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Strength and microstructure of eco-concrete produced using waste glass as partial and complete replacement for sand

Oluwarotimi M. Olofinnade^{1*}, Anthony N. Ede¹, Julius M. Ndambuki², Ben U. Ngene¹, Isaac I. Akinwumi¹ and Olatokunbo Ofuyatan¹

Abstract: The sustainable benefits of waste glass usage in concrete include the possibility of reducing solid waste and greenhouse gas emission and preservation of raw materials. This current study examines the effect of recycled waste glass as a partial and complete substitute for natural sand in producing eco-friendly concrete. The recycled waste glass was proportioned in levels of 25, 50, 75 and 100% by weight to substitute sand in the concrete using a mix ratio of 1:2:4 (cement:sand:gravel) at a W/C ratio of 0.5 targeting 20 MPa strength at 28 days. Tests, which include X-ray fluorescence (XRF), were conducted on the waste glass and cement materials; slump test was performed on the freshly prepared concrete at different percentage glass content. Compressive and tensile strength tests were performed on 60 specimens after 3, 7, 28 and 90 days of curing. The concrete microstructure was examined using the scanning electron microscope (SEM). Results showed that

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PUBLIC INTEREST STATEMENT

The need for a pollution-free and greener environment has increased the awareness on the seriousness of reducing wastes that are disposed in landfills or dump sites through reusing of these wastes. Moreover, concrete production is regarded as one of the largest consumer of natural resources. Consequently, there is a need also to make concrete production sustainable in a way that will preserve the natural resources from further depletion and reduce greenhouse gases emission. Therefore, investigations into ways of utilizing solid waste materials, such as waste glass, as replacements for natural aggregates in the production of concrete are receiving more attention. Determined research efforts have been focused on investigating waste materials with similar physical and engineering qualities to the traditional materials. Thus, a sure option of making concrete production more sustainable and eco-friendly is incorporating wastes as an alternative material for concrete production.

workability and the mechanical strength of the concrete produced decreased with increasing waste glass content. However, concrete containing 25% and 50% waste glass contents showed significant enhancement in strength, but it is recommended that the optimum glass content should be 25% for the production of sustainable eco-concrete.

Subjects: Civil; Environmental and Geotechnical Engineering; Concrete and Cement; Waste and Recycling; Environmental Health

Keywords: compressive strength; eco-friendly concrete; waste glass sand; microstructure; split tensile strength; sustainability

1. Introduction

The benefit of using waste glass as a substitute for natural aggregate in concrete offers a promising environmental solution to the growing problem of efficient management of glass wastes in developing nations. Glass is an indispensable material to man and one of the oldest man-made materials on earth. Because of its properties, glass can be formed into many shapes and forms, which include flat glass, bulb glass, container or bottle glass and cathode ray tube glass (in addition to being produced in many colours). However, glass has a limited life usage in the forms in which they are produced (Ali & Al-Tersawy, 2012). Moreover, based on chemical compositions, glass can be classified into different categories with the most widely used and readily available glass type being soda-lime glass (Shi & Zheng, 2007; Siddique, 2008).

In recent years, there has been a gradual increase in the amount of generated waste glass owing to increasing use of glass products. This has led to huge glass waste being dumped into landfills or dump sites (Rashad, 2014). In addition, the United States Environmental Protection Agency (U. S. EPA) stated that 11.5 million tonnes of waste glass are generated annually in the United States (U. S. EPA, 2014). Hence, the need for reusing or recycling of waste glass in order to prevent the environmental nuisance that is caused by stockpiling or dumping of glass waste in landfills or dump sites. Unlike other solid waste materials, glass is considered a non-biodegradable material, thus constitutes a menace to the environment through indiscriminate disposal.

Sobolev, Turker, Soboleva, and Iscioglu (2006) opined that theoretically glass is a 100 per cent recyclable material, meaning that glass waste can be endlessly recycled as cullet in glass production without any loss of purity and quality. However, Tan and Du (2013) reported that comparing the recycle of glass with those of other solid waste materials, less glass recycling is done in developing countries. In addition, a study by Afshinnia and Rangaraju (2016) stated that although there has been increasing effort to recycle glass waste in recent times, over 50% of collected waste glass in some parts of the world is still being disposed of in landfills. For instance, in the United States, 11,480 thousand tonnes of waste glass was generated in 2014 and only 26% was recycled, with the remainder being landfilled (EPA, 2014). Some of the challenges limiting its recycle include at-source mixing of dissimilar coloured glasses. In addition, other challenges include the operational cost and removal of contaminants and residues from the waste glass stream.

In recent years, attempts have been made to use the construction industry for managing solid waste since they provide the real potential means of consuming large quantities of generated solid waste or industrial byproducts (Ali & Al-Tersawy, 2012; Calkins, 2009; Chesner, Coollins, & Mackay, 1997; Ling, Poon, & Wong, 2013; Olofinnade, Ede, Ndambuki, & Bamigboye, 2016a; Rashad, 2014; Siddique, 2008; Sobolev et al., 2006; Tan & Du, 2013). According to Chesner et al. (1997), Shi and Zheng (2007), a huge amount of waste with proportionately low quality can be utilized as construction materials. Studies carried out by Shi and Zheng (2007), Jani and Hogland (2014), Akinwumi, Awoyera, Olofinnade, Busari, and Okotie (2016), and Olofinnade, Ede, and Ndambuki

(2017a) emphasized that wastes used in the production of concrete provides a potential way of managing wastes, such as glass bottles, construction and demolition waste, rice husk and fly ash. Furthermore, it is important to note that waste recycle and reuse are also sustainable ways of improving and preserving the environment. This is an effective way to reduce waste, extend the lifespan of landfills, reduce greenhouse gas (GHG) emissions, save energy, and preserve of natural resources (Sonebi, 2015). Moreover, with the increasing attention on the need to protect the environment, using solid wastes as ingredients of concrete production is becoming an option. This is because it offers great opportunities for efficient waste management, energy saving and preservation of raw resources in addition to creating a better performance concrete (Akinwumi et al., 2016; Federico & Chidiac, 2009; Matos & Sousa-Coutinho, 2012). Moreover, Shi and Zheng (2007) and Olofinnade et al. (2017a, 2017c) reported that utilizing recycled waste materials in producing sustainable and eco-friendly concrete is among the most innovative options for protecting and preserving the environment. As Kline and Barcelo (2012) pointed out, concrete is widely used as construction material and its production contributes to a large extent part of worldwide CO₂ emissions. In addition, Mehta and Monteiro (2006) estimated that yearly, the production of concrete consumes about 1.5 billion tonnes of cement, 9 billion tonnes of natural aggregate and 1 billion tonnes of water. Thus, based on this estimation, concrete production is expected to have significant impact on the environment as emphasized by Meyer (2009), Bamigboye, Ede, Raheem, Olofinnade, and Okorie (2016) and Ede, Olofinnade, Ugwu, and Salau (2018). Meyer (2009) estimated that by the year 2050, the demand for concrete would have increased to about 18 billion tonnes due to surging construction activities and expected infrastructural development. This implies that concrete would be of great importance in the coming future and the need, therefore, for concrete industry to embrace sustainability in a bid to conserve natural resources, save energy and reduce the amount of CO₂ emission in order to protect the environment cannot be ignored.

Waste glass offers equal alternative options as a replacement material for conventional aggregate in concrete and incorporating crushed granular waste glass as aggregate in concrete not only benefits the environment but also reduces the need for extracting raw materials. Several research studies have been conducted on recycling and reusing of waste glass as a substitute for the use of natural aggregates in concrete. A study by Shayan and Xu (2006) observed that glass powder could be used as a substitute for aggregate or cement in concrete up to 30% without any negative long-term effects on the concrete. In addition, field trial application of waste glass in concrete slab led to the recommendation of the use of combined glass aggregate and powder to produce 40 MPa concrete mixtures (Shayan & Xu, 2006). Topcu and Canbaz (2004) reported a decreasing tendency in the mechanical properties (compressive, flexural, and indirect tensile strengths) of concrete mixtures containing waste glass content as coarse aggregate replacement as the glass content increases. Results obtained by Olofinnade et al. (2017a) show a similar decreasing tendency for compressive and tensile strengths. However, it was found that 25% waste glass could be incorporated as a coarse aggregate replacement in concrete to improve the compressive strength of the concrete. Park, Lee, and Kim (2004) reported that the strength properties of concrete containing waste glass as fine aggregate exhibited a decreasing tendency with increasing waste glass content. A study by Olofinnade, Ndambuki, Ede, and Olukanni (2016b) recommended the use of combined fine and coarse glass aggregate by up to 25% content in concrete.

In addition, Ismail and Al-Hashmi (2009) opined that the observed low strength in glass concrete could be attributed to the weak adhesive bond between glass aggregate and the cement paste. Previous works have also reported the use of waste glass in finely powdery form as a partial substitute for Portland cement in concrete. From previous studies, it was reported that ground glass possesses pozzolanic capability at particle sizes below 100 µm, and its addition to concrete and mortar mixes has the capacity to enhance the strength development of concrete, increase resistance to sulphate attack and chloride ion penetration (Afshinnia & Rangaraju, 2015; Chen, Wu, & Yang, 2006; Idir, Cyr, & Tagnit-Hamou, 2011; Kara, Csetényi, & Borosnyói, 2016; Khmiri, Samet, & Chaabouni, 2012; Schwarz & Neithalath, 2008). In addition, Metwally (2007) opined that finely milled waste glass have a significant influence on the mechanical properties of concrete at much

later ages. A study by Shao, Lefort, Moras, and Rodriguez (2000) reported the feasibility of using crushed waste glass powder as a high-volume cement replacement in concrete. It was emphasized in their study that finely ground glass powder exhibited pozzolanic behaviour at particle size finer than 38 µm, and the pozzolanic activity could further be improved if the glass powder can be finer below 38 µm. Furthermore, studies by Khmiri et al. (2012) reported that glass powder having a particle size of about 20 µm improves its pozzolanic activity. A study by Olofinnade, Ede, and Ndambuki (2017b) mentioned that finely ground glass powder can be effectively deployed as inert material in the production of concrete with improved strength and better resistance to elevated temperature.

Several research studies have reported the limitations on the use of glass aggregate in concrete, which is the susceptibility of the glass aggregate material to chemical attack under high alkali environment from the hydrated cement paste in concrete or mortar resulting in the formation of alkali-silica reaction (ASR) gel. The reactive silica in glass interacts with the alkalis in the concrete pores to form a gel, and when this gel absorbs water it swells resulting in concrete instability and cracking. However, studies have reported some positive outcomes on mitigating the effect of ASR gel that occur due to the interaction between the alkalis in the pore solution of cement concrete and amorphous silica in the waste glass. These includes the use of pozzolanic materials or supplementary cementitious materials (SCM) as pozzolanic admixtures and low alkali cement in concrete, using lithium compounds in the concrete mixtures and crushing the glass into fine powder of at least 100 µm or less (Afshinnia & Rangaraju, 2015; Carsana, Frassoni, & Bertolini, 2014; Meyer, Egosi, & Andela, 2001; Tan & Du, 2013). For instance, a recommendation of 20% fly ash and 2% lithium compounds was suggested by the study of Topcu, Boga., and Bilir (2008) as a replacement to mitigate the expansion caused by ASR in waste glass mortars. Furthermore, according to Meyer et al. (2001), the deleterious effects of ASR in concrete can also occur in conventional concrete produced from natural aggregate containing reactive silica. The aim of this study is to investigate the feasibility of sustainable reuse of waste glass crushed into fine aggregate size as a replacement for sand in the production of moderate strength concrete.

2. Test programme

The proportions of the materials used to produce the concrete mixture in this study are presented in Table 1. The proportion details the percentage proportion of the concrete constituents wherein the recycled waste glass sand aggregate was used to substitute the natural sand for each concrete mixture except the control.

2.1. Materials

All concrete materials used in this current study were locally sourced. Typical ordinary Portland cement which complied with ASTM Type I cement suitable for general purpose construction was used. The chemical composition of the cement was determined according to ASTM C114 (2015)

Table 1. Percentage proportions of concrete constituents

Mix No.	Material Type	Binder Material	Aggregate Materials		
		Cement	Natural Sand	Natural Granite	Glass sand (FWG)
Control	Natural aggregate	100%	100%	100%	0
25% -FWG	Crushed glass aggregate materials	100%	75%	100%	25%
50% -FWG		100%	50%	100%	50%
75%-FWG		100%	25%	100%	75%
100%-FWG		100%	0%	100%	100%

using X-ray fluorescence (XRF). The chemical composition and physical properties of the cement are shown in Table 2. The waste glass was collected from different waste disposal sites and glass workshops within the environment of Ota, Nigeria. The collected glass waste contains majorly flat glass (windows) and container glass. After collection of the glass wastes, the glasses were soaked in water, then the glasses were washed and air dried openly. The essence of this was to remove contaminants, paper and plastic labels, metals, and dirt before crushing the glass to the required particle sizes. Figure 1 (a) and 1(b) show an example of the glass type and particle sizes used in this current study. The chemical composition of the waste glass was determined using the X-ray fluorescence (XRF) and is presented in Table 3. Visual comparison of the used river sand and crushed glass materials is shown in Figure 1(a), 1(b) and 1(c). The natural fine and coarse aggregate used during this research work were commercially obtained. The natural sand of 4.75 mm maximum particle size having its particle size grading conforming to ASTM C136 (2014), while the gravel having a maximum size of 19 mm was used in this study. The physical properties of both the crushed waste glass, sand and gravel aggregate materials are presented in Table 4. The particle size gradation for the glass sand, natural sand and gravel aggregate were carried out using sieve analysis and are presented in Figure 2.

The metallic oxides composition of the cement as presented in Table 2 shows the alkali compound of the Portland cement was 0.18%, estimated from $Na_2O_{eq} = Na_2O + 0.658K_2O$ indicating that the cement contains a low-alkali content. The chemical composition clearly depicts the cement material having a high percentage of CaO content. The results of the chemical composition of the crushed waste glass particles show that the glass has a high percentage of silica (SiO_2) content and sodium compound, which indicate the glass material to be soda-lime (Table 3). The sieve analyses performed to analyse the particle size distribution of the materials are presented in Figure 2. The sieve plots for the natural aggregate shows a consistent gradation of the particle size distribution, while the gradation curve for the waste glass fine aggregate also shows a very similar uniform gradation of particle size distribution

Table 2. Chemical composition and physical properties of cement

Chemical composition	Weight (%)	Physical properties	
SiO ₂	19.38	Fineness (m ² /kg)	358
Al ₂ O ₃	4.14	Specific gravity	3.15
Fe ₂ O ₃	3.19	Soundness (%)	0.52
CaO	56.92	Setting time	
MgO	2.44	Initial (min)	68
SO ₃	1.59	Final (min)	473
K ₂ O	0.21		
Na ₂ O	0.04		
TiO ₂	0.21		
P ₂ O ₅	0.28		
Mn ₂ O ₅	0.04		
Cr ₂ O ₃	0.02		
Na ₂ O _{eq} = Na ₂ O + 0.658K ₂ O	0.18		
Major compounds (Bogue's equation)			
C ₃ S	47.7		
C ₂ S	19.4		
C ₃ A	5.6		
C ₄ AF	9.7		

Figure 1. Aggregate materials used: (a) Waste glass material, (b) Crushed waste glass sand (FWG) and (c) Natural sand.

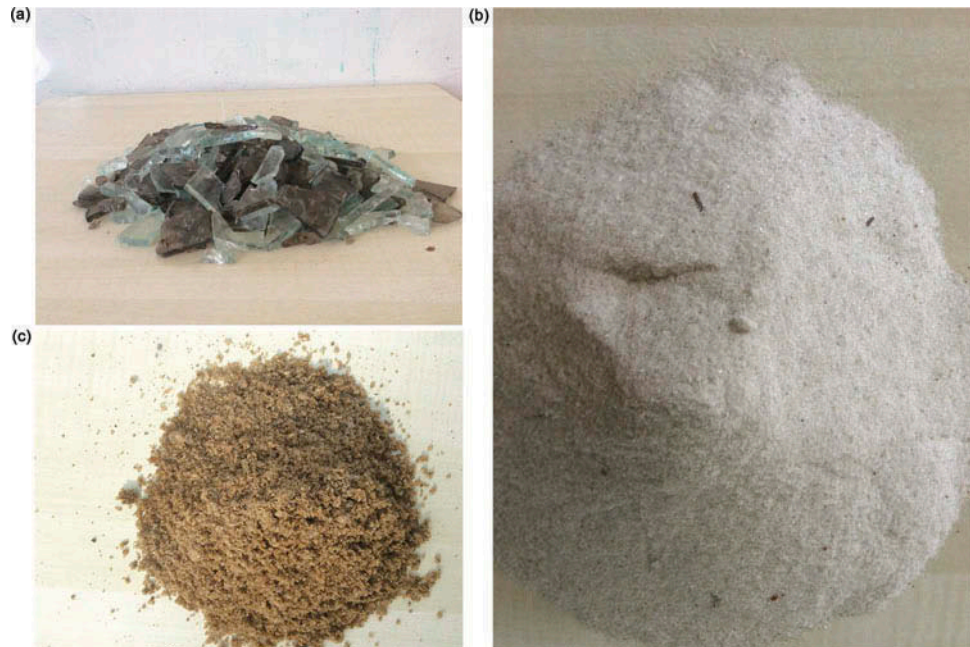


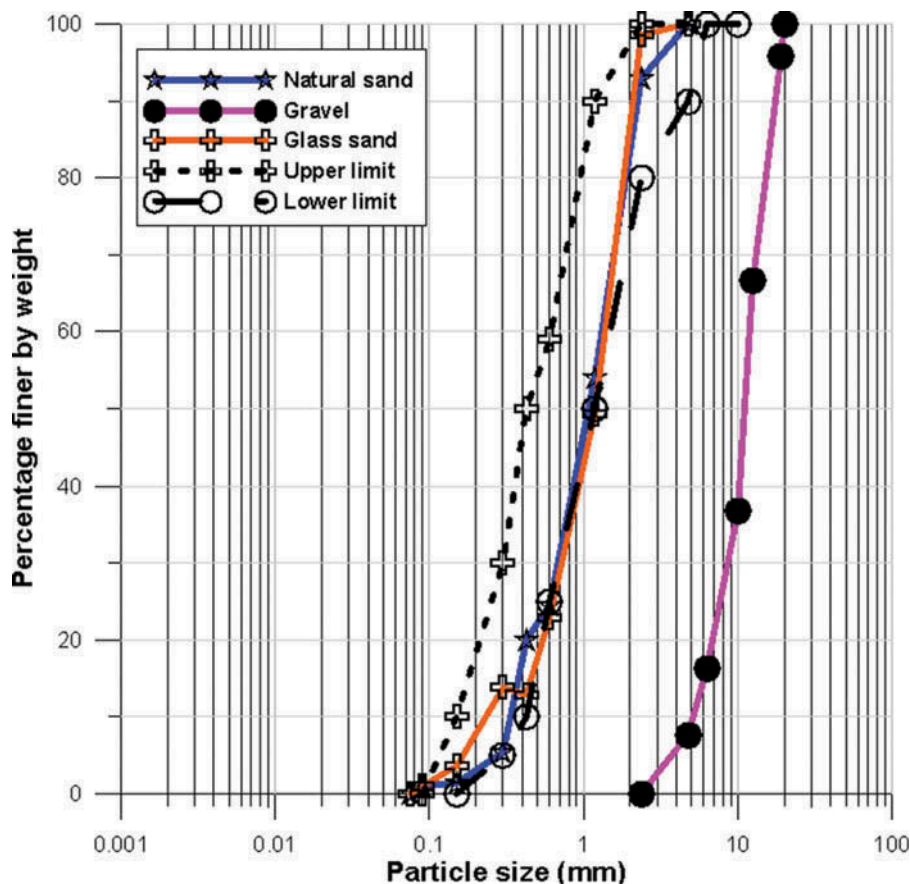
Table 3. Chemical composition and physical properties of waste glass

Composition	Weight (%)	Physical properties	
SiO ₂	64.31	Fineness Modulus	2.99
Al ₂ O ₃	19.98	Specific gravity	2.50
Fe ₂ O ₃	6.25	Water absorption (%)	0.40
CaO	10.61	Colour	Light grey
MgO	0.63	Density (kg/m ³)	1680
SO ₃	0.25		
K ₂ O	0.74		
Na ₂ O	12.52		
TiO ₂	0.61		
Cr ₂ O ₃	0.02		
Loss on ignition	1.47		

Table 4. Physical properties of sand and gravel stone materials

Properties	Natural material	
	Sand	Gravel
Fineness Modulus	2.69	5.30
Specific gravity	2.62	2.70
Density (kg/m ³)	1899	1683
Max size (mm)	4.75	19
Water absorption (%)	0.42	0.25
Aggregate Impact value (AIV) %	-	10
Aggregate Crushing value (ACV) %	-	24

Figure 2. Sieve analysis for natural sand, gravel and glass sand.



and compared well with the River sand used for the concrete production. Results of the sieve analyses indicate that the crushed glass sand particles can be used to substitute sand materials or blend with the sand materials.

2.2. Experimental procedure

2.2.1. Concrete mix proportioning

In this study, two types of concrete mixtures were prepared. The first mixture, which is the control mixture, comprises of sand and gravel aggregate, Portland cement and water combined at a water-binder (w/b) ratio of 0.5 to produce the plain concrete used for this study. The other mixture comprise of glass sand (FWG) as both partial and complete substitute for the natural sand in percentage dosages of 25, 50, 75 and 100% with the same amount of cement, gravel and the constant water-binder ratio of 0.5 as in the reference mixtures. Table 5 gives a summary of the concrete mixture proportioning used. All mixtures were batched by weight, using a proportioning ratio of 1:2:4 (cement: sand: gravel) to gives a 28-day target strength of 20 MPa for a moderate strength concrete. Mixing of concrete was carried out in accordance with BS 1881-125 (2009). Workability of all freshly prepared concrete mixes was determined through the slump test in accordance with BS EN 12350-2 (2009).

2.2.2. Preparation and testing of concrete specimens

Prior to casting, all the walls of the steel moulds were lubricated with oil to prevent concrete adhesion and water loss so as to ensure smooth demoulding of the concrete specimens. Cubes of dimension 150 × 150 × 150 mm and cylinders of 100 mm × 200 mm in height were cast in three layers in the moulds and compacted using a vibrating table for about 1 min to remove air bubbles.

Table 5. Concrete mixes used for this study

Mixtures		Binder (kg/m ³)	Aggregate (kg/m ³)			Water (kg/m ³)	Water to Cement ratio (w/c)
		Cement	Waste glass sand	Gravel	Sand		
Control	100% CA	275	0	1100	550	138	0.5
Glass sand— FWG	25%FWG	275	137.5	1100	412.5	138	0.5
	50%FWG	275	275	1100	275	138	0.5
	75%FWG	275	412.5	1100	137.5	138	0.5
	100%FWG	275	550	1100	0	138	0.5

The concrete specimens were removed from the moulds after 24 hours and to ensure good identification, each specimen was properly marked. All concrete specimens were immediately submerged in potable water for curing at room temperature and tested for compression and splitting tensile strengths at curing ages of 3, 7, 28 and 90 days. The compression and splitting tensile strengths were carried out in accordance with BS EN 12390 (2009) using YES-2000 compression machine (Figure 3), and the average compression strength of three specimens was recorded for each testing age. The microstructural examination was conducted on fractured surfaces of concrete selected from the tested specimens. A small fractured concrete specimen was mounted on the scanning electron microscope (SEM) brass stubs, no coating or polishing was applied on the specimen surfaces. The microstructural examination was performed on concrete specimens using the Phenom ProX scanning electron microscope machine. A summary of the test programme used is shown in Figure 4. The figure depicts a summary of the laboratory tests carried out on the concrete specimens containing FWG. All samples preparation, casting, and testing were conducted at the Structures and Material Laboratory of the Department of Civil Engineering, Covenant University, Ota, Ogun state.

3. Results and discussion

3.1. Properties of fresh concrete: workability

The test results for the slump recorded for the control and mixes containing fine glass sand at different proportion are shown in Figure 5. The results show the initial true slump value of 55 mm for the control mix, while the mixtures containing waste glass sand show a reduction tendency in slump ranging from 9% to 27% in response to the increases in the waste glass content. The decrease shows a strong correlation value of $r = -0.97$. Slump is used to determine the consistency of concrete mixtures. The decrease in the consistency of concrete with increasing glass content may be as a result of the grain shape and angular geometry of the waste glass particles, which reduces the amount of cement paste and hence reduces the fluidity of the concrete mixtures. Such findings were also reported by Ismail and Al-Hashmi (2009) as well as Adaway and Wang (2015). The slump result clearly depicts that concrete mixes containing glass sand would require more water content than traditional normal concrete mix to produce similar workability as observed by Polley, Cramer, and De La Cruz (1998). However, in spite of the observed reduction in the measured slump results, all sample mixes were considered to have good workability.

3.2. Mechanical properties of concrete

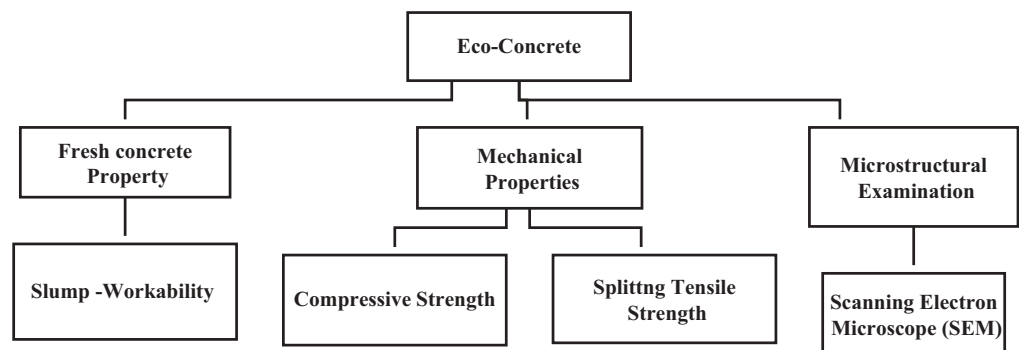
3.2.1. Compressive strength

Figure 6 illustrates the compressive strength variation of control concrete and glass sand concrete for curing periods of 3, 7, 28 and 90 days, respectively. The results clearly indicate that the use of

Figure 3. Compression machine used for this study.

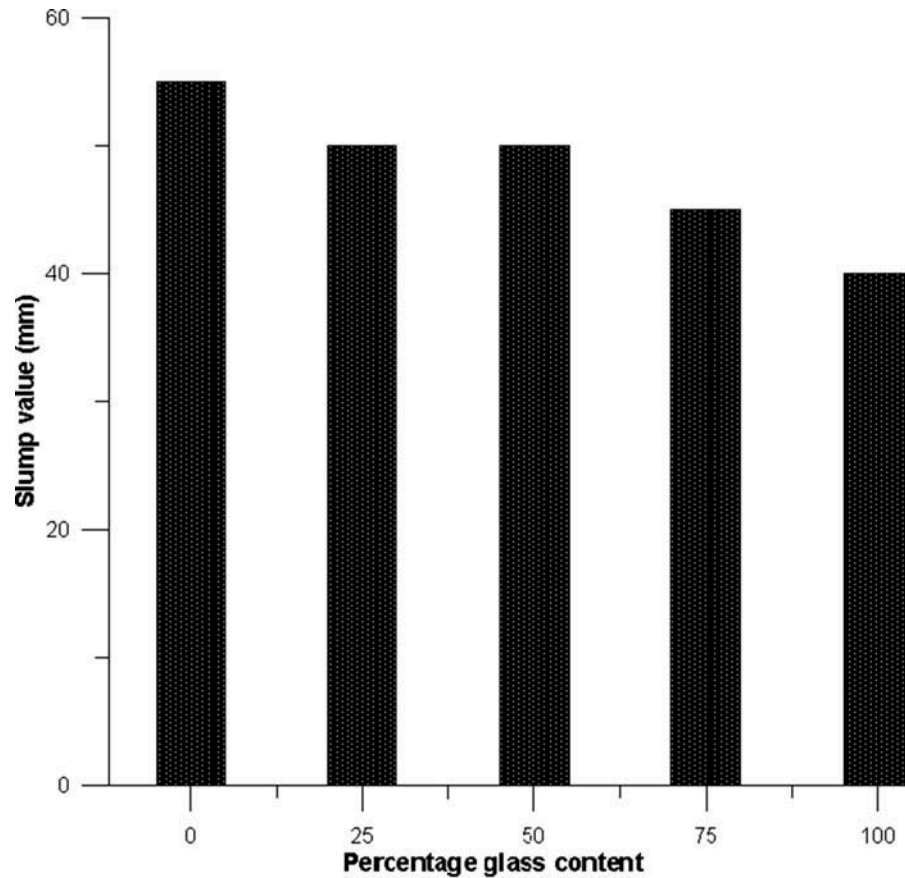


Figure 4. Test programme for concrete with crushed glass sand.



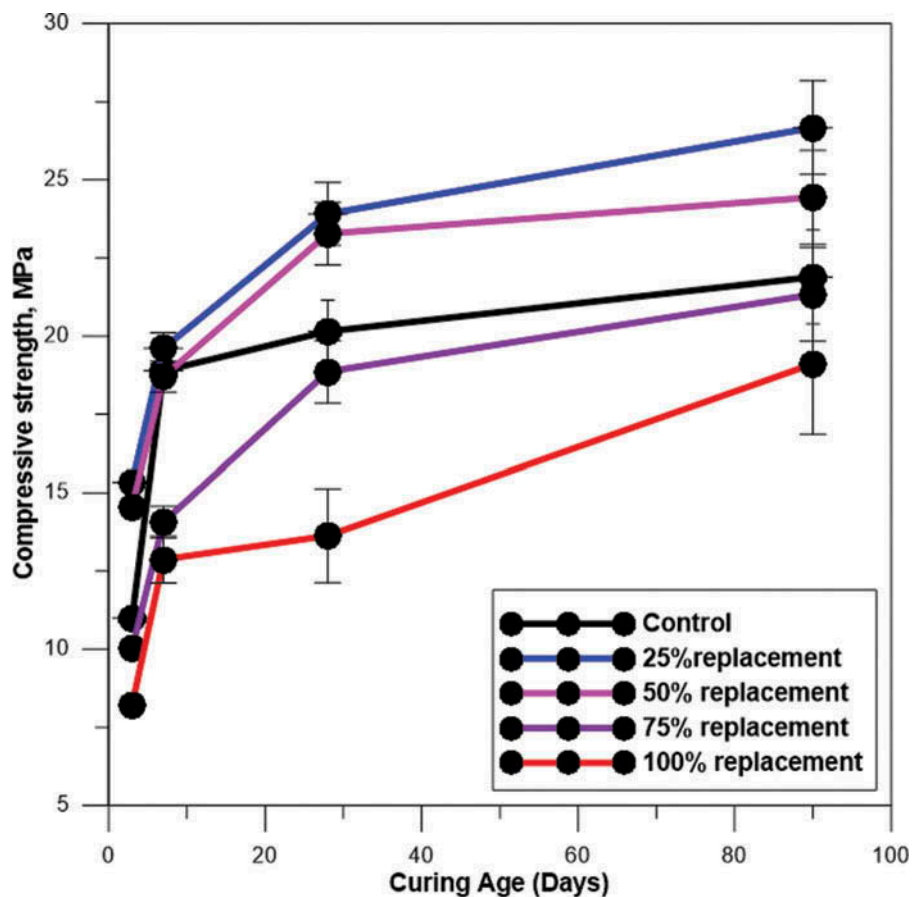
glass sand as a substitute for natural sand in concrete led to a reduction in the compressive strength as the percentage glass content increases beyond 50% replacement compared to the control. The decrease in compressive strength at both 28 days and 90 days of curing has correlation values of $r = -0.69$ and -0.60 , respectively. However, from the result, concrete containing 25%

Figure 5. Variation of concrete slump with increasing waste fine glass aggregate content.



glass content showed an increase in compressive strength from the early curing age of 3 days to 90 days. Moreover, concrete containing 50% glass content also showed comparable strength as those of the control concrete for all curing ages. The concrete mix containing 25% and 50% glass content as sand replacement achieved a 28-day compressive strength value of 23.9 and 23.3 MPa, respectively (20% higher than that achieved by the control). After 90 days of curing, the compressive strength increased by about 10% (26.67 MPa) and 4% (24.44 MPa) for 25% and 50% glass content, respectively. Meanwhile, concrete produced with 75% and 100% glass content showed the least compressive strength, achieving a 28-day and 90-day compressive strength values of 18.86 and 21.33 MPa, respectively for 75% glass replacement (about 6% and 3% lower than the strength achieved by the control). For 100% glass replacement, the 28-day and 90-day compressive strength values were 13.63 and 19.11 MPa, respectively (32% and 13% lower than that achieved by the control). The decrease in the compressive strength can be attributed to weaker bond and poor adhesion that developed at the Interfacial Transition Zone (ITZ) between the crushed glass particles and cement paste due to the smooth surface and angular shaped edges of the glass particles. The interaction between aggregates and cement paste in concrete at the Interfacial Zone is vital to the strength development of concrete. This is because the ITZ dominates the mechanical properties of the concrete as reported by Tan and Du (2013). Poorly bonded concrete mix at the ITZ usually results in a lower compressive strength (Afshinnia and Rangaraju, 2016). It should, however, be noted that concrete containing 75% glass sand (FWG) was able to achieve comparable strength with the control (achieving the target strength of 20 MPa after 90 days of curing). However, the optimum influence observed from the test results is at 25% natural sand substitute with blended glass particles (FWG) where the recorded characteristic compressive strength values at both early and later ages achieved 20% and 10% increase, respectively when compared with the control. The improved compressive strength value may be

Figure 6. Strength development of glass concrete with curing age at different percentage replacement.

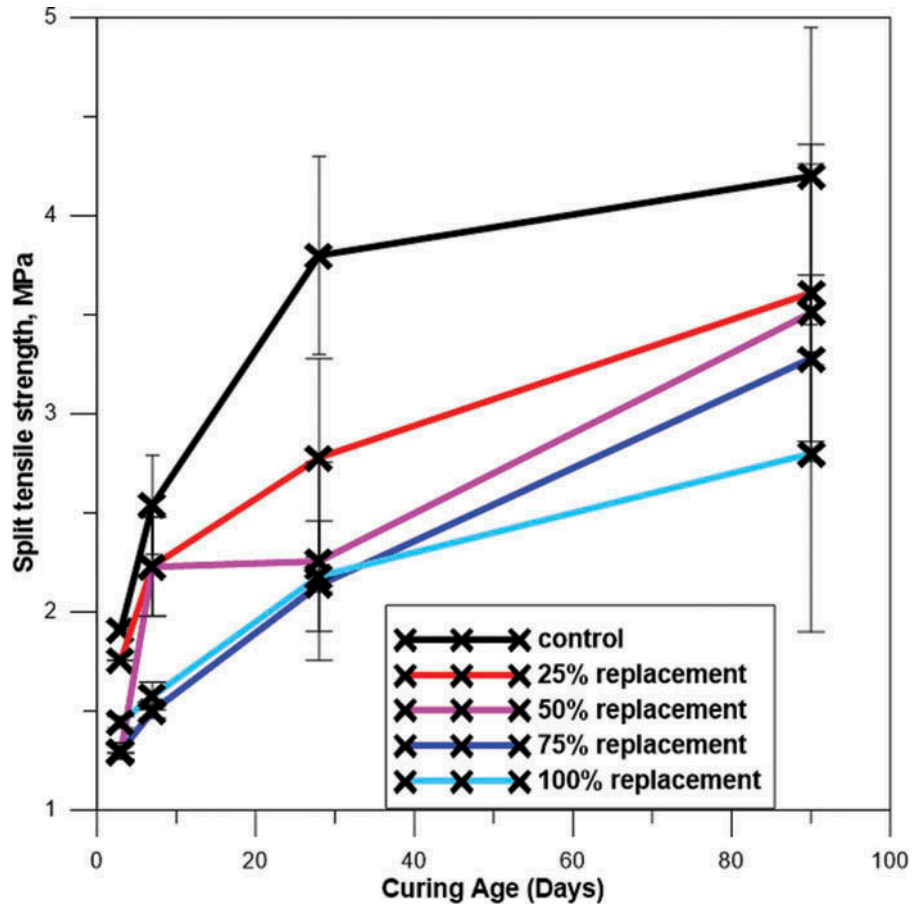


attributed to the geometry of the glass sand having increased surface area than the rounded natural sand particles which enables a greater bonding with the cement paste resulting in a much more improved concrete. The enhanced compressive strength, especially at later curing ages, can also be attributed to the influence of pozzolanic reaction. A similar pozzolanic effect was reported by Ismail and Al-Hashmi (2009). Moreover, Figure 6 also clearly shows the strength development of the concrete for the different percentage increase and at different curing ages. As expected, the strength development of all concrete mixtures including the control increased with age. The failure pattern of concrete cubes specimen containing glass content was observed to be similar to that of conventional concrete cubes that have its failure line typically parallel to the direction of the applied load (Figure 8 (a)).

3.2.2. Splitting tensile strength

The splitting tensile strength test results are presented in Figure 7 for various curing ages. The recorded splitting tensile strengths for the glass sand concrete varied between 2.18 MPa and 2.78 MPa at 28 days curing; being lower than 3.80 MPa recorded for control. Moreso, Figure 7 depicts the split tensile strength results at 90 days of curing to be between 2.8 MPa and 3.61 MPa, which is lower than the 4.20 MPa achieved at 90 days for the control. The observed test results clearly indicate that the increase in the proportion of glass sand content in the concrete mixes led to the decrease in the split tensile strength of the concrete, which may be attributed to the decrease in the adhesive strength of the glass sand concrete as the proportion of the glass content increases. Furthermore, the decrease in strength may also be as a result of the nonhomogeneous distribution of the aggregates owing to glass shape and geometry. A similar decrease in splitting strength was observed by Zhao, Poon, and Ling (2013). The decrease in tensile strength could be attributed to the weaker adhesive bond between the glass particles and binding paste as the proportion of the

Figure 7. Splitting tensile strength development of glass concrete with curing age at different percentage replacement.

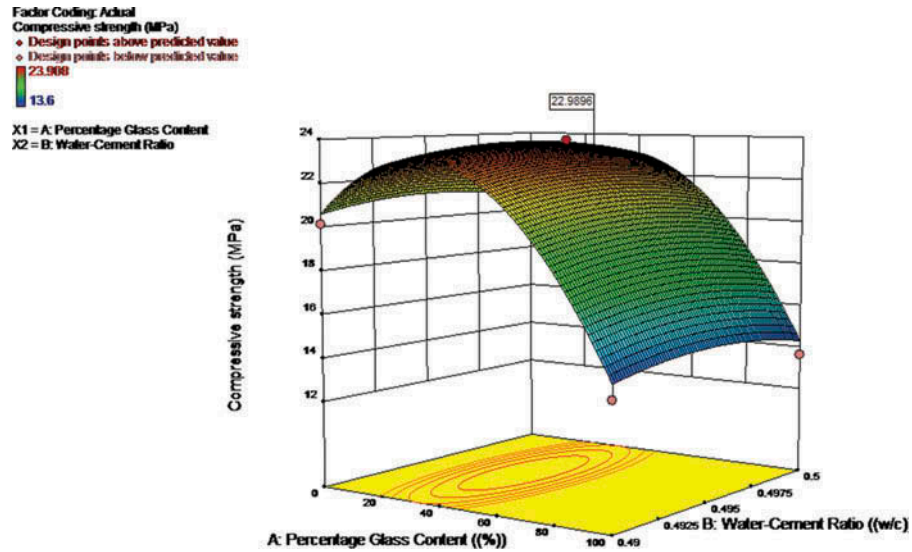


glass content increases. However, a lesser decrease in split tensile strength was observed for the concrete with 25% sand replacement, implying that the maximum influence is exhibited at 25% partial sand replacement with glass sand. But, further increase beyond the 25% reduced the tensile strength of the glass concrete. This implies that glass particles have a significant influence on the tensile strength development of the concrete, especially at higher percentage replacement. Figure 7 also depicts an increase in tensile strength of the concrete mixtures for both control and glass concrete specimens with curing age. However, a significant influence was observed to be at 25% partial natural sand replacement with glass sand. The observed splitting failure was through the middle as shown in Figure 8(b).

Figure 8. (a) Failure pattern of cube sample (b) Failure pattern of cylinder sample.



Figure 9. Response surface plot of compressive strength of glass sand concrete.



The obtained results clearly suggest that glass sand cannot be used to produce eco-friendly concrete by using more than 50% glass sand as a substitute for natural sand in order to ensure the production of moderate strength concrete of at least 20 MPa for structural application. Moreover, the results ascertain that percentage glass content in the range of 20–50% improved concrete strength as corroborated in Figure 9. The response surface plot for the compressive strength indicates that the significant effect of the glass content on the concrete strength is at the range of 20–40% replacement. The response surface plot for the variables shows that the compressive strength decreases with the increase of FWG contents for all w/c ratios and curing ages. This clearly indicates that glass content has a more significant effect on the strength development of the concrete. An optimum mix was developed so as to determine the best characteristic compressive and split tensile strengths, and also taking note of the concrete durability by limiting the quantity of glass content to less than 25% in the concrete mix. Figures 10 and 11 show the results

Figure 10. Optimized response surface of compressive strength of glass sand concrete.

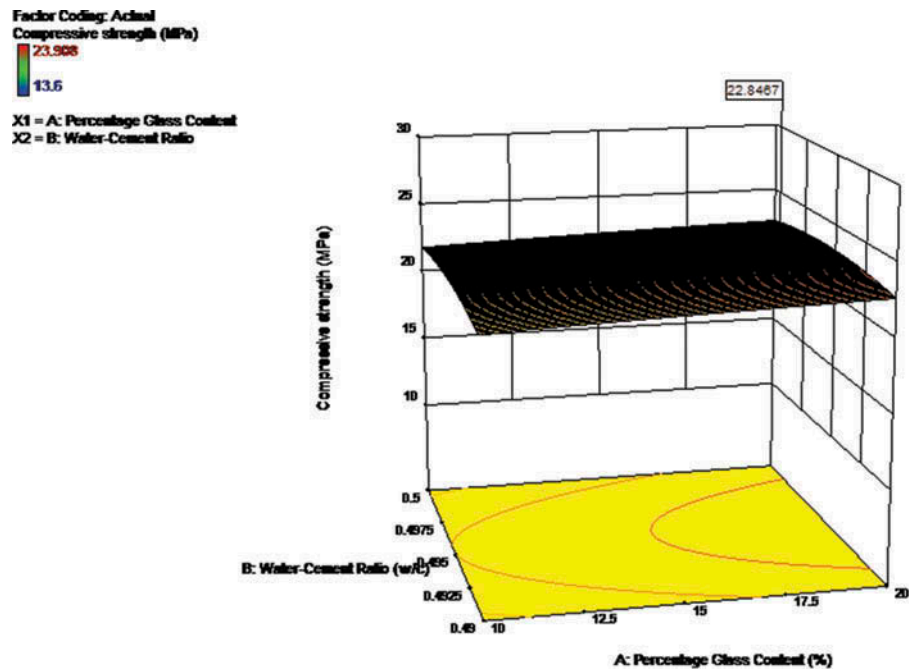
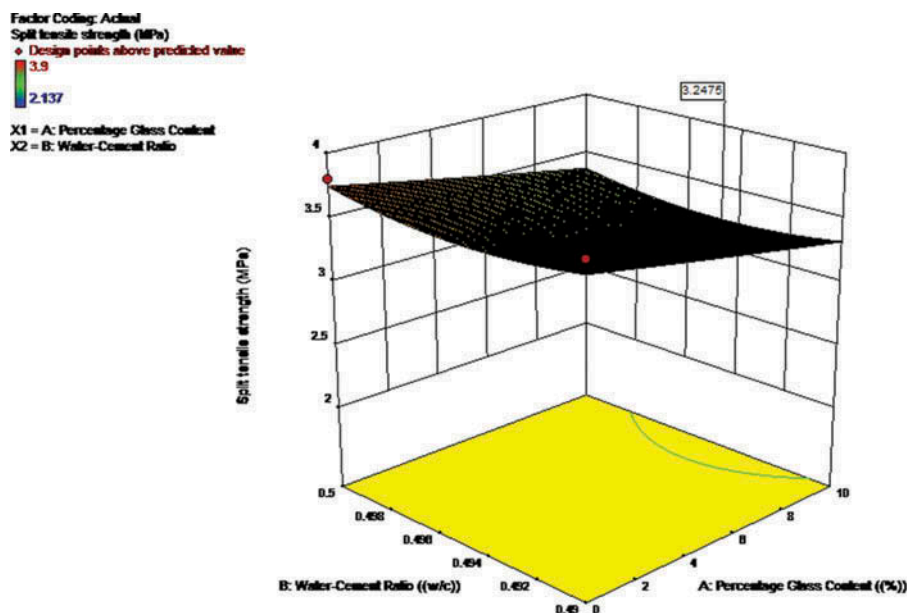


Figure 11. Optimized response surface of split tensile strength of glass sand concrete.



of the numerical optimization tests, which were carried out at 95% confidence prediction and desirability value of 0.8. The optimization results revealed that a mix proportion of 100% cement, 100% gravel, 80% natural sand, 20% glass sand and water cement ratio of 0.5 would give a compressive strength of 22.87 MPa and splitting tensile strength of 3.25 MPa after 28 days of curing.

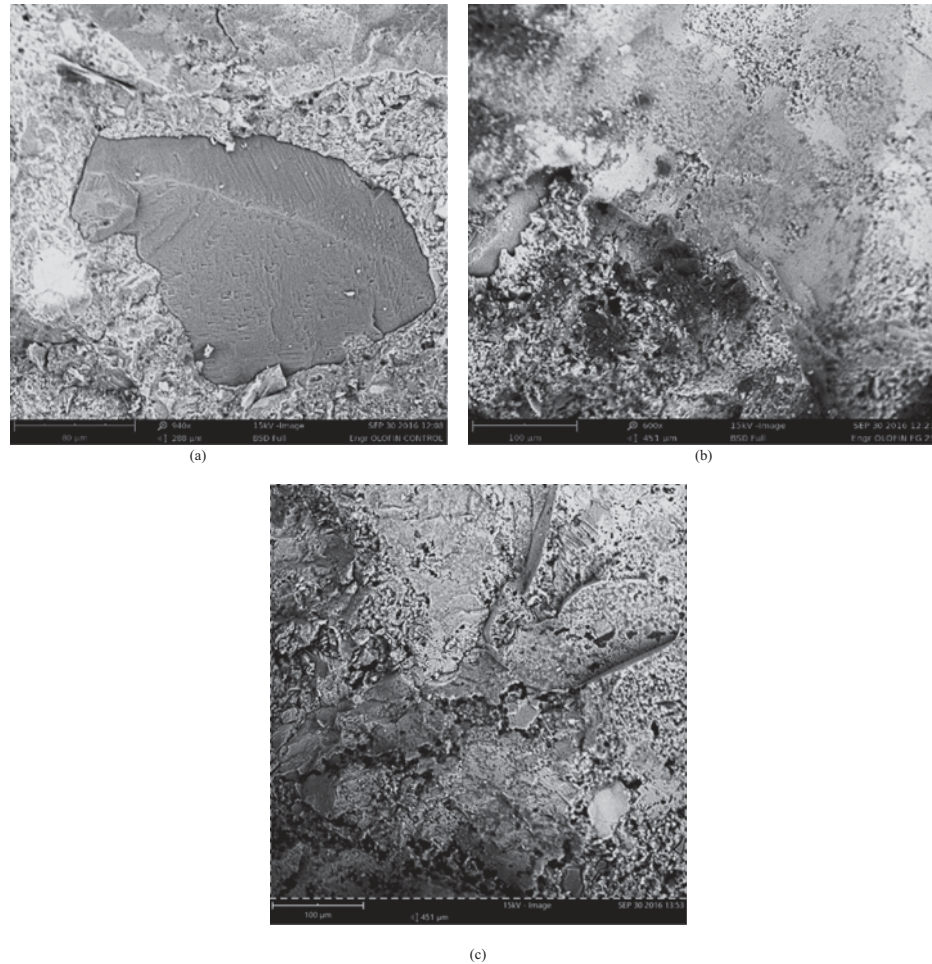
4. Scanning electron microscopy (SEM)

The microstructural examination of selected samples was conducted to analyse the bond between the concrete aggregate and cement paste at the microscopic level. Mindess, Young, and Darwin (2003) reported that the bonding between the aggregate and binder is considered vital for better transfer of stresses between the binder and aggregates especially at the interfacial zone, which influences the concrete strength. The SEM analyses were conducted on selected concrete samples cured for 28 days. Figure 12(a) shows the SEM micrograph taken on the fractured surface of concrete without glass sand aggregate. It shows a well-developed aggregate–cement paste interface and the hydration product having a structure with no pores and cracks. However, Figure 12(b) and 12(c) show the SEM images taken from the fractured surfaces of the concrete samples containing 25% and 100% glass sand aggregate (FWG) as a natural sand replacement, respectively. The SEM view of concrete containing 25% FWG shows compact microstructure like the control, however, very few voids can be seen but no cracks (see Figure 12b). But the SEM micrograph for the 100% FWG clearly shows a microstructure with many pores, which may be as a result of the angular grain shape and smooth surface of the waste glass sand particles resulting in poor bond formation especially at the interfacial zone (Figure 12(c)). According to Ollivier, Maso, and Bourdette (1995) and Mindess et al. (2003), it was mentioned that the concrete strength at the interfacial zone is significantly influenced by factors like the surface roughness of the aggregate, using inert micro-fillers and chemical reaction between the cement paste and aggregate. The SEM result also shows a nonhomogeneous concrete paste owing to the glassy texture of the glass particles surface. This explains the low results recorded for both the compressive and tensile strengths at 28 days especially at higher replacement dosages of glass sand.

5. Conclusions

The following conclusions can be drawn from this research:

Figure 12. (a) SEM micrograph on control concrete specimen. (b) SEM micrographs on concrete specimen containing 25% glass sand particles. (c) SEM micrographs on concrete specimen containing 100% glass sand particles.



- (i) The slump of the freshly produced concrete specimens decreases as the percentage of waste glass sand content increases. The reduction shows a strong correlation value of $r = 0.97$ which suggest that the fresh mixes show a decreasing tendency in workability as the waste glass content increases. This is believed to be caused by the grain shape of the waste glass sand particles.
- (ii) A significant decrease in the compressive and split-tensile strengths of the waste glass sand concrete was observed as the proportion of waste glass content increased from 50% to 100% natural sand replacement. This could be attributed to the weaker bond that develops between the waste glass sand particles and binding cement paste occasioned by the angular nature of the glass at the interfacial zone.
- (iii) Concrete produced with both 25% and 50% waste glass sand content as direct substitute for natural sand shows good improvement in compressive strength higher than the control at both 28 and 90 days of curing age. The optimum percentage with the highest compressive strength value is 25%.
- (iv) The SEM examination clearly revealed poor contact bond between the crushed glass sand and cement matrix as evident by the increase in voids as the glass content increased in the concrete mixtures. This is caused by the weak bond between the glass sand particles and cement paste due to the smooth surface of the glass particles especially at the interfacial zone resulting in weak adhesion and low strength.

- (v) From the research findings, it is evident that sustainable eco-friendly concrete can be produced with waste glass sand blended with natural sand in concrete mixes up to 50% natural sand replacement for structural application. However, it is recommended that the percentage of glass sand content should be limited to below 25%. The achieved results reveal that recycled waste glass can be utilized to produce sustainable concrete in order to rid the menace of glass waste in landfill sites. In addition, further study should be considered on its long-term effect in concrete.

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References

- Adaway, M., & Wang, Y. (2015). Recycled glass as a partial replacement for fine aggregate in structural concrete – Effects on compressive strength. *Electronic Journal of Structural Engineering*, 14, 116–122. Retrieved from <http://www.ejse.org/Archives/Fulltext/2015-1/2015-1-11.pdf>
- Afshinnia, K., & Rangaraju, P. R. (2015). Influence of fineness of ground recycled glass on mitigation of alkali-Silica reaction in mortars. *Construction and Building Material*, 81, 257–267. doi:10.1016/j.conbuildmat.2015.02.041
- Afshinnia, K., & Rangaraju, P. R. (2016). Impact of combined use of ground glass powder and crushed glass aggregate on selected properties of Portland cement concrete. *Construction and Building Material*, 117, 263–272. doi:10.1016/j.conbuildmat.2016.04.072
- Akinwumi, I. I., Awoyera, P. O., Olofinnade, O. M., Busari, A. A., & Okotie, M. (2016). Rice husk as a concrete constituent: Workability, water absorption and strength of the concrete. *Asian Journal of Civil Engineering*, 17, 887–898.
- Ali, E. E., & Al-Tersawy, S. H. (2012). Recycled glass as a partial replacement for fine aggregate in self-compacting concrete. *Construction and Building Materials*, 35, 785–791. doi:10.1016/j.conbuildmat.2012.04.117
- ASTM C114. (2015). *Standard chemical analysis of hydraulic cement*. West Conshohocken, PA: American Society for Testing and Materials International. doi:10.1520/C0114-15
- ASTM C136. (2014). *Standard test method for sieve analysis of fine and coarse aggregates*. West Conshohocken, PA: American Society for Testing and Materials International. doi:10.1520/C0136_C0136M-14
- Bamigboye, G. O., Ede, A. N., Raheem, A. A., Olofinnade, O. M., & Okorie, U. (2016). Economic exploitation of gravel in place of granite in concrete production. *Material Science Forum*, 866, 73–77. doi:10.4028/www.scientific.net/MSF.866.73
- British Standards Institute. (2009). *BS EN 12390-3: 2009. Testing hardened concrete; Part 3: Compressive strength of test specimens* (pp. 1–19). London: Author.
- British Standards Institute. BS 1881-125. (2009). *Testing concrete: Methods for mixing and sampling fresh concrete in the laboratory* (pp. 1–8). London: Author.
- British Standards Institute. BS EN 12350-2. (2009). *Testing of Fresh concrete; Part 2: Slump test* (pp. 1–12). London: Author.
- Calkins, M. (2009). *Materials for sustainable sites: A complete guide to the evaluation, selection, and use of sustainable construction materials*. Hoboken: Wiley. Retrieved from <http://eu.wiley.com/WileyCDA/WileyTitle/productCd-0470134550.html#see-less-rev>
- Carsana, M., Frassoni, M., & Bertolini, L. (2014). Comparison of ground waste glass with other supplementary cementitious materials. *Cement and Concrete Composites*, 45, 39–45. doi:10.1016/j.cemconcomp.2013.09.005
- Chen, C. H., Wu, J. K., & Yang, C. C. (2006). Waste E-glass particles used in cementitious mixtures. *Cement and Concrete Research*, 36, 449–456. doi:10.1016/j.cemconres.2005.12.010
- Chesner, W. H., Coollins, R. J., & Mackay, M. H. (1997). User guidelines for waste and byproduct materials in pavement construction. *US Administration*. Publication No. FHWA-RD, 97–148. doi:10.1016/j.cemconcomp.2012.08.028
- Ede, A. N., Olofinnade, O. M., Ugwu, E. I., & Salau, A. O. (2018). Potential of momordica angustisepala fiber in enhancing strengths of normal Portland cement concrete. *Cogent Engineering*, 5, 1431353. doi:10.1080/23311916.2018.1431353
- Federico, L. M., & Chidiac, S. E. (2009). Waste glass as a supplementary cementitious material in concrete – Critical review of treatment methods. *Cement and Concrete Composites*, 31, 606–610. doi:10.1016/j.cemconcomp.2009.02.001
- Idir, R., Cyr, M., & Tagnit-Hamou, A. (2011). Pozzolanic properties of fine and coarse color-mixed glass cullet. *Cement and Concrete Composites*, 33, 19–29. doi:10.1016/j.cemconcomp.2010.09.013
- Ismail, Z. Z., & Al-Hashmi, E. A. (2009). Recycling of waste glass as a partial replacement for fine aggregate in concrete. *Waste Management*, 29, 655–659. doi:10.1016/j.wasman.2008.08.012

- Jani, Y., & Hogland, W. (2014). Waste glass in the production of cement and concrete – A review. *Journal Environmental Chemical Engineering*, 2, 1767–1775. doi:10.1016/j.jece.2014.03.016
- Kara, P., Csetényi, L. J., & Borosnyói, A. (2016). Performance characteristics of waste glass powder substituting Portland cement in mortar mixtures. IOP Conference Series: Materials Science and Engineering. doi:10.1088/1757-899X/123/1/012057
- Khmiri, A., Samet, B., & Chaabouni, M. (2012). Assessment of the waste glass powder pozzolanic activity by different methods. *International Journal of Research and Reviews in Applied Sciences*, 10, 322–328. Retrieved from www.arpapress.com/volumes/vol10issue2/IJRRAS_10_2_18.pdf
- Kline, J., & Barcelo, L. (2012, May 14–17). Cement and CO₂, a victim of success! Cement Industry Technical Conference, IEEE-IAS/PCA, 53: 1–14, San Antonio, TX.
- Ling, T. C., Poon, C. S., & Wong, H. W. (2013). Management and recycling of waste glass in concrete products: Current situations in Hong Kong. *Resource, Conservation and Recycling*, 70, 25–31. doi:10.1016/j.resconrec.2012.10.006
- Matos, A. M., & Sousa-Coutinho, J. (2012). Durability of mortar using waste glass powder as cement replacement. *Construction and Building Material*, 36, 205–215. doi:10.1016/j.conbuildmat.2012.04.027
- Mehta, K. P., & Monteiro, P. J. M. (2006). *Concrete: Microstructure, properties, and materials* (3rd ed.). New York: McGraw-Hill.
- Metwally, I. M. (2007). Investigations on the performance of concrete made with blended finely milled waste glass. *Advances in Structural Engineering*, 10, 47–53. doi:10.1260/136943307780150823
- Meyer, C. (2009). The greening of the concrete industry. *Cement and Concrete Composites*, 31, 601–605. doi:10.1016/j.cemconcomp.2008.12.010
- Meyer, C., Egozi, N., & Andela, C. (2001, March 19–20). Concrete with waste glass as aggregate; in Recycling and reuse of glass cullet. In *Proceedings of the international symposium on Recycling and Reuse of Glass Cullet Organised by the Concrete Technology Unit, University of Dundee and Held at the University of Dundee, UK* (pp. 179–187).
- Mindess, S., Young, F. J., & Darwin, D. (2003). *Concrete* (2nd ed.). New Jersey: Prentice Hall.
- Ollivier, J. P., Maso, J. C., & Bourdette, B. (1995). Interfacial transition zone in concrete. *Journal of Advance Cement Based Material*, 2, 30–38. doi:10.1016/1065-7355(95)90037-3
- Olofinnade, O. M., Ede, A. N., & Ndambuki, J. M. (2017a). Sustainable green environment through utilization of waste soda-lime glass for production of concrete. *Journal of Material and Environmental Sciences*, 8, 1139–1152. www.jmaterenvironsci.com/Document/vol8/vol8.../121-JMES-2709-Olofinnade.pdf
- Olofinnade, O. M., Ede, A. N., & Ndambuki, J. M. (2017b). Experimental investigation on the effect of elevated temperature on compressive strength of concrete containing waste glass powder. *International Journal of Engineering and Technology Innovation*, 7(4), 280–291.
- Olofinnade, O. M., Ede, A. N., Ndambuki, J. M., & Bamigboye, G. O. (2016a). Structural properties of concrete containing ground waste clay brick powder as partial substitute for cement. *Material Science Forum*, 866, 63–67. doi:10.4028/www.scientific.net/MSF.866.63
- Olofinnade, O. M., Ndambuki, J. M., Ede, A. N., & Booth, C. (2017c). Application of waste glass powder as a partial cement substitute towards more sustainable concrete production. *International Journal of Engineering Research in Africa*, 31, 77–93. doi:10.4028/www.scientific.net/JERA.31.77
- Olofinnade, O. M., Ndambuki, J. M., Ede, A. N., & Olukanni, D. O. (2016b). Effect of substitution of crushed waste glass as partial replacement for natural fine and coarse aggregate in concrete. *Material Science Forum*, 866, 58–62. doi:10.4028/www.scientific.net/MSF.866.58
- Park, S. B., Lee, B. C., & Kim, J. H. (2004). Studies on mechanical properties of concrete containing waste glass aggregate. *Cement and Concrete Research*, 34, 2181–2189. doi:10.1016/j.cemconres.2004.02.006
- Polley, C., Cramer, S. M., & De La Cruz, R. V. (1998). Potential for using waste glass in Portland cement concrete. *Journal of Materials in Civil Engineering*, 10, 210–219. doi:10.1061/(ASCE)0899-1561(1998)10:4(210)
- Rashad, A. M. (2014). Recycled waste glass as fine aggregate replacement in cementitious materials based on Portland cement. *Construction and Building Materials*, 72, 340–357. doi:10.1016/j.conbuildmat.2014.08.092
- Schwarz, N., & Neithalath, N. (2008). Influence of a fine glass powder on cement hydration: Comparison to fly ash and modeling the degree of hydration. *Cement and Concrete Research*, 38, 429–436. doi:10.1016/j.cemconres.2007.12.001
- Shao, Y., Lefort, T., Moras, S., & Rodriguez, D. (2000). Studies on concrete containing ground waste glass. *Cement and Concrete Research*, 30, 91–100. doi:10.1016/S0008-8846(99)00213-6
- Shayan, A., & Xu, A. (2006). Performance of glass powder as a pozzolanic material in concrete, a field trial on concrete slabs. *Cement and Concrete Research*, 36, 457–468. doi:10.1016/j.cemconres.2005.12.012
- Shi, C., & Zheng, K. (2007). A review on the use of waste glasses in the production of cement and concrete. *Resources, Conservation and Recycling*, 52, 234–247. doi:10.1016/j.resconrec.2007.01.013
- Siddique, R. (2008). *Waste glass*. Chap. 4 in *Waste materials and by-products in concrete*. Springer. doi:10.1007/978-3-540-74294-4
- Sobolev, K., Turker, P., Soboleva, S., & Iscioglu, G. (2006). Utilization of waste glass in ECO cement, strength properties and microstructural observations. *Waste Management*, 27, 971–976. doi:10.1016/j.wasman.2006.07.014
- Sonebi, M. (2015, June 9–11). Embedded sustainability driven approach into construction. In *Proceedings of the first symposium knowledge exchange for young scientists (KEYS)* (pp. 25–30). ISBN 978-3-9817146-3-7.
- Tan, K. H., & Du, H. (2013). Use of waste glass as sand in mortar. Part I. Fresh, mechanical and durability properties. *Cement and Concrete Composites*, 35, 109–117. doi:10.1016/j.cemconcomp.2012.08.028
- Topcu, I. B., Boga, A. R., & Bilir, T. (2008). Alkali-silica reactions of mortars produced by using waste glass as fire aggregate and admixtures such as fly ash and Li₂CO₃. *Waste Management*, 28, 878–884. doi:10.1016/j.wasman.2007.04.005
- Topcu, I. B., & Canbaz, M. (2004). Properties of concrete containing waste glass. *Cement and Concrete Research*, 34, 267–274. doi:10.1016/j.cemconres.2003.07.003
- United States Environmental Protection Agency. (2014). *Advancing sustainable materials management: Facts and figures report*. Retrieved from <https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures>
- Zhao, H., Poon, C. S., & Ling, T. C. (2013). Utilizing recycled cathode ray tube funnel glass sand as river sand replacement in the high-density concrete. *Journal of Cleaner Production*, 51, 184–190. doi:10.1016/j.jclepro.2013.01.025



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