
Pozzolanic Reactivity of Cement with Soda-lime Silicate and Borosilicate Waste Glass Powder in Concrete Production

By

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ABSTRACT

The aim of this research is to study the pozzolanic reactivity of cement with waste glass (Soda-lime Silicate and Borosilicate) in Concrete. When waste glass particles are ball-milled to micro size powder, it is expected to undergo pozzolanic reactions with cement hydrates, forming secondary Calcium Silicate Hydrate. This research looked at the chemical analysis using X-Ray fluorescence (XRF) technique and found some differences in the chemical composition of soda-lime silicate and borosilicate waste glass. The major oxides detected were combined proportion of SiO₂, Al₂O₃, and Fe₂O₃ with percentage value of 73.202%, 72.998%, 0.411%, 0.201%, and 0.223%, 0.112% respectively. The Setting time of the specimens that contains waste glass powder was also determined and found that it delayed initial and final setting time, and the effect increases as the percentage replacement of cement with waste glass powder increases. The microstructural characterization was also carried out using Scanning Electron Microscope (SEM) and X-Ray Diffraction (XRD) to characterize the concrete samples. It was found that the morphology of concrete samples with waste glass powder (10%) was denser than the control sample (0%). Also, XRD results indicated that the intensity of the peaks, in particular of portlandite, is significantly reduced in the 10% waste glass sample than the control (10% of portlandite in the control, 2% of portlandite in 10% waste glass replacement). Various compositions of the samples (Control 0%, 5.0%, 10%, 15%, and 20%) of concrete cube, cylinder and beam samples were prepared and tested for strength at 7, 14 and 28 days of curing. The compressive strength test results of the control and the 10% waste glass replacement were 20.95 N/mm², 16.44N/mm² for 7, 26.52 N/mm², 24.14 N/mm² 14, and 31.38 N/mm², 28.82 N/mm² 28 days respectively. The tensile strength test results of the control and the 10% waste glass replacement were 2.08 N/mm², 1.65N/mm² for 7, 2.65N/mm², 2.41 N/mm² 14, and 3.13N/mm², 2.89N/mm² 28 days respectively. The flexural strength test results of the control and the 10% waste glass replacement were 3.96 N/mm², 3.17N/mm² for 7, 4.95N/mm², 4.58 N/mm² 14, and 5.87N/mm², 5.27N/mm² 28 days respectively. It can be concluded that all the samples can be used for structural purposes, this is because all the samples exceeded the maximum strength specified by ASTM 24.2 N/mm² at 28 days.

Keywords: compressive strength, scanning electron microscope, tensile strength, X-Ray diffraction, X-Ray fluorescence,

INTRODUCTION

Concrete is the primary building material and one of the most widely used construction materials in the world, which constitute a homogeneous mixture of Portland cement, coarse aggregates, fine aggregates, and water (Aliabdo *et al.*, 2016). However, the production of Portland cement which is an important constituent of concrete leads to the release of a high amount of a greenhouse gas (essentially CO₂), to the atmosphere which result in global warming and environmental devastation (Szabo *et al.*, 2006). There is a serious concern about environmental issues, and a switchover from the mass-waste and mass production society of the past to a zero-emanation of waste materials which is viewed as significant studies in recent years (Mane and Mane, 2012). The use of waste glass powder for the partial replacement of cement in concrete is a viable strategy for minimizing the use of Portland cement, and thus reducing the environmental and energy impacts of concrete production (Gopalakrishnan and Govindarajan, 2011).

The aim of this research is to study the pozzolanic reactivity of cement with waste glass powder (Soda-lime Silicate and Borosilicate) in Concrete. This can be achieved through determining the chemical properties of cement, soda-lime silicate and borosilicate waste glass, the fresh properties, the hardened properties, and microstructural characterization of hardened concrete samples. Pozzolan is an additive used in concrete to improve its quality, it reduces the temperature rise during initial hydration, and improves the strength development and durability of concrete materials (Rungrawee, and Boonchai, 2015). Several types of pozzolan are widely used, such as natural

pozzolan, fly ash, blast furnace slag, and silica fume (microsilica).

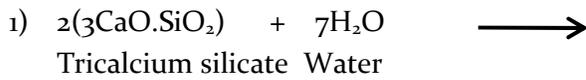
Many studies have shown that waste glass has potential for use in building material (Vijayakumar *et al.*, 2013), used as an aggregate replacement, a filler in concrete, or a cement replacement. Specifically, finely ground glass powder (particle size of less than 38 µm) has potential for use as pozzolan (Kara, *et al.*, 2016).

In addition, glass powder tends to improve the compressive strength more if it was more finely ground (Rungrawee, and Boonchai, 2015). Being amorphous and having relatively high silicon and calcium contents, glass is pozzolanic or even cementitious especially when the fineness of glass powder is much greater than that of Portland cement (Kara, *et al.*, 2016). When waste glass is milled down to micro size particles, it is expected to undergo pozzolanic reactions with cement hydrates, forming secondary calcium silicate hydrate (C-S-H) (Sadiqul, *et al.*, 2016).

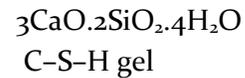
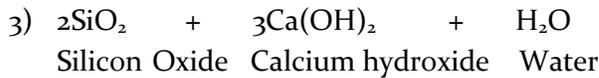
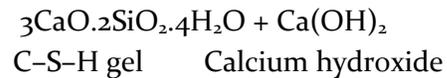
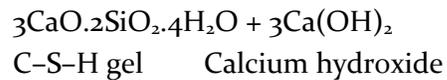
Kara, *et al.*, (2016) conducted research on the performance of soda-lime silicate glass as partial replacement of cement and concluded that 20% replacement level gave higher strength than the control at later curing age, Ramprashath and Chellakavitha, (2015) conducted research on the utilization of borosilicate glass powder as partial replacement of cement and concluded that beyond 20% replacement, compressive strength starts decreasing.

The use of finely divided glass powder as a cement replacement material has yielded positive results (Vijayakumar *et al.*, 2013). There still exist the need to determine if addition of borosilicate and sodalime silicate glass powder at different proportions in concrete production. The dominant product of these reactions is C-S-H gel, which is

principally responsible for the mechanical properties of the hydrated cement. C-S-H gel is generated by the interaction of the



replacement materials with portlandite, CH, liberated during the hydration of the alite and belite present in the cement (Taylor, 1997).



MATERIALS

1. Portland cement: A typical commercial Type I Portland cement (OPC, Dangote Brand) which conformed to the requirements of specification of BS EN 197-1: (2011).
2. Glass powder (Borosilicate and Soda-lime silicate glass waste): Two type of waste glass were obtained from damaged glass, windows, and fluorescence. The powder has the similar chemical compositions, as shown in Table 1. According to ASTM C618.
3. Fine aggregate: The fine aggregate use was natural sand. It was sieved with a 4.75mm BS sieve so as to remove impurities and larger aggregates. The fine aggregate conformed to provisions of BS EN 1260: (2013)
4. Coarse aggregate: The coarse aggregates used were crushed gravels which were obtained from single quarry. It is in conformity with the requirement of BS EN 1260: (2013)
5. Water: The water uses for mixing the concrete was clean fresh tap water free from impurities complying with the provisions of BS EN 1008: (2002).

METHODS

1. *Setting time test*

The Setting time test was conducted with Vicat apparatus, and the procedure stipulated by ASTM C 451 was strictly observed

2. *Compressive strength test*

Compressive strength was carried out after different curing ages of 7, 14, and 28 days for all the concrete samples. It was done as stipulated by ASTM C 39-05. Three cubes were tested to failure for all specimens. The maximum failure load was then recorded and the compressive strength was calculated using the relation:

$$\text{Compressive strength} = \frac{F}{A} = \frac{2}{2}$$

3. *Tensile strength test*

Tensile strength was carried out after different curing ages of 7, 14, and 28 days for all the concrete samples and was done as stipulated by BS 1881 (part 117).

The maximum failure load was then recorded and the tensile strength was calculated using the relation: Tensile Strength = $\frac{F}{A} = \frac{3}{3}$

4. *Flexural strength test*

Flexural strength was carried out after different curing ages of 7, 14, and 28 days for all the concrete samples and it was done as stipulated by BS 1881 (part 118). The maximum failure load was then recorded and the

flexural strength was calculated using the relation:

$$\text{Flexural strength} = \frac{4}{3} \times \frac{P \times L}{b \times d^2}$$

5. Mix design

Grade 30 concrete was designed because the target strength was 30N/mm². The constituent materials required for each sample were measured and weighed on a digital weighing balance i.e cement, sand and

aggregate, (borosilicate and sodalime glass). After mixing, the fresh concrete was casted into 100mm x 100 mm x100 mm moulds in two layers and was compacted in order to achieve smooth and level compaction for each sample. Samples were allowed to set for 24hours before demoulding and immersed in a pool of water tank for 7days, 14days and 28days.

Table 1: Mixing proportions of waste glass powder and cement

Mixing Batch	Cementing Material
Control	100%Portlandcement
5 %	95% Portland cement + 5% Glass powder
10 %	90% Portland cement + 10% Glass powder
15%	85% Portland cement + 15% Glass powder
20%	80% Portland cement + 20% Glass powder

RESULTS AND DISCUSSIONS

X-Ray fluorescence (XRF) Analysis

Table 2 shows the chemical composition of cement, soda-lime silicate and borosilicate glass which was conducted at the Centre for Minerals Research and Development Kaduna Polytechnic Kaduna state of Nigeria. The major oxides detected were combined proportion of silicon oxide

(SiO₂) Aluminium oxide (Al₂O₃) and Iron oxide (Fe₂O₃) with percentage value of 73.202%, 72.998%, 0.411%, 0.201%, and 0.223%, 0.112% respectively this result is similar to that of Novais *et al.*, (2016), except slight difference in the percentage composition of SiO₂ and Al₂O₃. This means that soda-lime silicate and borosilicate glass satisfy the requirement of ASTM C 618-2005

Table 2: Chemical Composition of Cement, Soda-lime silicate Glass and Borosilicate Glass

Oxides	Cement	Percentage Composition (%)	
		Borosilicate Glass	Soda-lime silicate Glass
Silica (SiO ₂)	20.211	72.998	73.202
Aluminium (Al ₂ O ₃)	4.698	0.201	0.411
Iron Oxide (Fe ₂ O ₃)	3.022	0.112	0.223
Sodium Oxide (Na ₂ O)	0.189	5.722	6.843
Calcium Oxide (CaO)	61.889	3.766	6.433
Magnesium Oxide (MgO)	2.619	0.723	1.269
Potassium Oxide (K ₂ O)	0.820	0.588	0.168
Sulfur Oxide (SO ₃)	3.889	0.135	0.158
Boron Oxide (B ₂ O ₃)	-----	5.251	-----
Loss on Ignition (LOI)	2.660	10.502	11.287

Setting time test

Figure 3 presents the result of setting time test of different cement pastes samples. Dangote Portland cement was used for the experimental work. The control has least initial setting time and final setting time of 113 minutes and 168 minutes respectively. The initial setting time and final setting time increases as the percentage replacement of cements with waste glass powder (Pozzolana) increases. This is as a result of absorption by the waste glass powder and delayed hydration, as Utsevu and Taku (2012) reported that waste glass powder delays

initial and final setting time. Therefore, higher strength will be developed after prolonged curing, also the mixing water increases as the percentage replacement of cement with waste glass powder increases. It is as a result of absorption by the powder glass since its specific surface area is smaller than that of cement; Abalaka, (2012) reported that an increase in mixing water as percentage replacement of cement with waste glass powder increases. It can be recommended that all the mixes can be used for structural work since the expansion due to soundness do not exceed 10mm.

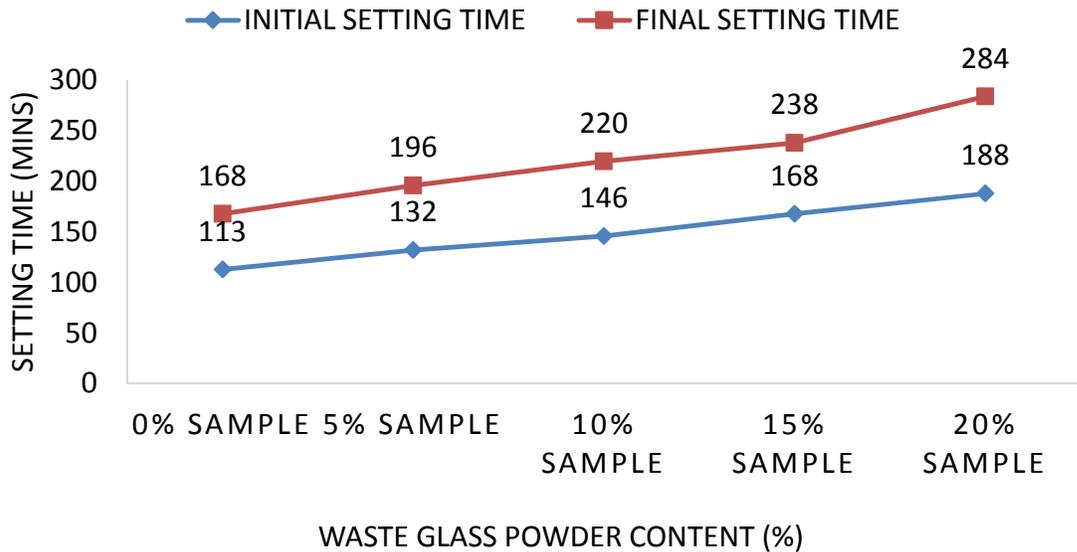


Figure 3: Initial and final setting time of the sample specimens

Compressive Strength Test of Samples

Figure 4 shows the compressive strength of all the sample specimens at 7, 14 and 28 days respectively. The compressive strength test results of the control and the 10% waste glass replacement were 20.95 N/mm², 16.44N/mm² for 7, 26.52 N/mm², 24.14 N/mm² 14, and 31.38 N/mm², 28.82 N/mm² 28 days respectively. This can be attributed to the fact that strength increase at the early stage due to higher temperature

during placing and setting but undesirably affect the strength at later ages while samples are continuously cured in water this can be as a result of rapid hydration process in the paste therefore the conventional concrete develop high early strength at early age this is an agreement with the findings of (Utsevu and Taku, 2013 : Vignesh *et al.*, 2014) reported that waste glass powder blended cement concrete have lower strength than the control.

It can be recommended that all the samples can be used for structural purposes, this is because all the samples exceeded the

maximum strength specified by ASTM 24.2 N/mm² at 28 days.

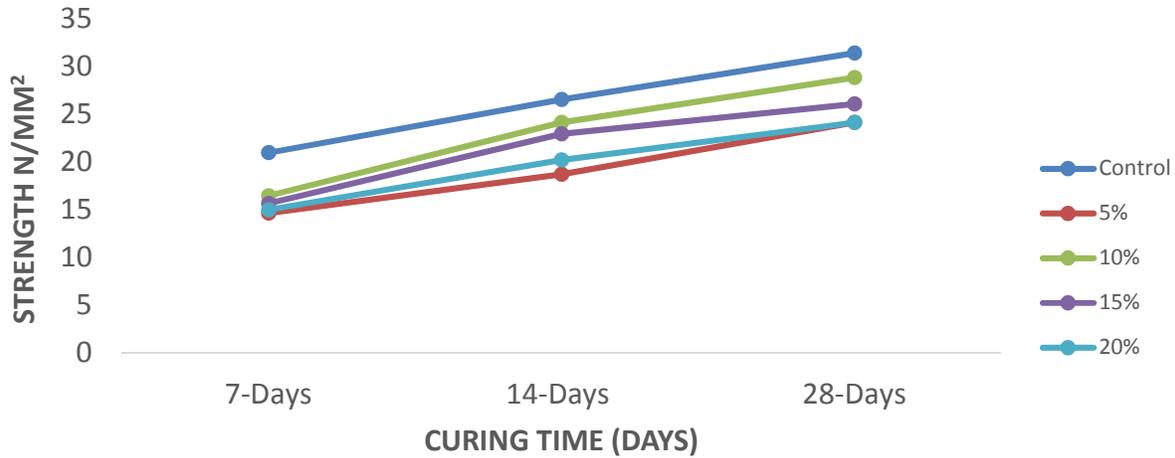


Figure 4: Compressive strength of samples cured in water.

Tensile Strength Test of Samples

Figure 5 shows the tensile strength of all the sample specimens at 7, 14 and 28 days respectively, The tensile strength test results 2.08 and 1.65, 2.65 and 2.41, 3.13 and 2.89 of the control and the 10% waste glass replacement were 2.08 N/mm², 1.65N/mm² for 7, 2.65N/mm², 2.41 N/mm² 14, and 3.13N/mm², 2.89N/mm² 28 days respectively., this can be attributed to the fact that strength increase at the early stage due to higher temperature

during placing and setting but undesirably affect the strength at later ages while samples are continuously cured in water this can be as a result of rapid hydration process in the paste therefore the conventional concrete develop high early strength at early age this is an agreement with the findings of (Vijayakumar *et al.*, 2013; Madhangopal *et al.*, 2014), reported that waste glass powder blended cement concrete have lower strength than the control, at 14 days and 28 days.

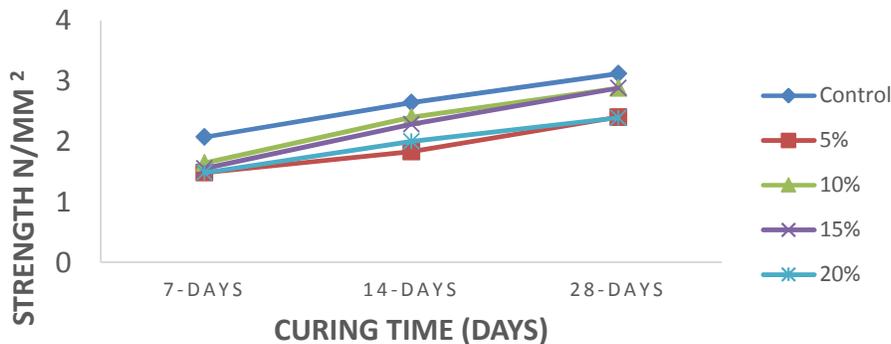


Figure 5: Tensile strength of samples cured in water.

Flexural Strength Test of Samples

Figure 6 shows the flexural strength of all the sample specimens at 7, 14 and 28 days respectively, at 7, 14 days the control samples had highest flexural strength of 3.96 N/mm² and 4.95 N/mm² respectively. This can be attributed to the fact that strength increased at the early stage due to higher temperature during placement and setting but undesirably affected the strength at later ages while

samples are continuously cured in water. This can be as a result of rapid hydration process in the paste therefore the conventional concrete develops high early strength at early age which agrees with the findings of (Vijayakumar *et al.*, (2013): Madhangopal *et al.*, (2014) reported that waste glass powder blended cement concrete have lower strength than the control, at 14 days and 28 days.

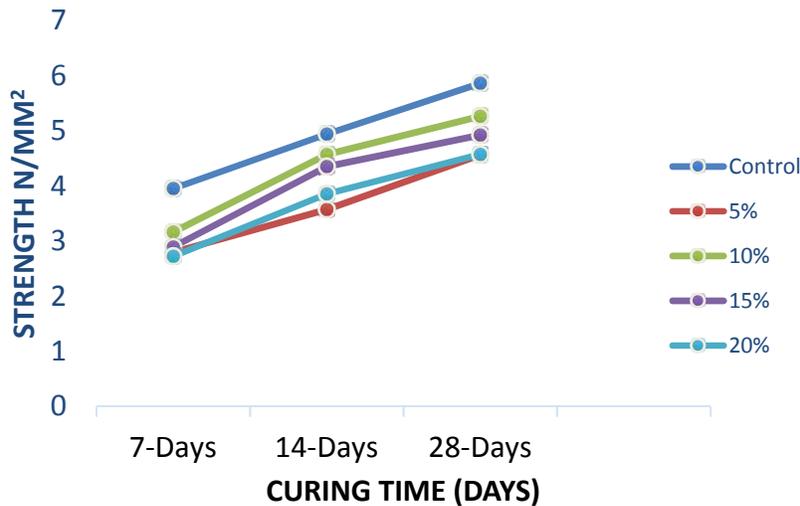


Figure 6: Flexural strength of samples cured in water.

X-Ray Diffraction (X-RD) Analysis

Figures 7, and 8 show the XRD patterns of hydrated cement paste of the Control, and 10% replacement of waste glass

after 28 days respectively, which was conducted at the Nigerian Geological Survey Agency Kaduna.

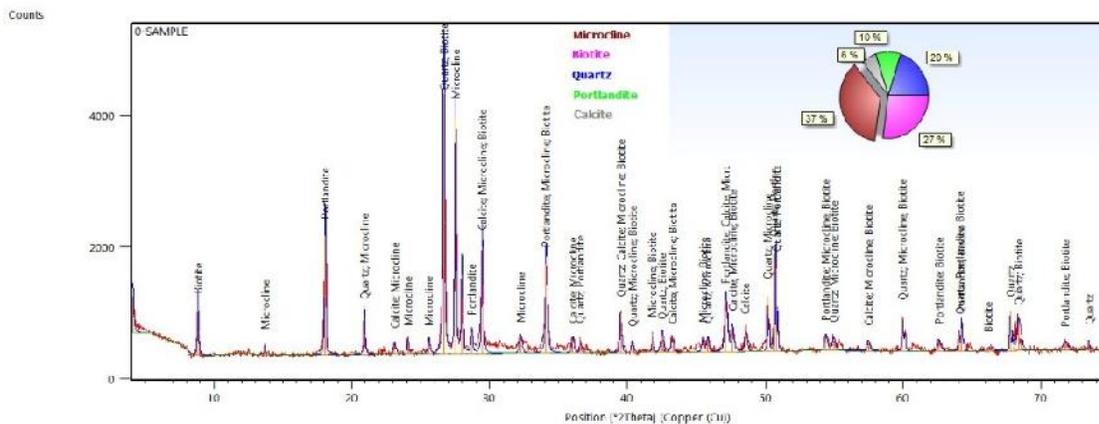


Figure 7: X-ray diffractograms pattern of the control 0% waste glass powder. It shows 10% of portlandite (Ca(OH)₂)

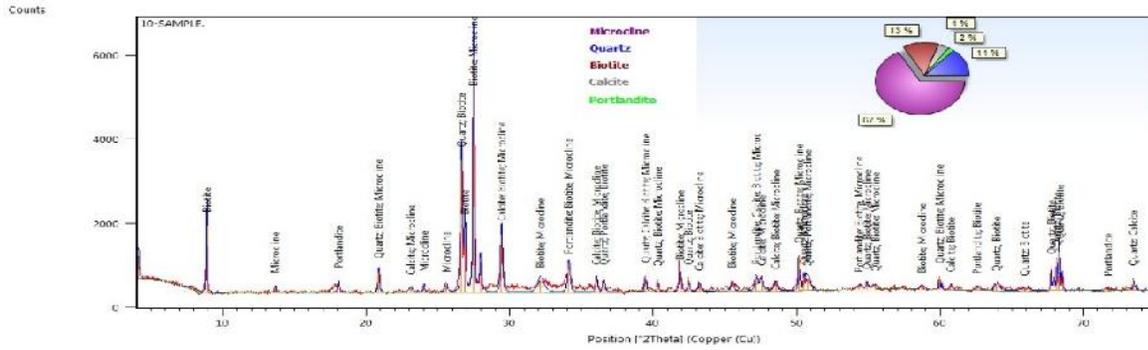


Figure 8: X-ray diffractograms pattern of the 10% waste glass powder. It shows 2% of portlandite (Ca(OH)₂)

Fig. 8. shows the X-ray diffractograms pattern of the 10% waste glass powder of concrete sample material cured at room temperature for 28 days, whose in the concrete mixture, several minerals present in the concrete mixture used as a precursor are identified, such as microcline, quartz, biotite calcite and portlandite (67%, 14%, 13%, 4% and 2% respectively) type; It is observed that the intensity of the peaks, in particular of portlandite, is significantly reduced in the 10% waste glass sample than the control in fig. 7 (10% of portlandite in the Control and 2% of portlandite in 10% of waste glass replacement).

The reduction of diffraction lines intensity of portlandite is mainly due to the addition of replacement materials to Portland cement which brings additional complexity to the chemical reactions developed during the hydration of the composite cements. This

allows to deduce that, in addition to hydration reactions of alite and belite, a partial dissolution of certain crystalline phases occurs; this is consistent with results reported by other authors for several types of precursors (Ahmari *et al.*, 2012). However, this decrease in intensity has also been attributed to the increase in the SiO₂/Na₂O ratio due to the presence of sodium silicate in the mixture (Komnitsas *et al.*, 2015). The small traces of portlandite (Ca(OH)₂) are attributed to the hydrated cement contained in the undissolved concrete mixture particles.

Scanning Electron Microscope (SEM) Analysis

Plate 1, and 2 show the microstructure of the Control 0%, and 10% waste glass powder replacement respectively, which was conducted at Sheda Science and Technology complex Abuja

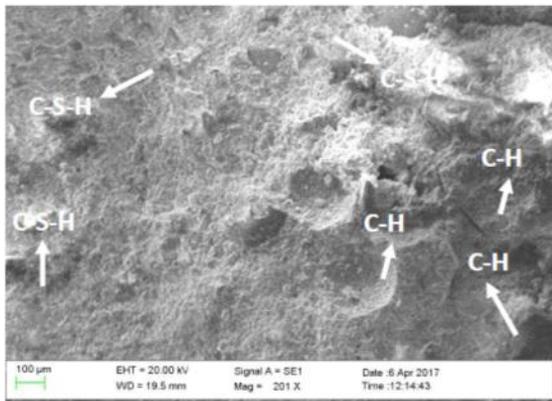


Plate 1: A SEM micrograph of control 0% Waste glass powder. CH = $\text{Ca}(\text{OH})_2$
C-S-H = Calcium Silicate Hydrate gel

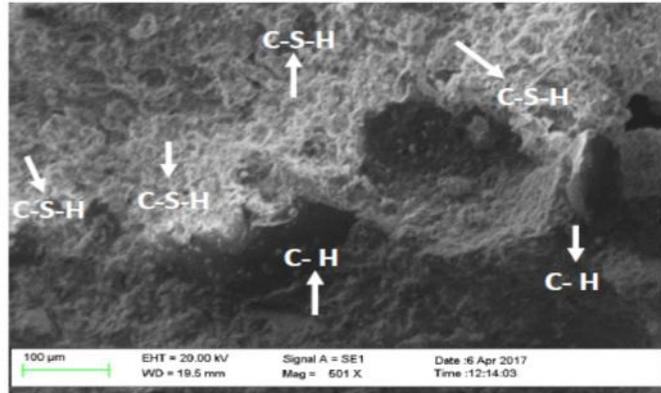


Plate 2: A SEM micrograph of 10% waste glass powder. CH = $\text{Ca}(\text{OH})_2$
C-S-H = Calcium Silicate Hydrate gel

Plate 1: shows the micrograph of the control 0% waste glass powder (Pure Portland cement) cured at room temperature for 28 days. In descending order of brightness, the anhydrous phases, calcium hydroxide, C-S-H gel and porosity (which appears black) can be distinguished, as indicated in plate 1.

The first connected the composition of C-S-H to that of portlandite, marked CH in plate 1 and corresponding to the cement hydration of alite and belite respectively. It is concluded that it must be finely intermixed with the C-S-H and excess of portlandite $\text{Ca}(\text{OH})_2$ of about 10% as indicated in fig. 8.

This results imply that the use of pozzolanic materials (SiO_2) reacted with the excess $\text{Ca}(\text{OH})_2$ promoted the formation of C-S-H, which was consistent with a high compressive strengths. In general, the microstructure of 10% (Plate 2.) waste glass replacement was denser than that of the control which was attributed to the presence of abundant and reactive particles of SiO_2 homogeneously dispersed. This result is similar to that of Escalante-Garcia and Sharp (2014).

The microstructure of control appeared less dense than the others, which was consistent with the excess of portlandite $\text{Ca}(\text{OH})_2$. On the other hand, it was noteworthy that unreacted waste glass powder particles were scarce, and that the smallest ones appeared completely reacted while the larger ones showed thick rims of reaction products (inner products).

This indicates that the SiO_2 strongly promoted the utilization of excess of portlandite $\text{Ca}(\text{OH})_2$, but not necessarily the reaction of SiO_2 with portlandite $\text{Ca}(\text{OH})_2$. The chemical composition of the rims of the waste glass powder particles had a composition similar to that of (Avila-López *et al.*, 2015) which indicates the presence of silica gel and C-S-H gel.

CONCLUSION

Soda lime silicate and Borosilicate glass waste are effective additives for improving the pozzolanic reactivity of cement-based cementitious materials, especially setting time, compressive strength and workability efficiency. Soda lime silicate and Borosilicate glass waste can increase the compressive strength and has a minor effect

on the setting time, concrete blended with boron and silicon compounds has appropriate setting performance and good mechanical strength. Various compositions of the samples (Control 0%, 5.0%, 10%, 15%, and 20%) of concrete cube, cylinder and beam samples were prepared and tested for strength at 7, 14 and 28 days of curing. It can be concluded that 10% waste glass replacement gave a promising result, and beyond 20% waste glass replacement the strength reduces drastically. Therefore, all the samples can be used for structural purposes, this is because all the samples exceeded the maximum strength specified by ASTM 24.2 N/mm² at 28 days.

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