40, 60, 80 and 100%, while the conventional mix was produced as the control. The constituent materials were weighed using the digital weighing balance and were thoroughly mixed to ensure uniformity and even distribution. The batching proportions of the constituent materials used for the production of the interlocking paving block unit samples are presented in Table 4. The plastic moulds used for casting the concrete paver samples were thoroughly oiled before the mixes were placed into the moulds in order to ensure easy removal of the hardened interlocking paving samples. During the casting processes, three layers of freshly prepared concrete was poured into the mould and manually compacted twenty-five times using a 25 mm tapping rod. All the mixing process was carried out manually. The workability of freshly prepared concrete was determined using the slump test in accordance with BS EN 12350–2 (2009) as shown in Figure 5.

Table 2. Oxides composition of OPC and WSF

Oxides composition	**Materials**	
	Portland cement	**WSF**
SiO_2	22.0	37.0
Al_2O_3	5.2	6.00
Fe_2O_3	1.2	18.2
MgO	2.9	-
CaO	64.0	33.1
SO_2	4.5	-
Na_2O	0.6	-
K_2O	0.1	0.60
LOI	0	-
$SiO_2+Fe_2O_3+Al_2O_3$	27.90	61.2

Table 3. Physical description and properties of materials

Properties	**Portland cement**	**Sand**	**Granite**	**WSF**
Surface area, m^2/kg	354			
Specific gravity	3.15	2.65	2.70	3.18
Fineness Modulus		2.69	5.12	2.68
Shape		Rounded	Slightly angular	Very angular
Surface texture		Smooth	Smooth	Rough
Colour		Light brown	Light greyish/black	Light black
Bulk density, kg/m^3		1692	1683	1710
Water absorption,%		0.95	0.25	0.30
Aggregate crushing value, %			24	22
Aggregate impact value, %			10	16
Loss-Angeles test, %				10 – 20

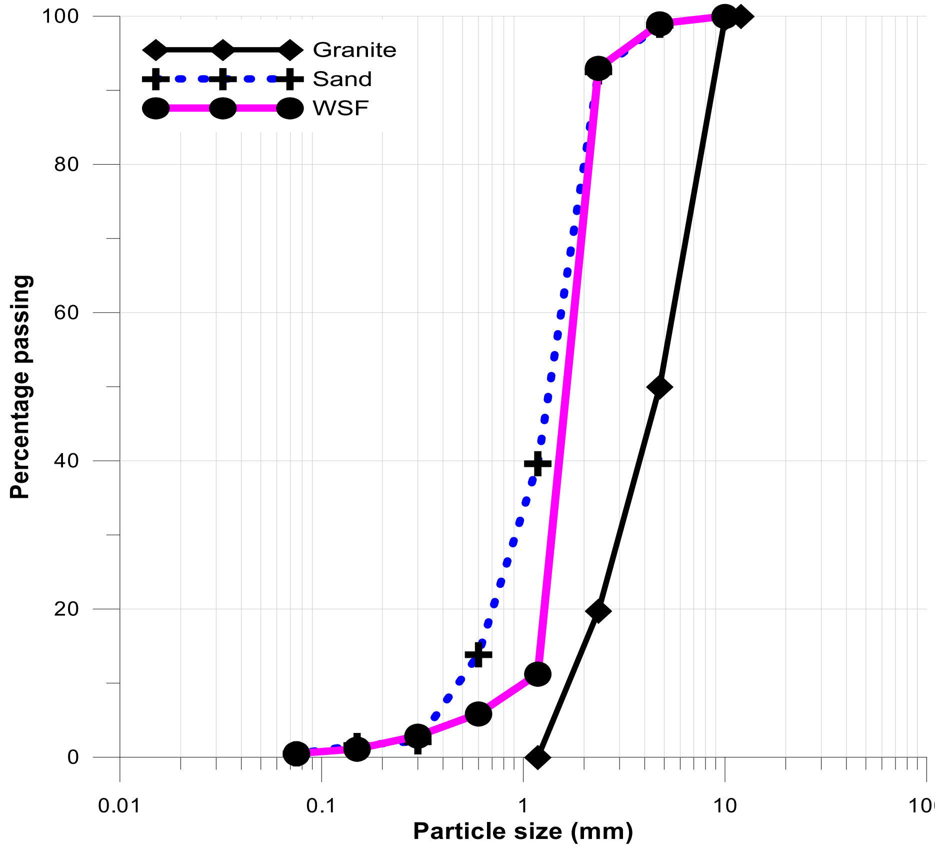


Figure 4. Particle size distribution of sand, granite and WSF

Testing of hardened paver samples

The concrete paver samples of H-type shape (Figure 5) with cross-sectional dimension of 0.032 m^2 and 60 mm thickness were prepared from each mix and covered with plastic sheet after casting for 24 hours. The thickness of the paver is in line with the recommendations of ASTM C936 (2001) on minimum thickness of pavers. The samples were demoulded and openly cured by water sprinkling twice daily throughout the duration of curing days at temperature ranges of 28 – 30 °C. The hardened interlocking paver samples were tested for compressive and split tensile strengths according to the provisions of BS 1881(1983) using a YES-2000 digital display compression machine (Figure 6). The test on concrete paver samples were carried out after 7 and 28-day curing. The water absorption tendency of the interlocking paver block samples was also evaluated after fully submerging the samples in water for 28 days, weighed and then oven dried to a permanent mass at the temperature of 115 ^oC. The water absorption capacity was determined by estimating the decrease in the mass of wet interlocking paver samples (W_2) and dry samples (W_1). Thus absorption rate is determined using Equation 1;

$$Water\ absorption\ capacity(\%) = \frac{W_2 - W_1}{W_1} \times 100 \qquad (1)$$

Where W_1= *weight of the dry block*, W_2= *weight of the wet block.*

Morphology of selected hardened concrete was examined using the Phenom ProX scanning electron microscope (SEM). All samples preparation and testing were carried out at the laboratory of Department of Civil Engineering, Covenant University, Ota.

Table 4. Batching of concrete constituent materials

Percentage substitute of sand with waste furnace slag, %	Paver concrete constituents (kg)				
	Cement	Sand	Furnace slag (WSF)	Granite	Water
0	20	30	-	60	12
20	20	24	6	60	12
40	20	18	12	60	12
60	20	12	18	60	12
80	20	6	24	60	12
100	20	-	30	60	12

Figure 5. Slump of concrete mix (*left*); Interlocking concrete paver block (*right*)

Figure 6. Testing of interlocking concrete paver (*left*); Failure mode of the paver sample containing WSF (*right*)

Results and Discussion

Physical properties and particle size distribution (*PSD*)

The oxide compositions in the WSF material used in this study are presented in Table 2. The result shows the major chemical oxides in the waste furnace slag (WSF) material include; SiO_2 (37.0%), Al_2O_3 (33.1%), Fe_2O_3 (17.1%), and CaO (6.0%). Thus, implies that the WSF aggregate contains sufficient silica content which can thus react with carbonate compounds in cement in the interlocking concrete pavers. Some of the tested physical properties of natural aggregate and crushed waste furnace slag (WSF) material are presented in Table 3. The WSF exhibited a low water absorption tendency compare to the recorded water absorption of 0.95% for the sand. In addition, the specific gravity of the sand and WSF were 2.65 and 2.69 respectively. The specific density of the river sand and WSF material were 1692 kg/m^3 and 1710 kg/m^3, thus indicating the WSF aggregate to be of heavier weight compare to the natural sand. The particle size distribution (PSD) of the natural sand and crushed waste slag furnace (WSF) are depicted in Figure 4, indicating the particle grading of both materials are closely similar. The Coefficient of Uniformity (*Cu*) of sand and WSF was 3.2 and 2.0, respectively, while the Coefficient of Curvature (*Cc*) were 1.01 and 1.00, respectively. This is an indication that the soil is well graded. The particle size distribution WSF is within 0.150 to 4.75 mm nominal sizes, while 1.0% of the river sand particle sizes were larger than 4.75 mm.

Workability and Density

The concrete mixes used in this study showed mostly moist mixes, with a measured slump ranging between the S2 class (50 – 90 mm) for lower WSF contents and S3 (100 – 150 mm) at 80% and 100% WSF contents. Figure 7 present the results of the measured slump depicting an increase in the workability of the concrete mixes as the percentage replacement of sand with WSF increases. The increase in the fluidity of the mixes can be attributed to the different water absorption capacity of both sand and slag materials. Sand has a higher water absorption tendency compare to slag, thus, an increase in the amount of slag content in the mixes made more water available in the mixes. A similar results was also reported by Awoyera *et al*. (2016) which suggested the increase in the slump of the concrete mixes might be due to the smoothness of the slag surface, while the findings by Al-Negheimish et al., (1997) also reported an increase in the slump with addition of superplasticizer. Liu and Guo, (2018) also reported an increase in the fluidity of concrete mixtures as the steel slag contents increases. However, the reported results on slump containing WSF did not corroborate the decrease in slump values reported by Sharba (2019).

Meanwhile, Figure 8 present the results on the densities of the interlocking concrete paver units containing WSF compare to the control. The results refer to the mean average of three samples for each of the percentage replacement. The results revealed an increase in the density of the hardened interlocking concrete paver blocks as the amount of WSF contents increases at 28-day curing ages considered. From the plot, the recorded average density obtained for the control at 28-day curing, was 2362 kg/m^3 while that of paver units containing 100% WSF was 2521 kg/m^3, representing about 6.7% increase. This can be attributed to the higher bulk density and specific gravity of the WSF materials compare to the replaced fine aggregate (sand).

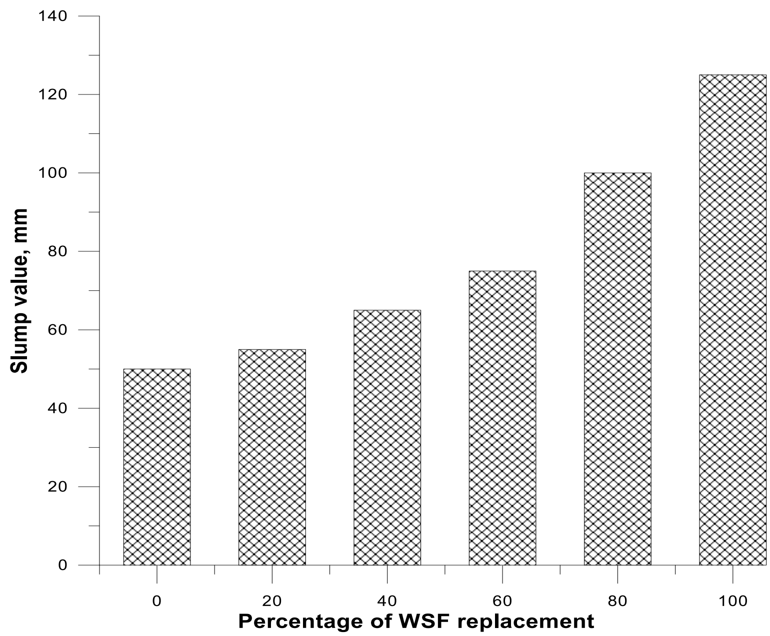


Figure 7. Slump for concrete mixes

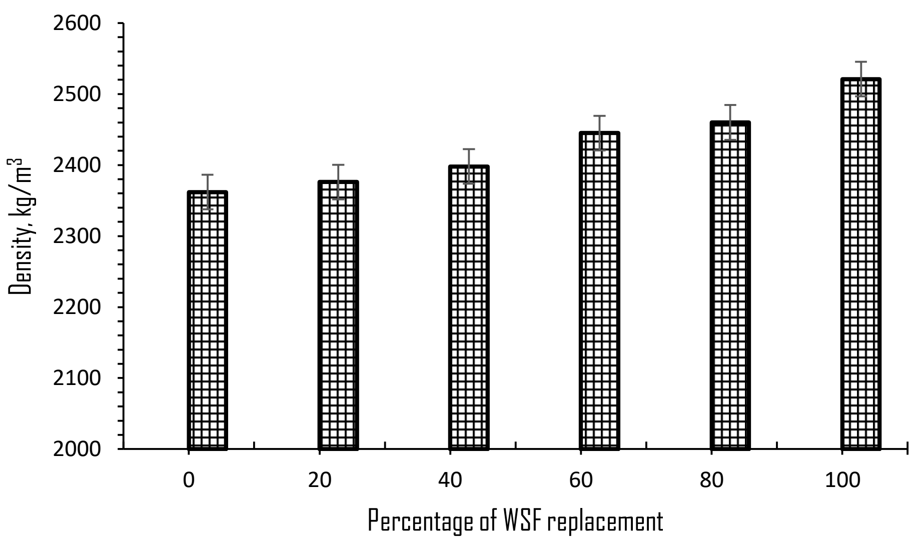


Figure 8: Density of the hardened concrete mix

Hardened properties of interlocking concrete pavers – Compressive strength

Figure 9 presents the compressive strengths development of the hardened interlocking concrete paver units. The Figure displayed an increase in the compressive strength for percentage replacement of sand with WSF at 20% and 40%. However, a reduction trends in the characteristic compressive strength of the interlocking concrete paver units was observed as the amount of WSF content increases beyond 40% replacement. Thus, indicating a significant strength loss with increasing amounts of WSF content irrespective of the mixture proportion. The use of 60%, 80% and 100% replacement lowered the compressive strength of the interlocking concrete pavers at the curing age of 7, 14 and 28 days. In addition, while appreciable mean compressive strength values were recorded for the interlocking concrete pavers for 60%, 80% and 100% WSF content, the values fall below the expected strength. The values of strength development of both concrete mixes at 20% and 40% WSF increased by 4.76% and 14.57% respectively, while the values of reduction in the compressive strength of the mixtures (60, 80 and 100%) were equal to 6.24%, 22.62% and 25.57% and, respectively. The results indicate that addition of WSF into the mixes contributed to the strength improvement of the interlocking concrete pavers at not more than 40% replacement of sand with the WSF material. This can be attributed to the good adhesion between the slag aggregate and the cement paste for enhance strength. A view that is also emphasized in the study of Rai *et al*. (2002) and Murari *et al*. (2015) and Abdelbary and Mohamed (2018). Also, a similar results was reported by Olonade *et al*. (2015) which attributed the enhancement in strength to the interlocking bond between the cement paste and slag aggregate. Meanwhile, at prolong curing the compressive strength is more pronounced at lower percentage replacement compare to the control concrete pavers.

In addition, the results at both 20% and 40% replacement met the minimum compressive strength of 3.45 MPa required by Nigerian Building and Road Research Institute (NBRRI, 2006) for interlocking paving brick units deploy for non-traffic uses, building driveways and premises and landscaping with minimal loading. However, the results did not meet the minimum strength requirements of 30 MPa recommended by BS 6717 (2001), IS 15658 (Bureau of Indian Standards, 2006) and ESS 4382 (Egyptian standard, 2004), and 40 - 55 MPa recommended by ASTM C936 (2002) and Interlocking Concrete Pavement Institute (ICPI, 2004) for non-traffic and normal duty applications. An increase in the compressive strength for the concrete pavers was noticed as the curing age increases from 7 to 28 days. The results show that an optimum 40% WSF content will be appropriate for the interlocking concrete pavers of the specific thickness and size considered in this study, beyond which the WSF materials appeared dormant in the concrete mixes, which could have been responsible for relative low strength at increased percentage replacement of 60, 80 and 100% WSF. Figure 5 depicts the produced interlocking concrete paver containing crushed waste furnace slag WSF as replacement for natural sand. Meanwhile, Figure 6 depicts the failure mode of a tested interlocking concrete paver unit sample containing WSF. The failure line was observed to be through the middle of the paver with line cracks showing on the surfaces of the paver.

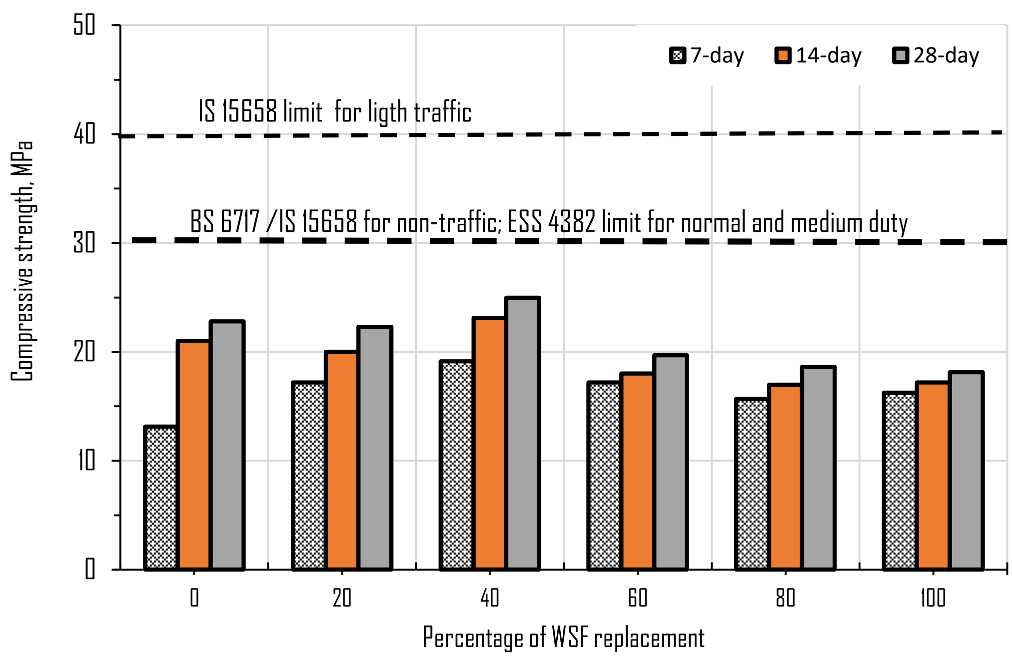


Figure 9. Compressive strength for load bearing interlocking pavers with furnace slag

Split tensile strength

Figure 10 depicts the results of the tensile strengths development of the hardened interlocking concrete paver units for all proportions replacement of sand with WSF at 7, 14 and 28 days of curing. From the results, the value of the tensile strength was observed to increase when the percentage substitute of the fine aggregate sand with WSF increases from 0 to 20%. Thus indicating that there is an improvement in the tensile strength resistance of the concrete paver units as the percentage replacement ranging between 0 to 20% compared to the control concrete pavers at 28 days. Meanwhile, a reduction trend in the tensile strength was noticed as the percentage replacement increases beyond 20%. The concrete paver units exhibited a reduction in the split tensile strength at 40%, 60%, 80% and 100% replacement levels. The reduction in the tensile strength performance of the concrete paver unit samples is similar to the outcome observed for compressive strength. The improve strength at 20% replacement may be due to the close interaction between the slag and other constituent and cementitious materials in the concrete mixes. This was also noted in a study by Awoyera *et al*. (2016) which mentioned that concrete containing slag aggregates with higher angularity causes an enhanced improved strength.

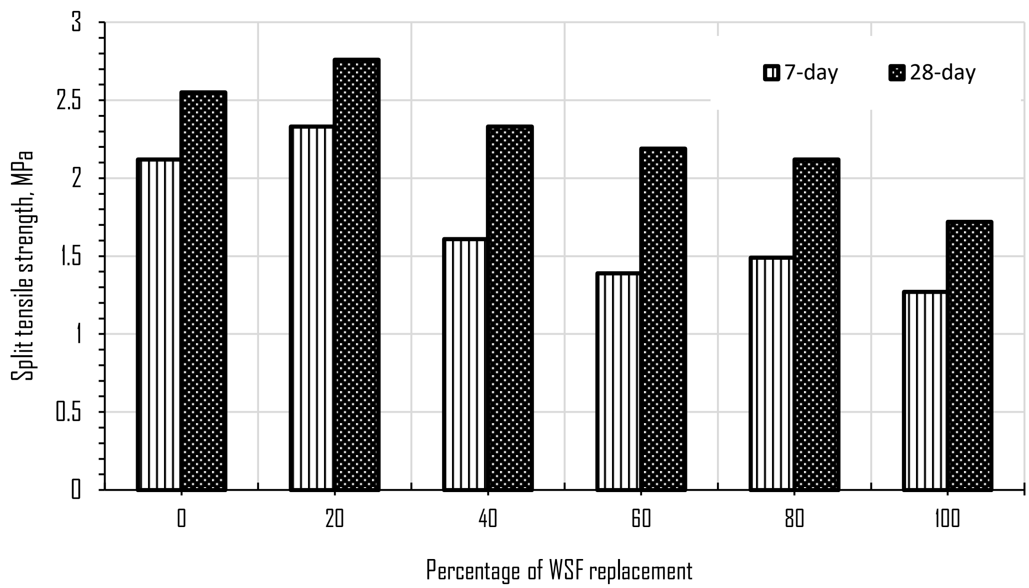


Figure 10. Split tensile strength for load bearing interlocking pavers with furnace slag

Water absorption

Figure 11 shows the water absorption tendency of the interlocking concrete paver unit samples after soaking in water for 24 hours. The results depicted that the water absorption tendency of the concrete paver units containing the crushed WSF decreases from 11.38% for 20% WSF to 6.471% for 100 WSF after the samples were cured for 28 days before tested for the water absorption. Meanwhile, it was noticed that the control samples produced with conventional materials exhibited the highest water absorption tendency of 14% after 28 days. The results indicated that the water absorption decreases as the WSF content increases as fine aggregate replacement in all the concrete paver mixes. However, while there is a slight decrease in the water absorption tendency for pavers containing 20% WSF compare to the control. The low water absorption capacity of the paver units could be attributed to the low water absorption tendency of the slag aggregates (WSF) materials in the paver matrix. Also, is the porous tendency of the slag materials compare to that of natural sand material used in the production of the Interlocking concrete paver units. The results showed a slight reduction in the water absorption as the percentage of WSF increases in the concrete mixes. Gencel *et al.* (2015) opined that the slag aggregate particles are enveloped by the cement paste, filling the pores, thus did not contribute to the water absorption tendency of the concrete pavers. A study by Penteado *et al*. (2019) mentioned that a high water absorption shows the presence of high porosity in the hardened concrete samples, thus reducing the strength properties of the concrete pavers. The recorded water absorption results for the interlocking pavers containing WSF fell within the maximum 6 - 8% required for paving blocks for non-traffic traffic applications as recommended by IS 15658 (2006) and ESS 4382 (2004), but surpasses the maximum requirement by ASTM C936 (2002).

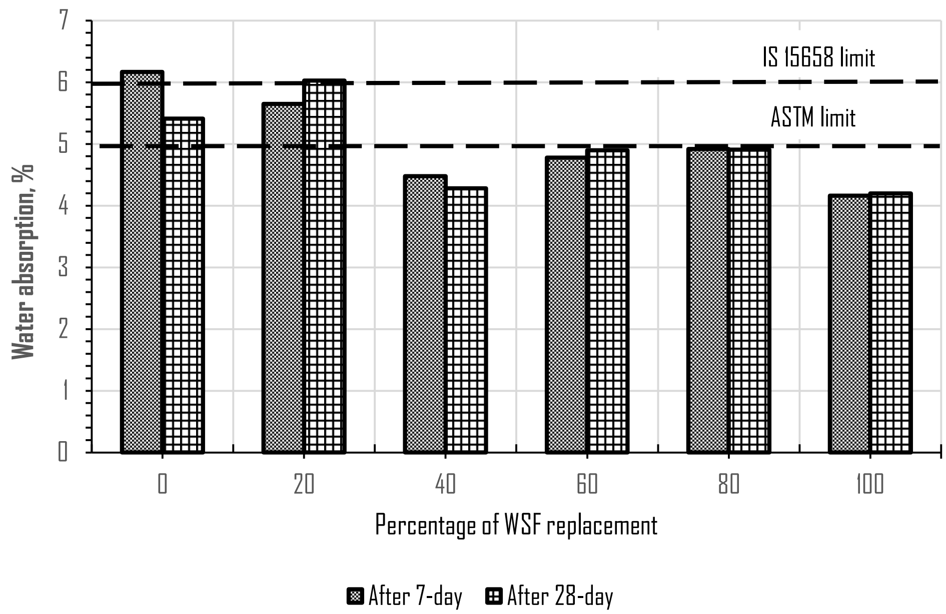
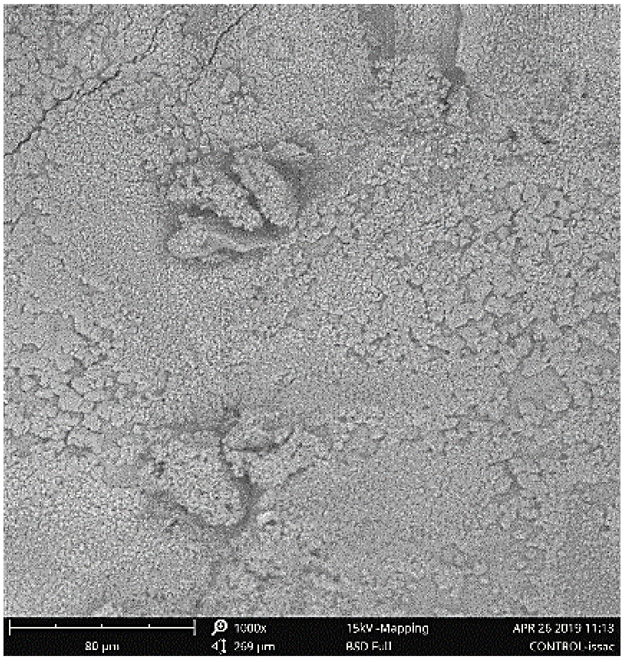


Figure 11. Water absorption value for load bearing interlocking pavers with waste furnace slag

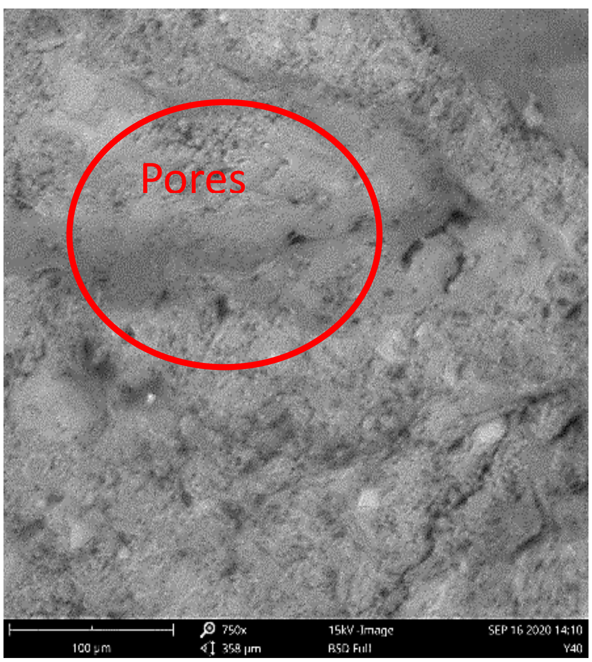
Microstructural examination

Figure 12(a – c) shows the SEM micrographs of the control and selected concrete mixes with 40% and 100% WSF respectively. The SEM image for the control in figure 12a, reveals a well compacted interface with no major pores, thus indicate the mix possesses a dense surface. The elemental compositions on the surface morphology are highlighted in the table beside micrographs for the reference sample. Meanwhile, the SEM image for the concrete mix with 40% WSF (figure 12b) revealed the presence of tiny pores on the interface, while the pores is more in the SEM image with 100% WSF (figure 12c). It is obvious from the SEM images that as the WSF contents increases in the concrete mixes, the presence of pores appears to increase resulting in the reduction in strength as noticed in the earlier results. However, while the images depict that there exist a good matrix-aggregate adhesion in the mixes, the presence of pores in the mix at high WSF content will likely result in weak interfacial zone. The elemental compositions on the surface morphology of the concrete containing 40% and 100% steel slag aggregate are highlighted in the tables beside micrographs.



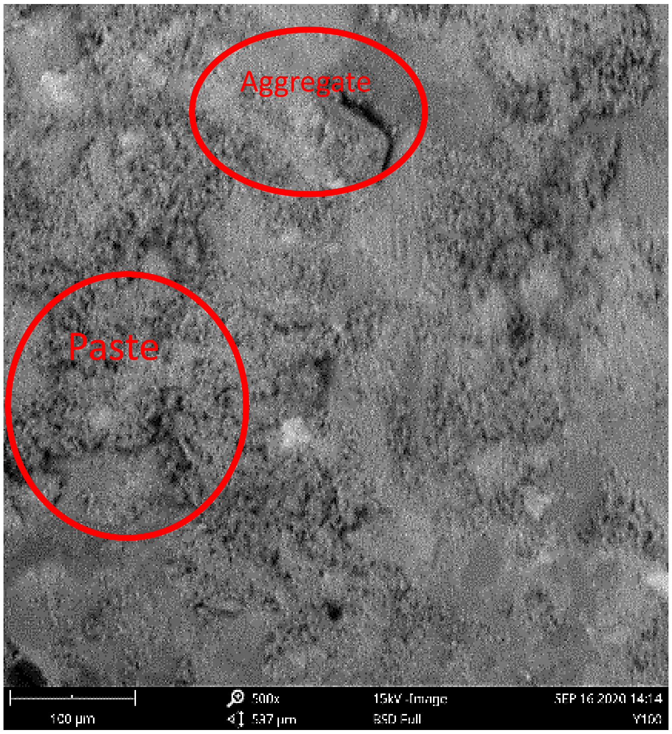
Element Symbol	Element Name	Atomic Conc.	Weight Conc.
Ca	Calcium	58.27	60.19
Si	Silicon	13.66	9.89
Nb	Niobium	2.47	5.91
Al	Aluminium	6.46	4.49
Fe	Iron	2.53	3.64
Ti	Titanium	2.60	3.21
Ag	Silver	1.00	2.77
K	Potassium	2.44	2.46
Y	Yttrium	0.97	2.23
S	Sulfur	2.38	1.96
Mg	Magnesium	2.27	1.42
C	Carbon	4.37	1.35
P	Phosphorus	0.57	0.46
Na	Sodium	0.00	0.00

(a)



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
Ca	Calcium	61.64	65.05
Si	Silicon	16.95	12.53
Fe	Iron	3.20	4.71
Al	Aluminium	4.80	3.41
Ag	Silver	0.86	2.45
Y	Yttrium	1.00	2.35
K	Potassium	1.72	1.78
S	Sulfur	2.05	1.73
Nb	Niobium	0.69	1.70
Mg	Magnesium	1.79	1.14
C	Carbon	2.73	0.86
Na	Sodium	1.27	0.77
P	Phosphorus	0.83	0.68
Zr	Zirconium	0.23	0.54
Ti	Titanium	0.24	0.30

(b)



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
Ca	Calcium	49.31	54.37
Si	Silicon	23.47	18.13
Al	Aluminium	9.11	6.77
Ag	Silver	1.03	3.07
Y	Yttrium	1.22	2.98
Fe	Iron	1.87	2.88
Na	Sodium	3.37	2.13
K	Potassium	1.79	1.93
S	Sulfur	2.09	1.84
Nb	Niobium	0.67	1.71
Mg	Magnesium	1.74	1.16
C	Carbon	2.79	0.92
Zr	Zirconium	0.34	0.84
Ti	Titanium	0.51	0.67
P	Phosphorus	0.69	0.59

(c)

Figure 12. SEM micrographs for *(a)* control; *(b)* 40% WSF; and *(c)* 100% WSF

Conclusion

This study evaluates the performance of furnace slag as substitute for natural sand in interlocking concrete paving block production. The following conclusions can be drawn from this study,

i. The study demonstrate the possible use of waste steel slag in production of eco-friendly interlocking concrete block units with higher density compare to the conventional interlocking concrete pavers.
ii. The results show a steady increase in the compressive strength of the interlocking paving stone with increasing proportion of furnace slag. However, it only increases up to 40% after which there is loss of strength. This therefore indicates that an optimum 40% is the maximum percentage for furnace slag to substitute natural sand without compromising the strength of concrete paver blocks.
iii. The study also indicates a reduction in the split tensile strength of the concrete paver blocks as the amount of the slag aggregate increases. However, concrete pavers at optimum 20% slag replacement for sand recorded the highest tensile strength compare to the control.
iv. The control concrete pavers were observed to show the highest water absorption capacity. Meanwhile, the water absorption decreased with an increase in the amount of WSF aggregate for all samples.
v. The results showed that the interlocking concrete paving blocks containing furnace slag meets the specified standard in terms of strength for interlocking paving block units that can be used in areas for non-traffic applications such as pedestrians walkways and landscape, or for very light traffic driveways for building premises and car park areas.

This study demonstrates that discarded steel slag material can be utilized in the production of eco-friendly interlocking concrete paving blocks to help prevent environmental pollution and indiscriminate disposal on the environment. The study also clearly indicate that slag can be adopted as an alternative innovative construction material in concrete constituent to achieve sustainable infrastructural development and greening of the environment. However, it is important that special attention should be focus on the needs for adequate weathering of the slag aggregates before usage in concrete.

Acknowledgement
The authors would like to express gratitude to Covenant University Centre for Research, Innovation and Discovery for the publication support.

Funding
No direct funding was received for this research.

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