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Sustainable Green Environment through Utilization of Waste Soda-Lime Glass for Production of Concrete

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Keywords

- ✓ waste soda-lime glass,
- ✓ coarse aggregate,
- ✓ workability,
- ✓ compressive strength,
- ✓ split tensile strength

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Abstract

Recycling and reuse of waste materials remains a major option for waste reduction, preserving the natural resources from further depletion and reduction in greenhouse gases emission thereby contributing to sustainable green environment. In this study, focus on the reuse of waste soda-lime glass crushed into coarse aggregate sizes as a substitute for natural coarse aggregate in normal concrete was investigated. The variables in this study is coarse aggregate while the cement, sand and water-cement ratio were held constant. The crushed waste glass was varied from 0 – 100% in steps of 25% by weight to replace the coarse aggregate in the concrete mix. Concrete mixes were prepared using a mix proportion of 1:2:4 (cement: sand: granite) at water-cement ratio of 0.5 targeting a design strength of 20 MPa. Slump tests were carried out on fresh concrete mixes and tests were also carried out on total number of 60 concrete cube specimens of size 150 x 150 x 150 mm and 60 concrete cylinder specimens of dimension 100 mm diameter by 200 mm height after 3, 7, 28 and 90 days of curing. Results on the slump tests shows a decrease in the concrete workability as the glass content increases. Test results also indicated that the compressive and split tensile strength of the hardened concrete decreases with increasing waste glass content compared with the control. However, concrete mix made with 25% waste glass content compared significantly well with the control and can be suitably adopted for production of normal concrete.

1. Introduction

The utilization of waste glass in the concrete industry is one attractive option that could help in achieving the effective management of waste glass disposal in landfill sites thereby preventing environmental pollution. Moreover, the other benefits of reusing waste glass in the production of concrete include; the preservation of natural resources from further depletion, reduction of greenhouse gases emission and energy savings thereby achieving environmental greening and sustainability [1, 2]. Estimation by [3] that, yearly, concrete production consumes about 1.5 billion tonnes of cement, 9 billion tonnes of aggregate and 1 billion tonnes of water for mixing and [2] pointed out that this consumption rate has a huge impact on the environment resulting in depletion of natural resources, intensive energy consumption and greenhouse gases emission. Again, with the demand for concrete expected to increase by the year 2050 to about 18 billion tonnes owing to increasing construction activities, it can be inferred that concrete would hold great significance in the nearest future [2]. According to [4], sustainability has become a critical issue in the construction industry, especially sustainability of construction materials. Of recent, research efforts have been invested on using concrete as a means of managing solid waste, and from the studies of [5, 6, 7, 8], it was reported that concrete provide a real potential means of reusing large quantities of solid waste materials like glass, fly ash and rice husk as substitute for concrete constituents. Moreover, [9] reported that reusing of waste materials in the construction industry is among the most effective options to manage waste because a significant quantity of these waste materials can be reuse in concrete with or without high conditions of quality. Reusing waste glass in production of fresh concrete is attracting an increasing interest in recent years. According to [10], there is a steady increase in the quantity of waste glass generated in recent years due to continual production and usage of glass products and a huge part of this generated waste glass are dumped into landfill sites. Report by the Environmental Protection Agency on Municipal solid waste (MSW) pointed out that in the US, a large portion of the 11.5 million tonnes of waste glass generated are soda-lime glass produced mainly from container bottles, flat glasses and packages [11]. Glass is an amorphous material that contains relatively large quantities of silica and calcium. It is also a non-biodegradable material constituting a major problem to landfill operation. But EPA report of 2013 pointed out that although of recent there has being an increase in waste glass recycling but about 74% of waste glass collected is still being disposed in landfills and some of the difficulties faced are attributed to comingling of different coloured glasses at the source, cost and as well as challenges encountered in removing other chemical contaminants and residues from the waste glass stream [11]. Therefore, in order to find an environmental friendly solution in managing waste glass materials, extensive investigation has been carried out on the use of waste glass in concrete in the form of crushed granular or powdered material as a replacement for aggregate and Portland cement in concrete production [12–27].

However, the main limitation on the use waste glass as a granular aggregate in concrete production, in particular soda-lime glass is the problem of Alkali-Silica reaction (ASR), a major durability concerns in the construction industry. Alkali-silica reaction is caused by the reaction between the silica content in glass, or any reactive aggregates and the hydroxyl ions within the cement concrete in the presence of moisture [14,21]. It is a chemical interaction between alkalis in concrete and reactive siliceous aggregate and the reaction takes a long time before it manifest. Meyer et al. [28], opined that “the problem of ASR is not restricted to glass aggregate concrete, but can also occur in conventional concrete, if (according to the definition of ACI Committee 116) the aggregate contains “certain siliceous rocks and minerals, such as opaline chert, strained quartz, and acidic volcanic glass”. Moreover, in the case of glass, [2,20] reported that ASR occur due to the deleterious reaction between the alkalis in the cement pore solution and the silica of the glass. This reaction produced ASR gel, and when this gel absorbs water, its swell. The swelling of the gel result in instability or expansion and cracking of the concrete [2]. The vulnerability of glass as a granular aggregate material, to alkali-silica reaction (ASR) distress has been a major obstacle in the use of glass material in concrete, limiting its widespread use as a construction material [13,20]. Various studies have researched on methods of controlling the expansion and cracking of the glass concrete caused by ASR. It was reported that eliminating one of the elements of the reaction; namely silica reactive aggregate, alkali in cement and water can help mitigate its detrimental consequences [2, 20, 27, 28]. Various approaches have been investigated as a way of mitigating or suppressing the effect of alkali-silica reaction in glass concrete [2]. These approaches as highlighted by [2] includes; the introduction of lithium chemical compounds into the concrete mix; using low alkali cement; sealing the concrete to protect it from moisture; making the glass materials alkali-resistant; modifying the glass chemistry; grinding the glass into powder of at least 100 μm; and addition of supplementary cementitious materials (SCM) or mineral admixtures as pozzolanic material into the concrete mixture. Addition of suitable pozzolan in appropriate proportions such as silica fumes (SF), fly ash (FA), ground blast furnace slag (GBFS) or natural pozzolana; Metakaolin, or clay brick [20, 27] can suppress ASR. Finely ground glass powder can also be used to suppress ASR in glass aggregate concrete [29, 30]. Of recent, ground fired-clay brick powder has been investigated as a potential pozzolan to mitigate ASR in reactive aggregate [31]. Using pozzolan in concrete is the most prudent and cost effective method of mitigating alkali-silica reaction. However, [2,14,29,31] opined that the effectiveness of the pozzolan depends on reactivity, amount and size of aggregate material, environmental conditions, total alkali content of the concrete mixture and the amount and type of pozzolan used.

The purpose of this study is to investigate the effect of substituting granite with waste soda-lime glass crushed into coarse granular aggregate size on the workability, splitting tensile and compressive strength of the resulting concrete. Many Studies have investigated the effect on fresh concrete mix and mechanical properties of concrete containing crushed glass aggregate materials (15-19). Study by [17] that the colour of glass aggregate particles had no serious influence on the fresh and hardened properties of concrete rather that these properties are controlled by the physical characteristics of the glass particles. Study by [15] and [17] reported a reduction in the slump values of concrete and increase in the air content of the concrete [17] with increasing contents of glass aggregate as fine aggregate replacement which was attributed to the poor geometry and angular shape of the glass particles. It was also concluded that the angular shape and poor geometry of the glass particles causes a decrease in the workability of the fresh concrete as the glass content increases, resulting in increase of the concrete air content

[15,17]. Furthermore, work by [16] on concrete containing waste glass as either coarse aggregate or as fine aggregate reported that using less than 25% waste glass as aggregate replacement in concrete have a negligible effect on the workability of fresh concrete; however, using waste glass as coarse aggregate replacement at increase level of 50% and above improved the workability of the concrete mixture, agreeing with the report of [19]. This was attributed to the weak cohesion between the cement paste matrix and the coarse aggregate particles. But a higher level of concrete segregation was observed in self-compacting concrete containing waste glass as sand replacement [19]. Research work of [18] establishes that using waste glass as coarse aggregate replacement in concrete have very negligible influence on the concrete workability, but the air content of the glass concrete reduces due to the smooth surface of the glass particles, which decrease the porosity between the cement paste and the glass particles.

Ismail and AL-Hashmi [32] reported that the slumps of waste glass concrete produced using window glass as aggregate replacement decreased with increases in the waste glass content due to the grain shapes of the glass, however, good workability of the concrete mixtures were reported. In addition, the pozzolanic effect of waste glass in concrete is more obvious at the later age of 28 days with an optimum percentage replacement value of 20% reported. Study by [33] using waste flint glass (from windows glass) and green glass (from soda bottles waste) at levels of 0%, 10%, 20%, 40% and 50%, by weight to partially replaced natural sand in mortars reported that flint glass concrete showed higher ASR expansion than that containing green glass. Furthermore, Saccani and Bignozzi [34] reported that mortars containing lead-silicate glass exhibited the highest expansion while lime-glass showed the least expansion when the natural sand was partially replaced in mortars with different types of crushed waste glass which includes; soda-lime glass, uncoloured boro-silicate glass, amber borosilicate glass and lead-silicate glass at levels of 10%, 25% and 35%, by weight.

Studies have also found that the use of glass aggregate in concrete have negative influence on the strength of hardened concrete. It was established by [17, 8, and 27]; that as the glass particles content of a concrete increases, the compressive and tensile strength decreases. Ismail and AL-Hashmi [32] reported that the low strength observed in glass concrete could be attributed to the decrease in the adhesive strength between the surface of the waste glass aggregates and the cement paste. Consequently, this research work seems attractive because of its potential to re-establishes the possibility of reusing glass particles in much quantities as coarse aggregate replacement in normal concrete and rid of waste glasses from dump sites and environmental nuisance associated with its disposal.

2. Experimental Program

In Table 1 is presented proportions of the materials used in this study for the normal concrete mixtures wherein crushed waste glass aggregate (CWG) was used as a replacement for the granite material (natural coarse aggregate) in the concrete mixtures. In addition, one concrete mixture was prepared as control without the waste glass aggregate material.

Table1: Relative proportions of material used in preparation of concrete mixtures.

Mixture No.	**Coarse Aggregate Type**	**Cementitious material**	**Aggregate Materials**		
			Fine Aggregate	**Coarse Aggregate**	
		Portland cement	River Sand	Granite (CA)	Glass (CWG)
Control -CA	Natural aggregate (CA)	100%	100%	100%	0
25% -CWG	Crushed glass aggregate	100%	100%	75%	25%
50% -CWG		100%	100%	50%	50%
75%-CWG		100%	100%	25%	75%
100%-CWG		100%	100%	0	100%

2.1 Materials

2.1.1 Cementitious material

Cement: The Portland cement (ASTM Type I) of grade 42.5 used for this study was sourced commercially. The equivalent sodium alkali content of the Portland cement was 0.89%, calculated from $Na_2Oeq = Na_2O + 0.658K_2O$. The chemical composition determined using the X-ray fluorescence (XRF) and physical properties of the Portland cement are given in Table 2.

Table 2: Chemical composition and physical properties of Portland cement

Chemical composition Mass (%)		Physical properties	
SiO_2	24.08	**Initial setting (min)**	68
Al_2O_3	19.40	**Final setting (min)**	185
Fe_2O_3	6.28	**Soundness (%)**	0.52
CaO	74.25	**Specific gravity**	3.15
MgO	3.96		
K_2O	0.85		
Na_2O	0.33		
TiO_2	0.62		
P_2O_5	1.21		

2.1.2 Aggregate Material

The River sand and granite aggregate (natural aggregates) used for this study were sourced commercially. River sand having its particles size ranging from 0.075 to 4.75 mm and granite having a maximum size of 12.5 mm were used for production of the concrete used for this research study. The physical properties and the particle size distribution for both River sand and granite materials are presented in Table 3 and Figure 3.

Table 3: Physical properties of the aggregate and glass aggregate materials

Physical Properties	Natural aggregate		Waste glass aggregate
	Sand	Granite	Granular glass aggregate (CWG)
Fineness Modulus	2.69	2.85	2.73
Specific gravity	2.62	2.70	2.40
Water absorption (%)	0.42	0.25	0.36
Aggregate Impact value (AIV) %	-	10	39
Aggregate Crushing value (ACV) %	-	24	43

2.1.3 Crushed Waste Glass Aggregate Material (CWG)

The waste soda-glass used for this research work were obtained from dump sites and collection bins within Ota, Ogun state, Nigeria. The waste consists mainly of flat glass (window glass) and glass containers (bottles). In order to remove impurities and dirt, metals, plastic taps, and labels were removed and then, the waste glass was thoroughly washed with potable water and air dried before crushing to the required granular particle sizes equivalent to the size of the natural coarse aggregate using a jaw crusher. Figure 1 shows the size comparison of both the crushed granite and granular glass aggregate materials. The chemical composition of the waste glass is presented in Figure 2 showing the glass having a high silica content by percentage mass and also a high content of sodium compound (Soda). The physical properties and the particle size distribution for granular glass aggregate materials are also presented in Table 3 and Figure 3.

(a) (b)

Figure 1: Coarse aggregates used in this study; (a) glass coarse aggregate (CWG); (b) granite

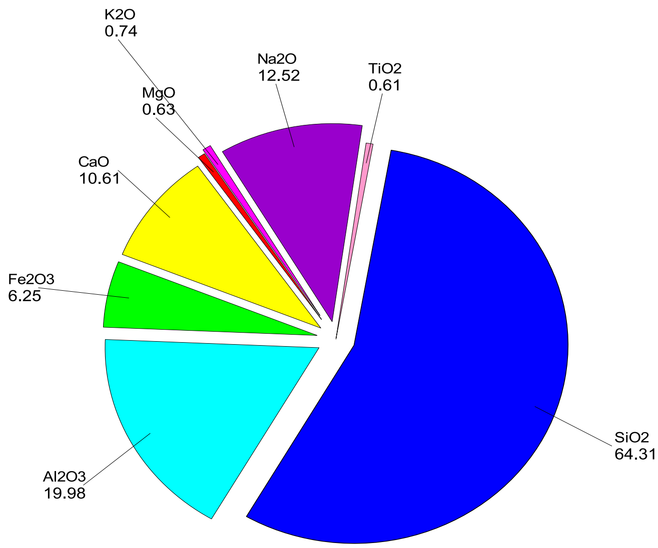


Figure 2: Chemical composition of the glass coarse aggregate (CWG)

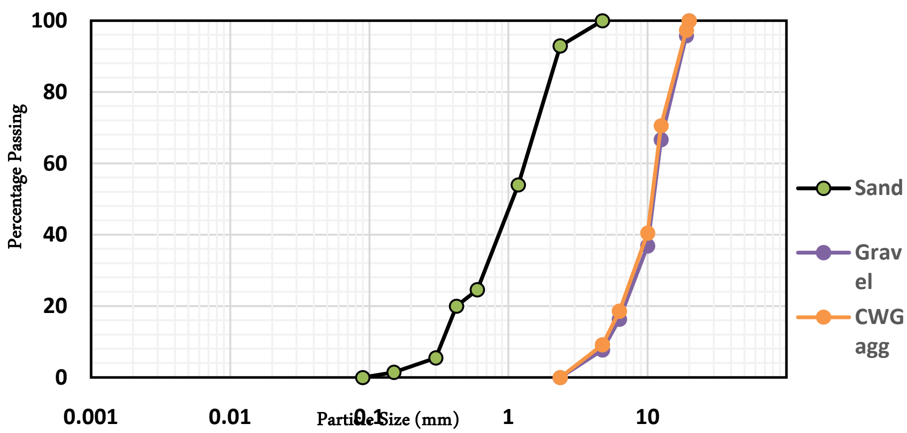


Figure 3: Particle size distribution for the sand, gravel, glass coarse aggregate (CWG)

3. Experimental Methods

The Table 4 below shows the mix proportions used in this research study for the concrete mixtures wherein granular waste glass aggregate was used as a coarse aggregate replacement in the production of normal concrete. To prepared the concrete mixes, River sand (passing through 4.75 mm sieve but retained on 0.075 mm sieve) and gravel aggregate of size 10 – 12.5 mm combined with the ordinary Portland cement were used to produce the control concrete used for this study. The fineness modulus and particle size distributions of the sand and granite were determined by sieve analysis. All the mixes were batched by weight, using a proportion of 1:2:4 (cement: sand: granite) and constant water – cement ratio of 0.5 for all the mixes, targeting a 28-day design strength of 20 MPa. Four resulting concrete mixtures were prepared by incorporating the crushed granular waste glass material as a replacement for granite (coarse aggregate) in proportion of 25%, 50%, 75% and 100% at a constant water-cement ratio of 0.5. Slump test was carried out on fresh concrete mixes to determine the workability of the various batches of concrete in accordance with [35]. Potable water was used for both mixing and curing of the concrete.

Concrete cubes of dimension 150 x 150 x 150 mm were cast in steel moulds and cylinders of 100 mm diameter by 200 mm in height were cast in mould and removed after 24 hours. The moulds were filled with concrete mixtures in 50 mm layers and compacted, with a steel tamping bar, with a minimum of 35 tamps per layer. After the tamping of each layer, the sides of the mould was slightly tapped to close the top surface of each layer. However, the last layer was slightly overfilled with concrete in the mould and the top layer was trowelled off, so as to level the top of the mould. Each specimen was properly labelled for identification. Both the cubes and cylinders were cured in potable water by immersion at room temperature and tested for compressive and split tensile strengths at ages of 3, 7, 14, 28 and 90-day for each percentage replacement of granite with granular waste glass aggregate materials. An average strength of three specimens was determined for each of the curing periods and waste glass replacement of granite in the hardened concrete. The compressive strength of concrete cubes and the split tensile strengths of the concrete cylinders were determined in compliance with the provisions of [36, 37] using YES-2000 digital display compression machine.

Preparation and testing of concrete samples were carried out at the Structures and Material Laboratory of the Department of Civil Engineering, Covenant University, Ota, Ogun state.

Table 4: Batching of Concrete Constituents

Mixtures		**Cementitious Materials (kg/m^3)**	**Aggregate (kg/m^3)**			**Water (kg/m^3)**	**Water to Cement ratio (w/c)**
		Cement	Glass aggregate	Granite	Sand		
Control	100% CA	275	0	1100	550	138	0.5
Glass Aggregate –	25%CWG	275	275	825	550	138	0.5
	50%CWG	275	550	550	550	138	0.5
	75%CWG	275	825	275	550	138	0.5
	100%CWG	275	1100	0	550	138	0.5

Microstructural examination of fractured parts of the concrete were carried out using the scanning electron microscopic (SEM). The type, amount, size, shape, and distribution of phases present in a material formed its microstructure and through the SEM technique, it is possible to analyze the microstructure of the materials to a fraction of one micrometer. Mehta and Monteiro [3], reported that concrete is the most widely used structural material, but its microstructure is heterogeneous and highly complex because at the macroscopic level, concrete may be considered as a two-phase material, consisting of the aggregate particles dispersed in a matrix of cement paste. While at the microscopic level, complexities of the concrete microstructure are evident that two phases are neither homogeneously distributed with respect to each other, nor are they themselves homogeneous [38]. The microstructure of the concrete mixes was observed on fractured surfaces. Fractured small concrete samples were mounted on the SEM stubs with no coating applied. The scanning electron microscopic studies of selected concrete samples and constituent materials were carried out using Phenom ProX scanning electron microscopy. The SEM tests were carried out concrete specimens cured in water for 28 days at ambient temperature.

4. Results and Discussion

4.1 Properties of Fresh Concrete: Slump

Slump of concrete is used to assess the workability of a concrete mix. Figure 4 shows the variation of test results for the slump of fresh concrete mixture with glass aggregate content. As presented in the Figure 4, the control mix gives a slump value of 40 mm at water-cement ratio of 0.5, however, the mixes containing waste glass aggregate demonstrate a reduction trend in slump with increasing waste glass content at the same water-cement ratio.

The slump of the glass concrete was reduced by 20 to 50% as the glass aggregate content increases compared to the control mix. The decrease in slump with increasing percent of glass aggregate (CWG) content in the concrete is strongly correlated, r = - 0.986. From the Figure 4, it can be clearly observed that the slump decreased with the increase in percentage of waste glass content. This reduction in slump may be attributed to the angular geometry of the granular particles of the glass which reduces the fluidity of the mix as the glass content increases resulting in less availability of cement paste required for the concrete fluidity as reported by [12, 18, 39]. Moreover, for concrete containing glass aggregate to achieve same workability with conventional concrete, it would require a higher water content [40]. However, all mixes are workable with no excessive segregation, especially for concrete mixture containing 25% waste glass coarse aggregate. Moreover, Neville and Brooks [41] stated that, segregation is difficult to measure quantitatively but it is easily detected when concrete is prepared.

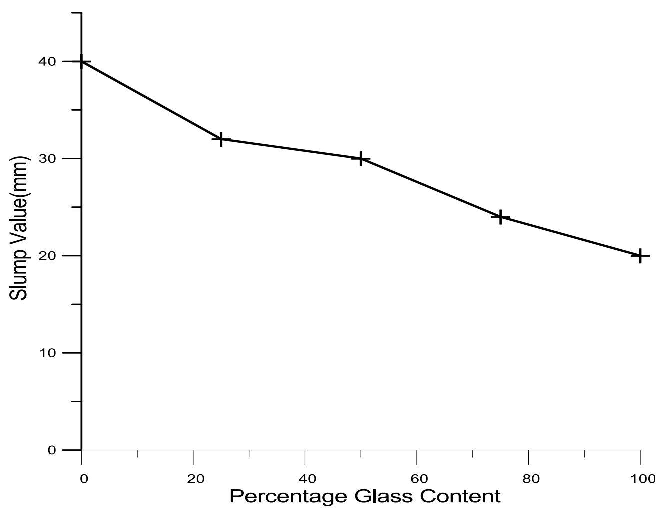


Figure 4: Variation between the slump and percentage glass aggregate content

4.2 Properties of Hardened Concrete

4.2.1 Compressive Strength

Figures 5(a), 5(b), 5(c) and 5(d) clearly indicate that as the percentage replacement of granite with glass aggregate increases beyond 25% replacement, the compressive strength of the concrete decreases at early curing age of 3 and 7-day; later curing age of 28 and 90-day. The decrease in the compressive strength of the concrete at both 28-day and 90-day of curing shows a strongly correlated value of, r = – 0.787 and – 0.640 respectively.

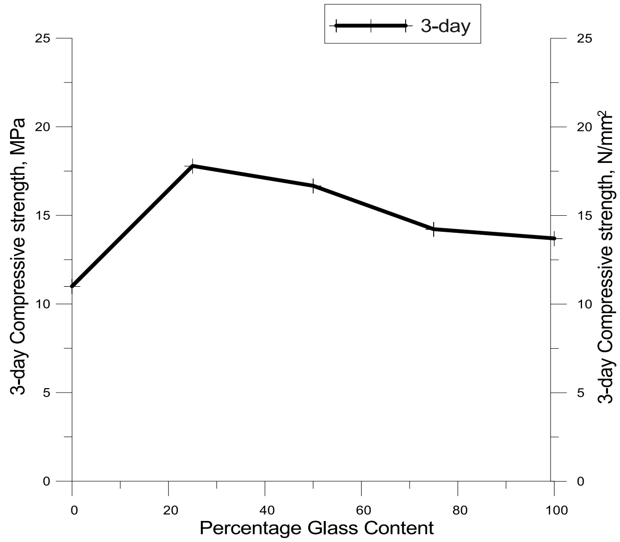


Figure 5 (a)

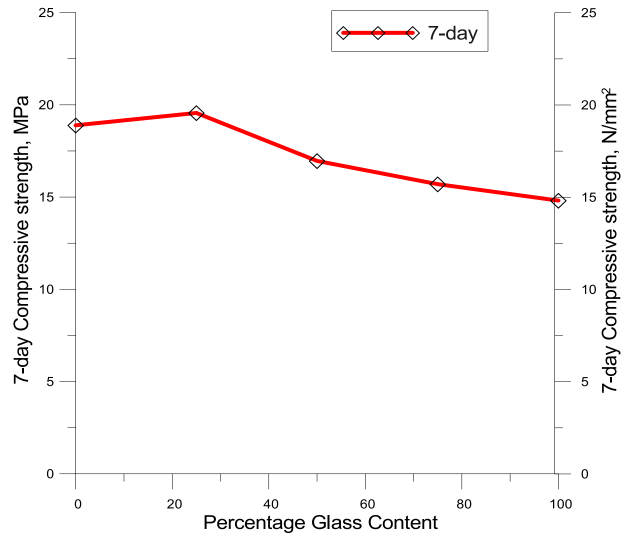


Figure 5 (b)

Figure 5: Variation of compressive strength with percentage glass content: (a) at 3-day curing, (b) at 7-day

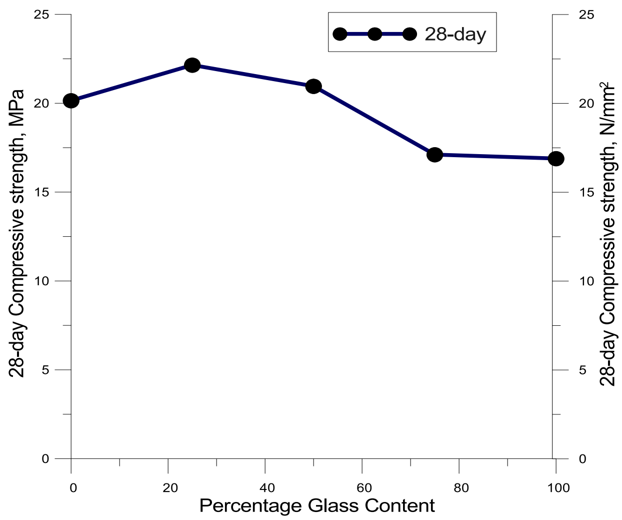


Figure 5 (c)

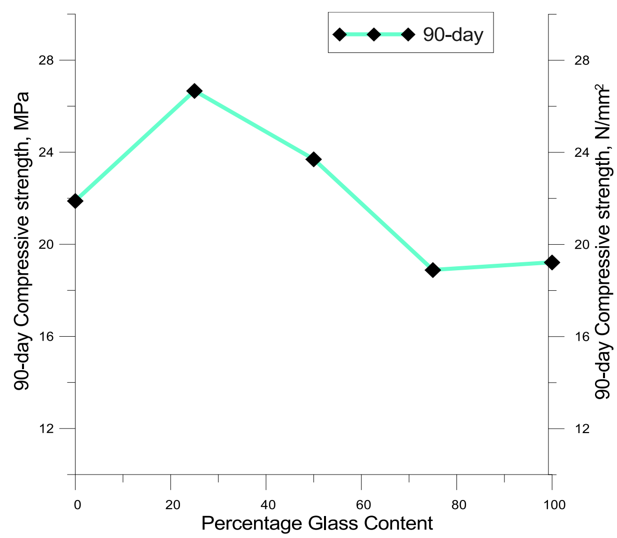


Figure 5 (d)

Figure 5: Variation of compressive strength with percentage glass content: (c) at 28-day curing, (d) at 90-day curing

After replacing 75% and 100% of the granite in the normal concrete mixture with waste glass aggregate materials (WGC), the compressive strength of the resulting concrete decreased by about 15.1% and 16.2% for 28-day curing age; 13.7% and 12.2% for 90-day curing age. The observed lower compressive strength of the concrete mixtures containing 75% and 100% CWG granular aggregate was attributed to the weaker bond strength between the sharper edges and smooth surface of the glass particles and the cement paste matrix at the interfacial Transition Zone (ITZ). Again, this was to be expected as it was earlier stated that increase in glass content result in decrease in the adhesive strength between the surface of the waste glass aggregates and the cement paste as reported by [32], which implies weaker bond. A poor bond concrete mix usually result to a lower compressive strength [13]. Study by [18] pointed out that the high brittleness of glass particles could lead to incomplete adhesion between the glass aggregate and cement paste interphase.

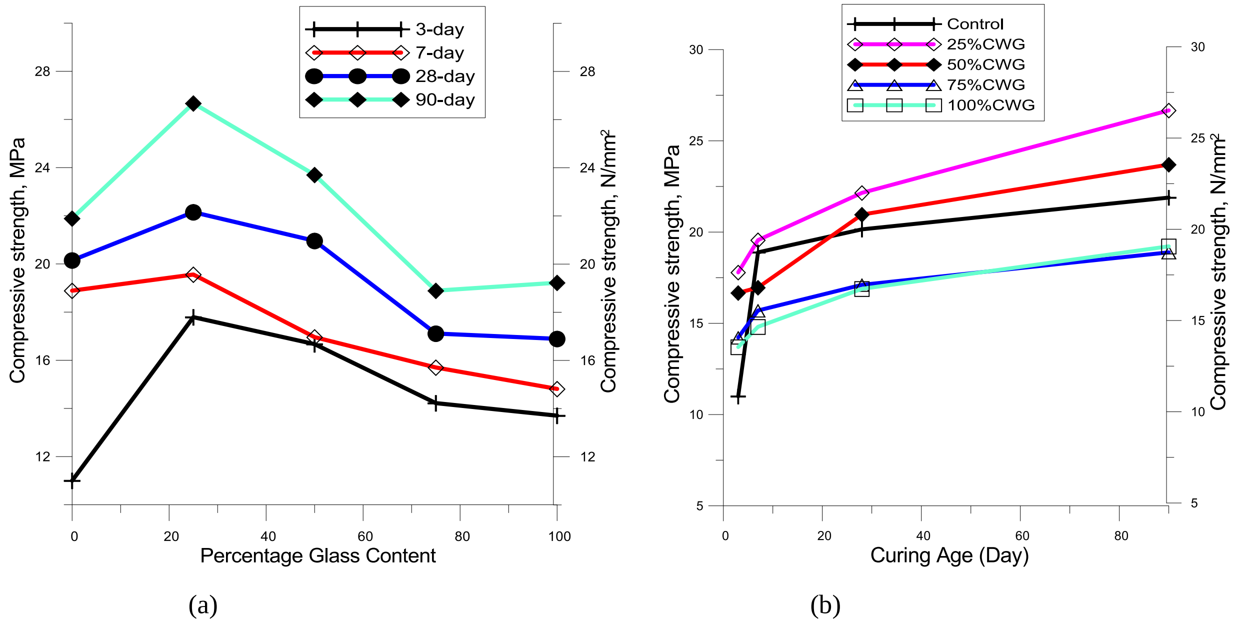


Figure 6 (a): Variation of compressive strength with percentage glass content at 3, 7, 28 and 90-day curing, (b) Strength development with age of percentage glass content

Again, emphasizing that due to the poor geometry of glass aggregate, homogenous distribution of aggregates could not be achieved leading to lower compressive strength. However, an increase in the compressive strength was observed for 25% and 50% replacement of granite with the glass aggregate (WGC) compare with the control mix for 28 and 90-day of curing. From the test results, it can be clearly observed that concrete mixture containing 25% and 50% granite replacement with glass aggregate were able to achieve the targeted design strength of 20 MPa after 28 and 90-day of curing in water respectively (Figure 5(c), 5(d) and 6(a)). As shown in Figure 5(c), 5(d) and 6(a), the 28-day and 90-day compressive strength of the concrete specimens containing 25% glass aggregate was significantly higher than that of the control concrete specimens containing granite aggregate by about 10% and 29% respectively. For instance, the recorded 28 and 90-day compressive strength of the concrete specimens containing 25% CWG were 22.15 and 26.67 MPa, respectively. Again, as shown in Figure 5(c), 5(d) and 6(a), the 28-day and 90-day compressive strength of the concrete specimens containing 50% glass aggregate was observed to be slightly higher than that of the control by about 3.9% and 7.6% respectively. For instance, the recorded 28 and 90-day compressive strength of the concrete specimens containing 50% CWG were 20.96 and 23.7 MPa, respectively. However, it was observed that the optimum influence of the glass aggregate content is at 25% granite replacement, where the increases in compressive strength at both early and later age reaches 38% and 29%, respectively higher than the control. This can be attributed to the interlocking influence of the particle edged shape and angular geometry of the crushed CWG aggregates and the subangular shape of the natural coarse aggregates, resulting higher interparticle interaction or friction within the concrete mixture coupled with sufficient cement paste. But decrease in compressive strength beyond 25% percentage granite replacement may be attributed to the friable nature and smooth surface of the glass particles which also could result in lower compressive strength. As expected in Figure 6(b), the strength development of the concrete mixtures for both control and glass concrete increases with age and clearly indicate the optimum effect of 25% granite replacement. It was also observed that the failure mode pattern of glass concrete cubes was explosive and not parallel to the direction of applied load as usually observed for conventional concrete cubes (Figure (9)).

4.2.2 Splitting Tensile Strength

The results of the splitting tensile strength tests are shown in Figure 7(a), 7(b), 7(c) and 7(d) for 3, 7, 28 and 90-day of curing. The glass aggregate concretes exhibited splitting tensile strengths varying between 2.14 and 2.50 MPa at 28-day compared to 3.80 MPa for the control mix Figure 7(c). Figure 7(d) shows the splitting tensile strengths of the glass aggregate concrete at 90-day curing varying between 3.71 and 3.19 MPa compared to 4.20

MPa for the control mix. Form the test results, it is clear that increase in the glass aggregate content decrease the values of the splitting tensile strength compared to the control mix which may be as a result of reduction in the adhesive strength of the glass concrete as the percent glass content increases. However, at 25% granite replacement with glass content, the splitting tensile strength exhibit maximum influence compared to the control. But increase in glass content beyond the 25% reduces the splitting tensile strength of the glass concrete. The reduction in the splitting tensile strength is less prominent in the concrete containing 25% glass content and this may be attributed again, to the sharper edge and angular shape of the crushed glass aggregate which resulted in higher degree of internal friction as reported by [42]. Again, as expected Figure 8(a) and (b) shows the strength development of the concrete mixtures for both control and glass concrete increases with age and showing the maximum effect of 25% granite replacement (Figure 8(b)). It was also observed that the splitting pattern of the glass concrete cylinder was through the middle of the concrete cylinder as observed in Figure (10).

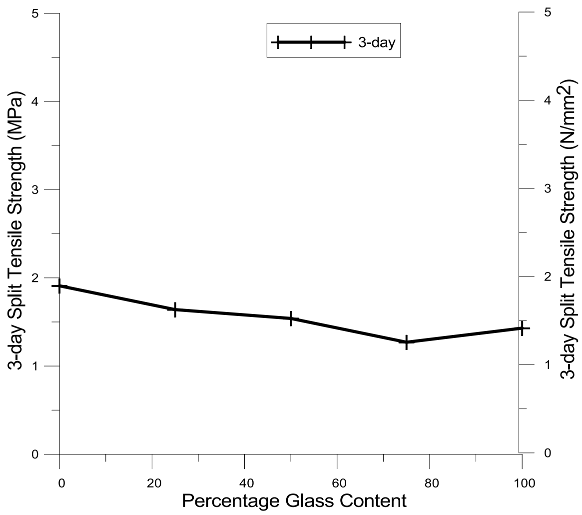


Figure 7(a)

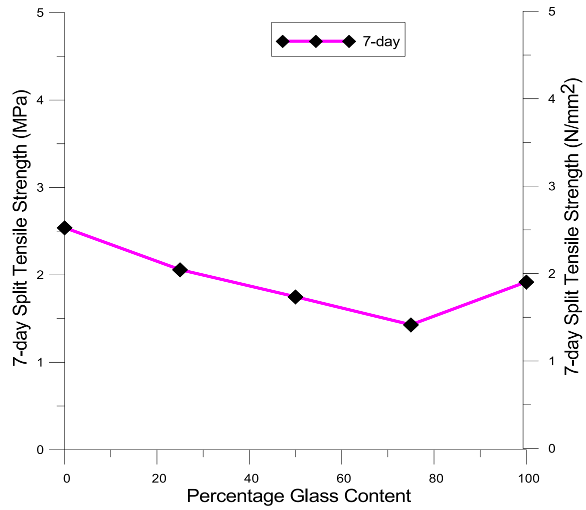


Figure 7(b)

Figure 7: Variation of split tensile strength with percentage glass content: (a) at 3-day curing, (b) at 7-day curing

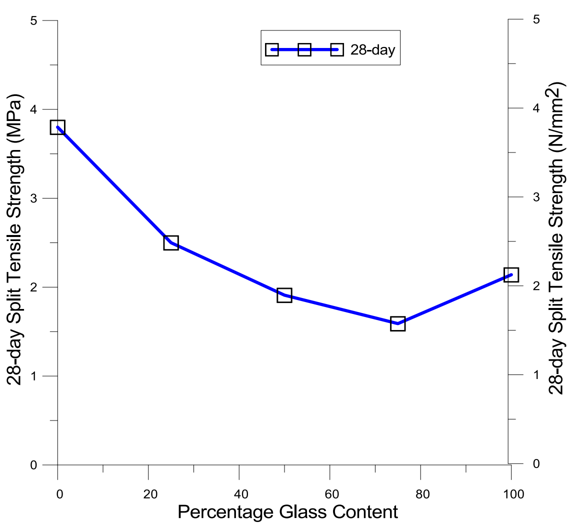


Figure 7(c)

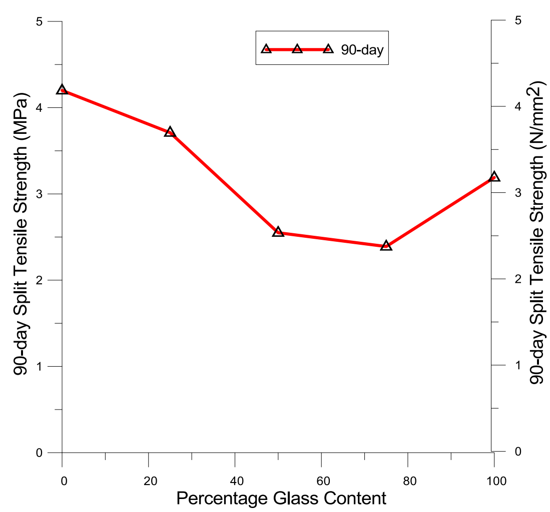
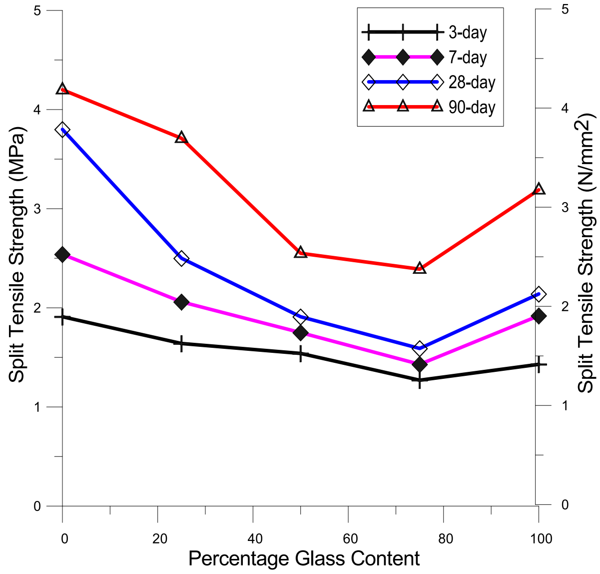
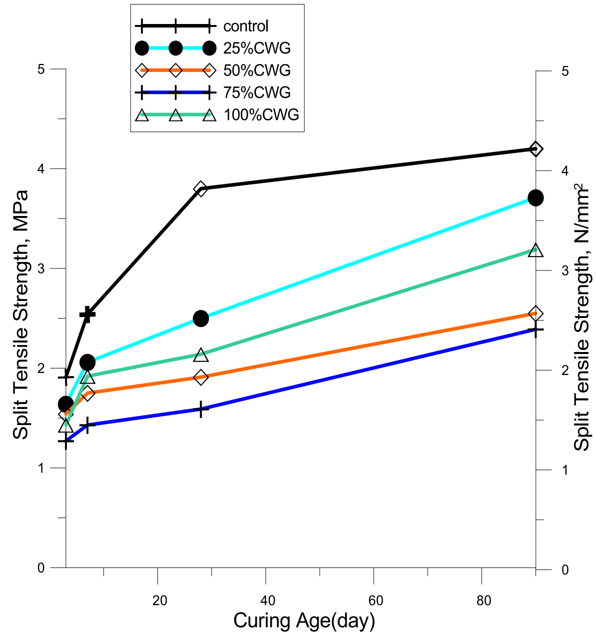


Figure 7(d)

Figure 7: Variation of split tensile strength with percentage glass content: (c) at 28-day curing, (d) at 90-day curing



8(a)



8(b)

Figure 8(a): Variation of split tensile strength with percentage glass content at 3, 7, 28 and 90-day curing (b) Strength development with age of percentage glass content

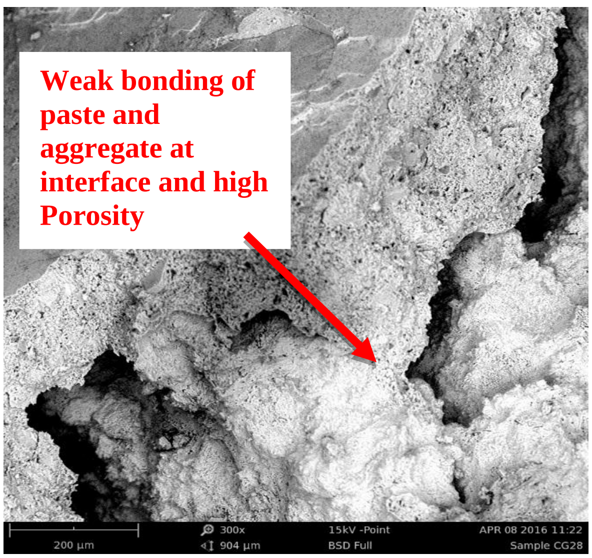
Figure 9: Crushed glass concrete cube at failure

Figure 10: Failed pattern of glass concrete cylinder after testing

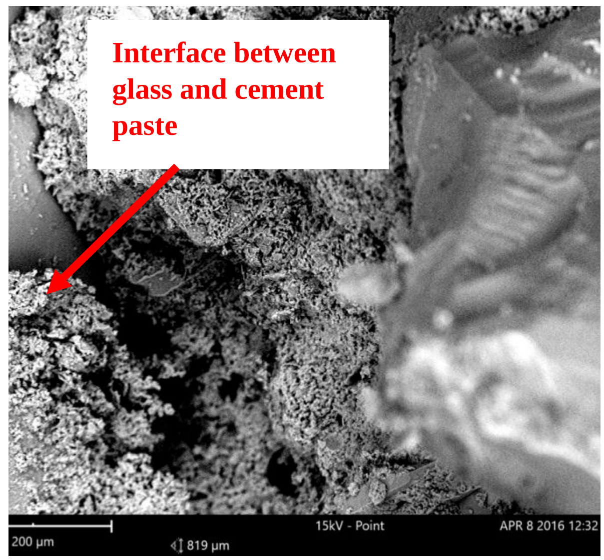
The use of more than 25% coarse aggregate replacement with waste soda-lime glass during the production of normal concrete is not recommended, in order to ensure the development of appreciable strength that can withstand compressive load of at least 20 MPa. Moreover, this value of characteristic compressive strength may be used for structural design for the various structural elements of concrete structure.

4.2.3 Microstructural Examination

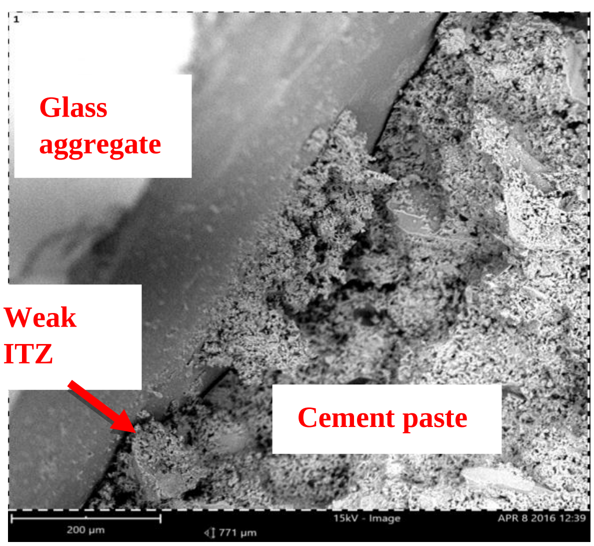
Microstructural examination using SEM on selected concrete samples containing glass aggregates were conducted to further assess the bond between the cement paste and aggregate at the interfacial zone. The samples of concrete cubes part were examined at the age of 28 days. According to [43], the bond that is between cement paste and aggregate is very important because the bond is considered as a vital component in the movement of stresses between the cement paste and the aggregate materials which influence the mechanical properties of the concrete. Figure 11 (a), (b) and (c) show the SEM imagery of sample parts of selected concrete at 28 days containing waste glass particles as coarse aggregate. From the SEM images, it is clear that glass aggregate particles have a smooth surface interfacing with the cement paste thereby providing poor interlocking between the two phases, which may result in poor mechanical properties of the concrete. [43, 44] stated that the bond performance within the interfacial transition zone (ITZ) is influence by various factors which include use of micro-fillers, roughness of the aggregate surface, chemical interaction between the paste and aggregate. The SEM images clearly shows that lack of strong bond between the cement paste and glass aggregates further resulted in the lower compressive and tensile strength results at 28 days obtained for the concrete especially at higher levels of glass content.



(a)



(b)



(c)

Figure 11(a) (b) (c): SEM images on concrete samples containing waste glass aggregate particles showing the bonding at the interface zone

Conclusions

Based on the test results obtained in this research investigation, the following conclusions are drawn on the effect of using crushed granular glass aggregate materials as natural coarse aggregate replacement material on the fresh and hardened properties of normal concrete:

1. A decrease in the workability of the concrete mixtures was observed for freshly prepared concrete containing crushed glass aggregate as the waste glass aggregate content increases at constant water cement ratio compared to equivalent concrete mixture containing natural aggregate. This reduction in workability is attributed to the poor geometry and angular shape of the crushed glass aggregate. However, no excessive segregation was observed for concrete mixtures containing crushed glass aggregates.
2. A significant reduction in the compressive strength of the hardened concrete containing crushed glass aggregate was observed as the percentage content of glass increases from above 25% to 100% granite replacement for 3 and 7 day curing samples with approximately constant strength for 28 day curing sample with above 80% granite replacement while the 90 days curing sample experienced slight recovery with above 80% granite replacement because of the develop weakened bond at the interfacial transition zone between the glass aggregate particles and the cement paste caused by the angular nature and smooth surface of the glass and voids that develop in the concrete as reported by [9]. Again, a steady reduction in the tensile strength of the hardened concrete cylinder containing crushed glass aggregate was observed as the percentage content of glass increases from 0% to 80% followed with significant recovery for above 80% granite replacement for all the samples.
3. However, replacement of natural granite aggregate by 25% crushed glass aggregate content yielded higher compressive strength of concrete compare with the control concrete made granite aggregate. But the strength development for both the compressive and tensile strength increased with curing age.
4. Therefore, based on research findings, normal concrete of targeted strength of 20 MPa can be produced with soda-lime waste glass crushed to coarse aggregate sizes and blend with natural coarse aggregate in concrete mixture up to 25% replacement. Moreover, the implications of the achieved results depict that waste glass can be reuse for the production of concrete instead of the indiscriminate disposal of the waste glass.

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