

International Journal of Civil Engineering and Technology (IJCIET)

Volume 9, Issue 8, August 2018, pp. 734–743, Article ID: IJCIET_09_08_074

Available online at <http://www.iaeme.com/ijciyet/issues.asp?JType=IJCIET&VType=9&IType=8>

ISSN Print: 0976-6308 and ISSN Online: 0976-6316

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Scopus Indexed

INFLUENCE OF ALKALI CONCENTRATIONS ON THE MECHANICAL PROPERTIES OF GEOPOLYMER CONCRETE

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ABSTRACT

Geopolymer concrete is an innovative alkali-activated concrete that has been gaining applications due to its higher strength and excellent durability. In this paper, utilization of ground granulated blast furnace slag (GGBFS) and corncob ash (CCA) is investigated as source materials. The source materials were activated with the solutions of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) for the production of geopolymer concrete (GPC). Sodium hydroxide was prepared in 12 Molar, 14 Molar, and 16 Molar concentrations while grade 30 (M30) concrete was used as mix design proportion. Ground granulated blast furnace slag was substituted by CCA in 20%, 40%, 60%, 80% and 100%, while compressive strength, flexural strength, and split tensile strength were tested and cured in ambient conditions, and compared with Portland cement concrete (PCC). The findings reveal that 14 molar exhibits the best concentration for the activation of GGBFS-CCA based GPC having maximum compressive strength at 100% GGBFS with 45.57 MPa while the optimum replacement level shows 60% GGBFS and 40% CCA with 38.40 MPa compared with 35.12 MPa for PCC at 28 days curing. Thus, it is inferred that GPC has better

strength when compared with PCC, and ground granulated blast furnace slag and corncob ash prove to be innovative materials in the production of GPC.

Key words: Geopolymer concrete, Portland cement concrete, Sodium hydroxide, Sodium silicate, Compressive strength.

Cite this Article: Solomon Oyebisi, Anthony Ede, Festus Olutoge, Olatokunbo Ofuyatan and John Oluwafemi, Influence of Alkali Concentrations on the Mechanical Properties of Geopolymer Concrete. *International Journal of Civil Engineering and Technology*, 9(8), 2018, pp. 725-733.

<http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=9&IType=8>

1. INTRODUCTION

Geopolymer concrete was developed by the French Scientist, Professor Joseph Davidovits in 1978, and this has helped solve the structural deterioration that occurs within 10-20 years to reinforced concrete structures built by the Portland cement in the 21st century [1]. Geopolymer concrete is an inorganic chemical reaction between the aluminosilicate of source materials and the concentrations of alkali solutions resulting in polymeric binder [2]. It is generally known that Portland cement is widely used in the building of reinforced concrete structures but its negative implications cannot be overemphasized in that its production results in the emission of carbon dioxide to the atmosphere. Reference [3] stated that every one ton of Portland cement production emits one ton of carbon dioxide and its contribution is estimated to be approximately 1.35 billion tons annually or approximately 7% of the total greenhouse gas emissions to the earth's atmosphere. Similarly, References [4], and [5] established that carbonation-induced corrosion in reinforced Portland cement concrete structures would globally raise due to the increase in carbon dioxide levels; and that higher temperatures would possibly increase the deteriorating rates. Thus, the potential solution to the challenges of carbonation, chlorination, and environmental pollution is the adoption of geopolymer concrete which utilizes low carbon footprint and aluminosilicate materials. Moreover, ground granulated blast furnace slag and corncob ash have been utilized as supplementary cementitious materials in the production of concrete and other Civil applications by many researchers [2, 6, 7, 8, 9, 10, 11]. However, granulated blast furnace slag, fly ash, metakaolin, rice husk ash, silica fume have been utilized in the production of geopolymer concrete but no practical and theoretical experimentation exists in the utilization of both ground granulated blast furnace slag and corncob ash for the production of geopolymer concrete. Thus, this study eliminates heat curing of fresh geopolymer concrete which happens to be uneconomical and impracticable in the construction field by curing the specimens in ambient conditions at 7 and 28 days in order to replicate its utilization in the field. The ratio of sodium silicate-to-sodium hydroxide solutions was chosen as 2.5 based on the relevant studies [8, 12] while the 12 molar, 14 molar, and 16 molar concentrations were selected based on the germane studies [8, 13]. In addition, percentage replacement levels were selected based on the applicable studies [14, 15]. Moreover, this study eliminates weaknesses in the design of GPC mix design proportion. Density and aggregates are normally assumed without recourse to the specific gravities, water absorption capacity, and the moisture contents of materials used.

2. MATERIALS AND METHODS

2.1. Materials

Dangote 3x grade 42.5R Portland cement was used and sourced from cement dealer in Ota, Nigeria. Aggregates were obtained from tipper garage, Ota, Nigeria. Aggregates were used in saturated surface dry condition (SSD) with 12.5mm and 19mm size of coarse aggregate.

Sodium silicate gel, Sodium hydroxide pellets, and Conplast SP-430 were sourced from chemical dealer in Lagos, Nigeria. Water from laboratory was used for preparation and mixing purposes. Granulated blast furnace slag was obtained from Federated Steel (Nigeria) Limited, Sango-Ota, Nigeria. It was dried, ground, and then sieved with BS 90 μm sieve. Corncobs were gotten in Agbonle, Nigeria, and burnt by open process. It was also sieved with BS 90 μm sieve. The chemical compositions of both GGBFS and CCA were determined by X-Ray Fluorescence (XRF) in Lafarge Holcim Plc, Sagamu, Nigeria. The results of chemical compositions is presented in Table 1.

Table 1 The chemical compositions of GGBFS and CCA

Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	Na ₂ O	M.C	LOI
GGBFS (%)	36.52	35.77	14.11	0.92	1.08	9.45	0.30	0.52	0.32
CCA (%)	12.62	60.50	8.78	9.13	1.25	1.23	0.65	1.25	0.49

Notes: M.C (Moisture Content); LOI (Loss of Ignition)

2.2. Methods

2.2.1. Determination of Physical Properties of Materials used

The physical properties of materials used were carried out at civil engineering laboratories, Covenant University, Ota, Nigeria. The specific gravities of sodium hydroxide pellets, sodium silicate gel and conplast sp-430 were obtained from the manufacturers' manuals, and the results are presented in Table 2.

Table 2 The physical properties of materials used

Material	Specific Gravity (%)	Water Absorption (%)	Fineness Test BS 90 μm residue (%)	Moisture Content (%)
Cement	3.15	-	7.7	-
CCA	2.44	-	7.4	-
GBFS	2.90	-	7.3	-
FA	2.60	0.7		0.3
Combined CA	2.64	0.8		0.2
NaOH	1.49	-		-
Na ₂ SiO ₃	1.60	-		-
Conplast SP-430	1.20	-		-

Notes: FA (Fine Aggregates); CA (Coarse Aggregates- 12.5 mm and 19 mm sizes)

2.2.2. Design of Concrete Mix

Both the Portland limestone cement concrete and geopolymer concrete mix proportions were designed in accordance with [16, 17] to arrive at initial mix proportions in order to achieve true mix. The mix replacement levels are presented in Table 3 while the quantity of mixture proportion for the concrete constituents is summarily presented in Table 4. Target strength and absolute volume are presented in Eqns. (1) and (2) respectively.

Table 3 The mix proportions for the concrete

S/N	Constituent Proportions	Mix ID.	Remarks
1	PCC	PCC	Control sample
2	100% GGBFS + 0% CCA	GPC 1	
3	80% GGBFS + 20% CCA	GPC 2	
4	60% GGBFS + 40% CCA	GPC 3	
5	40% GGBFS + 60% CCA	GPC 4	
6	20% GGBFS + 80% CCA	GPC 5	
7	0% GGBFS + 100% CCA	GPC 6	

Specified strength (f^1c) = 30MPa (ACI 214R. Table 5.3)

$$\text{Targeted strength } (f^{1cr}) = \frac{(f^1c - k)}{(1 - zV)} \quad (1)$$

$$= \frac{(30 - 3.5)}{(1 - 2.33(0.1))} = 34.60\text{MPa}$$

$$(1 - 2.33(0.1))$$

Water-cementitious material ratio by mass of 30MPa at 28 days = 0.54.

Assume 75-100mm slump without Conplast SP-430 and a maximum of 200mm to 250mm after the SP is added to the mix. Thus, for 75-100mm slump of non-air-entrained concrete, water contents for 12.5mm and 19mm coarse aggregates are 216 and 205 respectively. Averagely, 210 was used for the trial mix design.

Thus, water content = 210kg/m³.

The air content relating to combined coarse aggregate used = 2%.

$$\text{Cementitious materials content} = \frac{210\text{Kg/m}^3}{0.54} = 390\text{kg/m}^3$$

Fineness modulus of fine aggregate = 2.80

$$\text{Coarse aggregate content} = 0.64 \times \text{bulk density} = 0.64 \times 1600 = 1024\text{kg/m}^3$$

$$\text{Superplasticizer (SP) content} = 0.015 \times 390 = 5\text{kg/m}^3 \text{ approximately.}$$

$$\text{Fine aggregate content (Absolute Volume)} = 1 - (V_C + V_W + V_{CA} + V_A)$$

Where V_C , V_W , V_{CA} , and V_A is the absolute volumes of cement, water, coarse aggregate and air respectively.

$$V = \frac{\text{Absolute volume} = \frac{M}{Sg \times \delta}} \quad (2)$$

Where M = mass of loose material (kg)

Sg = specific gravity of material

δ = density of water, taking as 1000kg/m³ @ room temperature.

Absolute volume of fine aggregate content (m³) =

$$1 - \frac{390}{3.13 \times 1000} + \frac{1024}{2.64 \times 1000} + \frac{210}{1.00 \times 1000} + \frac{2}{1.00 \times 100} = 0.258\text{m}^3$$

Mass of dry fine aggregate = $0.2.58 \times 2.60 \times 1000 = 670\text{kg}$

Moisture content of CA at saturated surface dry condition = $1024 \times [(1 + 0.007)] = 1031\text{kg}$

Moisture content of FA at saturated surface dry condition = $670 \times [(1 + 0.008)] = 675\text{kg}$

Table 4 Quantity of concrete ingredients (kg/m³)

Mixture ID	PCC	GGBFS	CCA	CA 1	CA 2	FA	SS	SH	SP	AL/B	W/S
PCC	390	0	0	516	516	675	NA	NA	3.9	0.54	-
GPC 1	0	390	0	516	516	675	150	60	3.9	0.54	0.26
GPC 2	0	312	78	516	516	675	150	60	3.9	0.54	0.26
GPC 3	0	234	156	516	516	675	150	60	3.9	0.54	0.26
GPC 4	0	156	234	516	516	675	150	60	3.9	0.54	0.26
GPC 5	0	78	312	516	516	675	150	60	3.9	0.54	0.26
GPC 6	0	0	390	516	516	675	150	60	3.9	0.54	0.26

Note: CA 1 (12.5mm Coarse Aggregate size); CA 2 (19mm Coarse Aggregate size); FA (Fine Aggregate); SS (Sodium Silicate solution); SH (Sodium Hydroxide solution); SP (Superplasticizer); AL/B (Alkali Liquid/Binder- for GPC, and Water/Binder- for PCC); W/S (Water-to-Geopolymer Solids ratio).

2.2.3. Preparation of Alkaline Activators, Mixing and Casting of Fresh Concretes

The alkaline activators were prepared 24 hours prior to casting of GPC in order to cool down the exothermic reactions of NaOH solutions to ambient conditions. A 354 gram, 400 gram, and 443 gram of sodium hydroxide pellets with 99.9% purity were dissolved in 646 gram, 600 gram, and 557 gram of clean water for the 12 molar, 14 molar, and 16 molar concentrations respectively in accordance with the standard chemistry laboratory procedures [18]. After 24 hours, sodium silicate solutions was added 3 hours prior to casting and stirred for 10 minutes. The mixing was carried out in an ambient condition (23 ± 5 °C; 60 ± 5 % RH). Both dry and liquid constituents were thoroughly mixed for 5-7 minutes until homogeneity was obtained. The fresh mix was manually cast, and then filled in the moulds and compacted accordingly. PCC samples were demoulded 24 hours after casting and immersed in water curing tank until testing day while GPC specimens were kept in rest period for 72 hours before being removed from the cubes to allow for proper polymerization. All samples were cured at room temperature in ambient condition (23 ± 5 °C; $60\% \pm 5$ % RH). For each mixture, three samples were prepared for each testing age.

2.2.4. Tests Methods

The summary of experimental tests for this study is presented in Table 5. A digital testing machine with 2000 KN maximum capacity was used for the specimens' tests as shown in Fig. 1.

Table 5 The summary of experimental tests

Test	Specification	No of Tested Samples/Mix	Sample Size (mm)	Curing (day)
Compressive strength	Reference [19]	3 cubes	150 × 150 × 150	7 and 28
Flexural strength	Reference [20]	3 beams	100 × 100 × 500	7 and 28
Split tensile strength	Reference [21]	3 cylinders	150 ϕ × 300	7 and 28



Figure 1 Experimental testing machine

3. RESULTS AND DISCUSSIONS

3.1. Chemical Compositions

The results of the chemical compositions for GGBFS in Table 1 indicate that it is suitable for use as a slag since it satisfies the requirements of [22] which specifies silicon dioxide (SiO_2) + calcium oxide (CaO) + magnesium oxide (MgO) $\geq 67\%$, and LOI $< 3.0\%$. Similarly, the chemical compositions of CCA meet the specifications of [23] which recommends silicon dioxide (SiO_2) + aluminium oxide (Al_2O_3) + iron oxide (Fe_2O_3) $\geq 70\%$, and LOI $< 10.0\%$. Hence, desirable for use as a pozzolanic material.

3.2. Compressive Strength

The results of the compressive strengths as shown in Fig. 2 indicate that compressive strength increases as GGBFS replacement level increases. Comparing the three molar concentrations, the results reveal that 14 molar (14 M) concentration of NaOH exhibits the highest compressive strength with 33.33 MPa and 45.57 MPa at 7 and 28 days curing respectively compared with 20.42 MPa and 35.12 MPa for control concrete (PCC). This infers that there is an increase in compressive strength of GPC with 38.73% and 22.93% over PCC at 7 and 28 days curing respectively. Moreover, 60% GGBFS and 40% CCA proves to be an optimum limit for GPC replacement level with 36.54 MPa, 38.40 MPa, and 36.11 MPa for 12M, 14M, and 16M respectively when compared with 35.12 MPa for PCC at 28 days curing. The higher strength of GPC both in early and later ages compared with PCC is attributed to the reactive presence of calcium-silicate-aluminate-hydrate (C-S-A-H) in the geopolymeric paste which compacts the microstructure and reduces the pores of geopolymer matrix [24]. At 16 molar concentration, compressive strength results decrease when compared with 14 molar and 12 molar concentrations. This result is contrary to [8] that the higher the molar concentration of NaOH solution, the higher the strength because more aluminosilicate will be dissolved. The reduction in compressive strength may be attributed to the fact that efflorescence develops due to the reaction of excess alkali with atmospheric carbon dioxide to form sodium carbonate crystals, resulting in the cosmetic product rather than binder product [25]. Furthermore, the amorphous structure of the source materials may be encased in the spheres and the deposit of alkali reaction products may be acted as a barrier to alkaline dissolution.

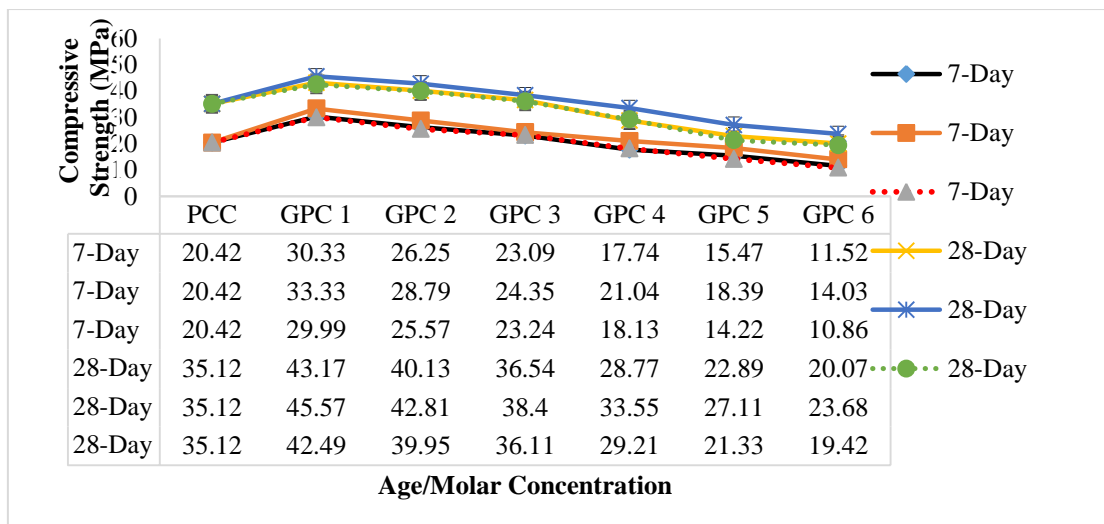


Figure 2 Graph of compressive strength against age/molar concentration

3.3. Flexural Strength

The result of flexural strength is presented in Fig. 3 and it shows that flexural strength increases as the compressive strength increases. GPC activated with 14 molar concentration at both curing days produces the maximum flexural strength when compared with other mixtures while the 12 molar and 16 molar concentrations indicate a similar trend. The optimum replacement level is 60% GGBFS and 40% CCA with 5.82 MPa when compared with 5.22 MPa for PCC at 28 days curing. This infers that GPC resists more bending or stress under an applied load than PCC.

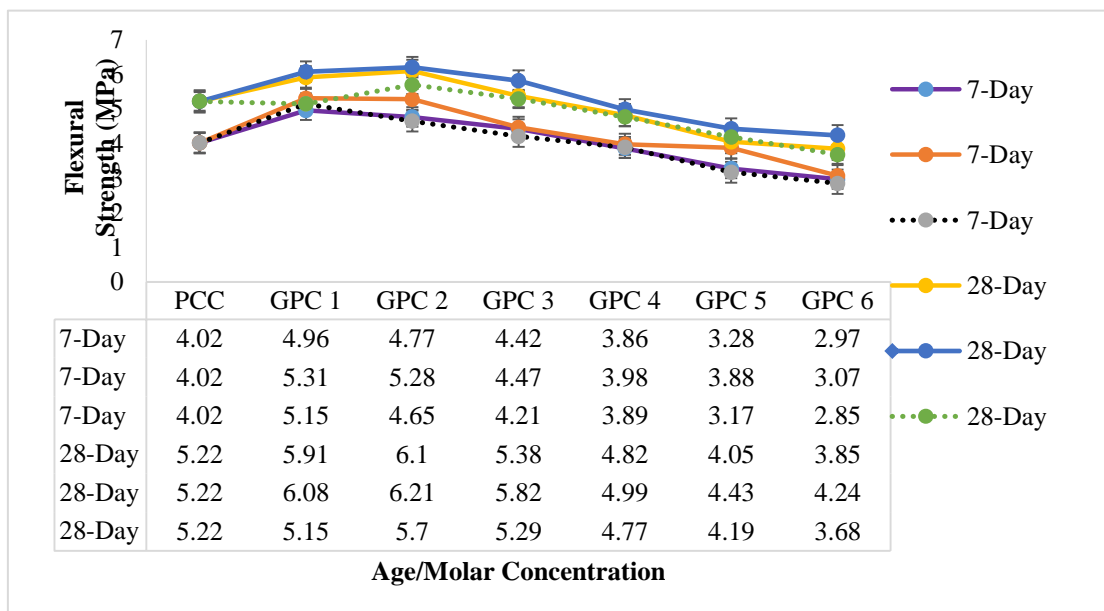


Figure 3 Graph of flexural strength against age/molar concentration

3.4. Split Tensile Strength

The results of split tensile strength presented in Fig. 4 indicate that split tensile strength increases as the compressive strength increases. GPC 1, GPC 2, and GPC 3 indicate an increase of 22.79%, 20.76%, and 17.21% for 14 molar concentration over the PCC at 28 days curing. The optimal replacement level occurs at GPC 3 with 4.01 MPa when compared with

3.22 MPa for PCC. This shows that GPC resists more tensile splitting under an applied load or induced stress than PCC.

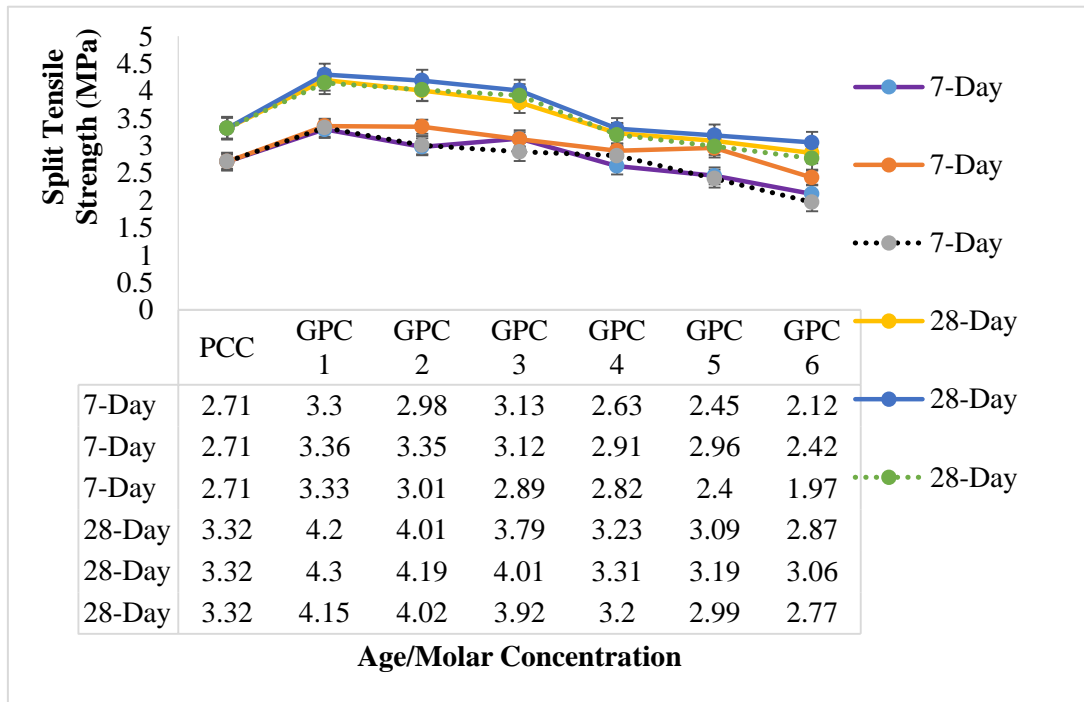


Figure 4 Graph of split tensile strength against age/molar concentration

4. CONCLUSIONS

Consequent upon the experimental findings, it is thus concluded that alkali activation of ground granulated blast furnace slag and corncob ash exhibits a geopolymer concrete with better mechanical properties when compared with the Portland limestone cement concrete. Moreover, optimum replacement level of ground granulated blast furnace slag and corncob ash for GPC is found to be 60% and 40% respectively with 14 molar concentration alkali activation as the best results. Finally, a practical and suitable geopolymer concrete is produced without being cured at elevated temperature regime by utilizing ground granulated blast furnace slag and corncob ash as source materials.

ACKNOWLEDGEMENTS

The authors appreciate Covenant University management for the financial support in course of the study and the use of laboratory facilities.

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