

PAPER • OPEN ACCESS

Effects of 12 Molar Concentration of Sodium Hydroxide on the Compressive Strength of Geopolymer Concrete

To cite this article: Solomon Oyebisi *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **413** 012066

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

Effects of 12 Molar Concentration of Sodium Hydroxide on the Compressive Strength of Geopolymer Concrete

Solomon Oyebisi¹, Anthony Ede¹, Olatokunbo Ofuyatan¹, Tolulope Alayande¹, Grace Mark¹, Joshua Jolayemi¹ Stephen Ayegbo¹,

¹Civil Engineering Department, Covenant University, Ota, Nigeria

E-mail address: solomon.oyebisi@covenantuniversity.edu.ng

Abstract. Geopolymer concrete is an emerging and innovative alkali-activated concrete that has been growingly studied because of its superior mechanical strengths and durability properties. This study, therefore, investigates the utilization of both corncob ash (CCA) and ground granulated blast furnace slag (GGBFS) as source materials activating with both sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) solutions in the production of geopolymer concrete (GPC). Sodium hydroxide was prepared in 12 molar concentration using Grade 30 MPa mix design ratio. GGBFS was replaced by CCA in varying percentages 20, 40, 60, 80, and 100% and cured in ambient conditions. Slump, density, and compressive strength of GPC were determined and compared with Portland Cement Concrete (PCC) of the same grade. The research findings indicate an optimal strength of 100% GGBFS with a compressive strength of 43.17MPa at 28 days curing for GPC compared with 35.12MPa for PCC. The result reveals that GPC has better strength than PCC and, CCA and GGBFS can be utilized as aluminosilicate materials to replace cement in the production of GPC.

Keywords: geopolymer concrete; corncob ash, ground granulated blast furnace slag; regression model; sodium silicate; sodium hydroxide; compressive strength

1. Introduction

Geopolymer concrete is an inorganic binder formed by the chemical reactions of aluminosilicate source materials of geological origin such as fly ash, slag and metakaolin activating with alkaline liquid to produce a geopolymeric gel ^[1]. To date, geopolymer concrete has been identified as a possible alternative binder to Portland limestone cement concrete due to its superior engineering properties and environmental benefits ^[1]. Portland limestone cement is the most usable binding agent in the production of conventional concrete in the construction industries, but it is generally known that cement production is a significant contributor to the emissions of carbon dioxide (CO₂) and greenhouse gasses to the atmosphere. In 2011, *Stewart, Wang, and Nguyen* established that the increase in carbon dioxide levels would globally raise the carbonation-induced corrosion in reinforced Portland cement concrete structures and that higher temperatures would possibly increase the deteriorating rates ^[2]. Similarly, *Saha and Eckelman* further forecast in 2014 that in construction projects, carbonation and chlorination penetrations in the existing Portland cement concrete structures would surpass current code-stipulated concrete cover thickness within 65 and 40 years respectively due to carbon dioxide emissions to the atmosphere ^[3]. In 2002, *Malhotra* approximately reported that Portland cement (PC) production contributes 7% of the total greenhouse gas emissions to the earth's atmosphere ^[4]. In comparison, there are about 70-80% less carbon dioxide emissions and 43-59% less energy required in the production of geopolymer cement, slag by-product ^[5]. Hence, the application of geopolymer concrete can significantly reduce the emissions of carbon dioxide into the atmosphere.

In 2017, the *United Nations Statistics Division Sustainable Development Goals (UNSDSDGs)* established that in 2014, 9 in 10 residing in urban areas breathed air which did not conform to World Health Organizations air quality guidelines as a result of greenhouse gasses and CO₂ into the atmosphere ^[6]. Moreover, rapid urbanization has brought great challenges such as increased air pollution, inadequate housing, and lack of opportunity for sustainable services and infrastructure most especially in developing countries like Nigeria. Therefore, safety, inclusiveness, resilience, and sustainability of cities and human settlements depend on the considerable alternative to the utilization of Portland limestone cement in the



production of concrete in Nigerian construction industries^[7], and one of these alternatives is geopolymer or green concrete which does not use any Portland limestone cement in its production process and the source materials are pozzolanic which are supplementary cementitious materials such as ggbfs, cca, metakaolin, and fly ash^[8-12].

Geopolymer concrete has been reported to attain excellent strength and durability when it is cured at a higher temperature normally 60-85⁰C because the ambient temperature will be too low to activate the aluminosilicate compound of the source materials and alkaline liquids^{[9][13]}. This type of elevated curing condition is not suitable and applicable for in-situ cast concrete and thus, it is important to develop a promising binder without curing at a higher temperature in order to establish a practical applicability of concrete in real fieldwork. Also, the energy requirement and cost connected with the elevated curing process will be minimally reduced.

The use of pozzolans such as CCA and low calcium fly ash as the only source material will retard the setting time, early and later age strengths. But in an attempt to achieve a geopolymer concrete cures at ambient conditions, *Nath and Sarker* in 2012, and *Parthiban, Saravanarajamohan, Shobana, and Bhaskar* in 2013 reported that an addition of ground granulated blast furnace slag significantly reduces the setting time and increases the early and later age strengths. It was discovered that the significant factor is the percentage replacement of slag with pozzolan in addition to the types of alkaline activators and molarities^[14-15]. In 2013, *Pugilla and Mondal* observed that the addition of slag speeds up pozzolan dissolution and enhances the formation of reaction products in ambient curing condition^[16]. Furthermore, higher compressive strength is achieved when a higher concentration of sodium hydroxide is used because more aluminosilicates will be dissolved thereby, forming stronger bonds^{[9][17]}. Thus, it is important to carry out a study focusing on the effects of sodium hydroxide concentration on the mechanical strength of GGBFS and CCA based-GPC.

Therefore, this study provides an understanding of slump, density and compressive strength of geopolymer concrete cured in ambient conditions at 7 and 28 days. CCA and GGBFS were used as binder materials while sodium hydroxide and sodium silicate solutions were used as alkaline activators and the investigation was done for grade 30 MPa concrete. Density and compressive strength were further analyzed by regression model to develop model equations and predict their relationships suitable for geopolymer concrete. The optimum scope of the mixture proportions was selected based on the relevant studies of *Rajini and Rao*, and *Fang, Ho, Tu, and Zhang*^[18-19]. Finally, all the experimental works in this study were carried out at the Civil Engineering Department, College of Engineering, Covenant University, Ota, Nigeria.

2. Materials and Methods

2.1. Materials

Dangote 3X Portland limestone cement Grade 42.5R was used and obtained from a cement dealer in Ota, Ogun State, Nigeria. Both fine and coarse aggregates were sourced from tipper garage, Chelsea, Ota, Nigeria. The combined coarse aggregates used in this study were 12.5mm and 19mm sizes. Fine and coarse aggregates were used in saturated surface dry (SSD) condition in consonant with the *American Society for Testing and Materials*^[20-21]. Russian made sodium hydroxide (NaOH) pellet with 99% purity and sodium silicate (Na₂SiO₃) solution were both used and sourced from Obi-Dan & Sons Chemicals Division, Lagos, Nigeria. The ratio of sodium silicate solution-to-sodium hydroxide solution was 2.5. Furthermore, the naphthalene-based superplasticizer (Conplast- SP 430) or high-range water-reducing admixture was sourced from Fine Coat Paint Industry, Lagos, Nigeria and administered at 1.0% of the binder materials in accordance with *Okoye, Durgaprasad, and Singh*^[22]. Corncobs were obtained from the heaps of waste cobs which exist in large quantity in Agbonle (8° 53' 0" North, 3° 31' 0" East), Oyo State, Nigeria. Open air burning was adopted. The corncob ash was then sieved with a 90µm sieve and then analyzed for its oxides compositions using X-Ray Fluorescence (see Figure 1) while the granulated blast furnace slags was sourced from Dolphin Steel (Nigeria) Limited, Papalanto, Nigeria. It was further

dried, ground (see Figure 1) and then sieved with a 90 μ m sieve, analyzed for its oxides composition using X-Ray Fluorescence. Finally, water was sourced from the laboratory tap and used for the production process.

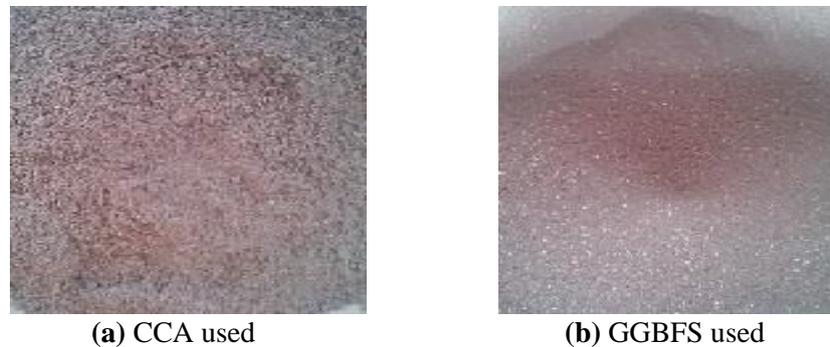


Fig. 1 The source material used

2.2 Design of Concrete Mix Proportion

Both the Portland limestone cement concrete and geopolymer concrete mix proportions were designed in accordance with the *British Standards* [23-24], taking into considerations the specific gravities, water absorptions and moisture contents of the constituents in the mix. The mix proportions and mix number is presented in Table 1 while the results of volumetric computations for both PCC and GPC are presented in Table 2 and Table 3 respectively.

Table 1 The mix proportions for the concrete

S/N	Ingredient Proportions	Mix No.	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	

Note: PCC (Portland Cement Concrete); GGBFS (Ground Granulated Blast Furnace Slag); CCA (Corncob Ash); GPC (Geopolymer Concrete)

Table 2 The volumetric computation of M30 PCC

S/N	Constituent	Weight (Kg/m ³)	Specific Gravity	Absolute Volume (M ³)	Adjusted Volume (M ³)	Ratio
1	Cement	390	3.15	0.124	0.124	1.00
2	FA (SSD)	675	2.60	0.260	0.259	2.09
3	CA (SSD)	1031	2.64	0.390	0.388	3.13
4	Water	204.15	1.00	0.204	0.204	1.65
5	Air content	2.00	-	0.020	0.020	-
6	SP	3.90	1.20	0.005	0.005	0.04
	Total	2306		1.004	1.000	7.91

Note: FA (Fine Aggregate); CA (Coarse Aggregate); SSD (Saturated Surface Dry); SP (Superplasticizer); M30 (Grade 30 Concrete); PCC (Portland Cement Concrete)

Table 3 The volumetric computation of M30 GPC

S/N	Constituent	Weight (Kg/m ³)	Specific Gravity	Absolute Volume (M ³)	Adjusted Volume (M ³)	Ratio
1	GGBFS/CCA	390	2.90/2.44	0.134	0.142	1.00
2	FA (SSD)	675	2.60	0.260	0.276	1.94
3	CA (SSD)	1031	2.64	0.390	0.414	2.92
4	NaOH solution	60	1.49	0.040	0.042	0.30
5	Na ₂ SiO ₃ solution	150	1.60	0.094	0.100	0.70
6	Conplast SP-430	3.90	1.20	0.005	0.005	0.04
7	Air content	2.00	-	0.020	0.021	-
	Total	2306		0.943	1.000	6.90

Note: GGBFS (Ground Granulated Blast Furnace Slag); CCA (Corncob Ash) FA (Fine Aggregate); CA (Coarse Aggregate); SSD (Saturated Surface Dry); SP (Superplasticizer); M30 (Grade 30 Concrete)

2.3 Preparation of Alkaline Activators

The sodium hydroxide (NaOH) solid pellet (354g) was measured and dissolved in 646g of clean water based on the 12 molar concentration ^[25]. This correctly resulted in 1000g of sodium hydroxide solution. The sodium hydroxide solution was prepared 24 hours prior to cool down the solution up to ambient condition. Thereafter, NaOH solution was added to Na₂SiO₃ (water glass) two hours prior to casting of concrete to enhance its performance for the best result ^[17].

2.4 Mixing and Casting

The cementitious materials and aggregates were thoroughly mixed for about three minutes until a homogenous mixture was obtained. The liquid and dry components were added and the mixing continued for further 5 minutes. The fresh mix was manually cast, and then filled in the moulds and compacted accordingly. Workability of fresh concrete was measured by slump cone apparatus after making the homogeneous mix. PCC samples were removed from the moulds 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 demoulded 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.

2.5 Experimental Test Methods

Slump, density and compressive strength were carried out in accordance with the procedures set out in *British Standards* ^[26-28] respectively. Slump test on freshly mixed concrete was carried out on 7 different samples. Compressive strength and dry density tests were conducted on the hardened concrete sample. Each test was examined on three samples with size 150 mm × 150 mm × 150 mm curing at 7 and 28 days.

3. Results and Discussions

3.1 CCA Oxides compositions

The results of the oxides compositions are presented in Table 4. It showed a silicon dioxide (SiO₂) content of 59.50% which is greater than the minimum requirement of 25.0% by mass recommended by the *American Society for Testing and Materials* ^[29]. Moreover, a total of (SiO₂ + Al₂O₃ + Fe₂O₃) content of 77.41% met the minimum specification of 70.0%. The magnesium oxide (MgO) and the sulphur oxide (SO₃) contents of 1.23% and 1.25% respectively are below the maximum requirement of 4.0%. The loss of ignition and the moisture contents of 0.49% and 1.25% are below the maximum specifications of 10% and 3% respectively. From the above analysis, it is inferred that the Corn

Cob Ash (CCA) used is a suitable material for use as a Pozzolan as it satisfied the required specifications [29].

Table 4: The oxides compositions of the CCA used

Composition	SO ₃	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	M.C	LOI
Properties (%)	1.25	59.50	8.78	9.13	18.23	1.23	0.65	1.25	0.49
ASTM C 618 Requirements	≤ 4%	SiO ₂ +Al ₂ O ₃ + Fe ₂ O ₃		-	≤ 4%	> 0.70	≤ 3%	≤ 10%	
		> 70%							

3.2 GGBFS Oxides compositions

The oxides compositions of the GGBFS used is presented in Table 5 and the result indicates that GGBFS is suitable for use because its properties met the requirements of the *American Society for Testing and Materials* [30].

Table 5: The oxides compositions of the GGBFS used

Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	Na ₂ O	M.C	LOI
Properties (%)	36.52	35.77	14.11	0.92	1.08	9.45	0.30	0.52	0.32
ACI 233R Requirements	32-45	32-42	7-16	0.1-1.5	0.7-2.2	5-15	-	-	-

3.3 Slump

Figure 2 shows the slump values of the geopolymer concrete (GPC) at various ground granulated blast furnace slag replacements. The results revealed that slump values were influenced by the replacement levels of ground granulated blast furnace slag (GGBFS) in the geopolymer concrete because the control sample (PCC) exhibited the similar slump to GPC (100% GGBFS). In the mixtures, the slump values increased with the decrease of ground granulated blast furnace slag content, and it is in agreement with the studies by [14] [18] [31] who reported an increase in a slump as the slag replacement levels decrease. The result can be attributed to the induced and stimulated reaction of calcium and the angular shape of ground granulated blast furnace slag when compared with the spherical shape of CCA [31]. Hence, the workability of geopolymer concrete is categorized as a highly workable concrete because the slump values exceed 90mm based on the condition of compaction [32].

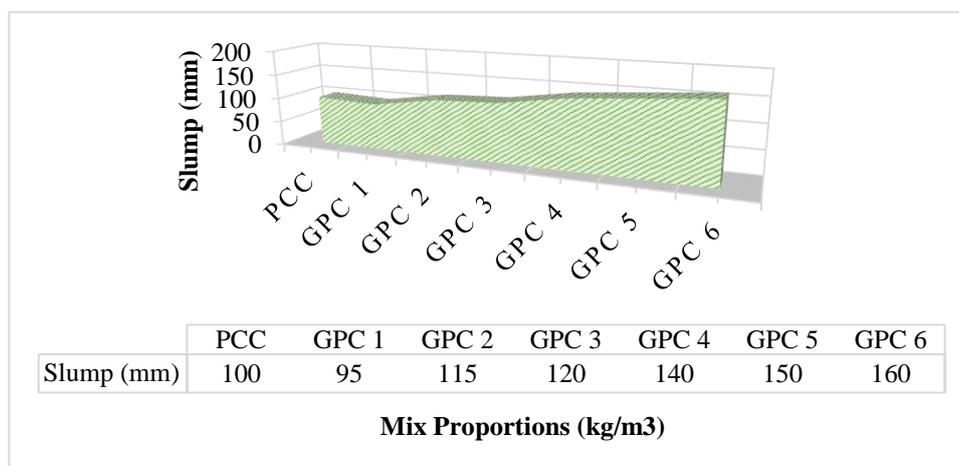


Fig. 2 Graph of a slump test

3.4 Density

The density of Portland cement concrete (PCC) from Figure 3 ranges from 2420kg/m³ in 7 days to 2400kg/m³ in 28 days. The density slightly decreases with ages as a result of the degree of hydration in the concrete. A similar pattern was noticed for geopolymer concrete (GPC 1 to GPC 3) with a density ranging from 2425kg/m³ in 7 days to 2386kg/m³ in 28 days. From GPC 4 to GPC 6, there is a slight decrease in density from 2373kg/m³ in 7 days to 2250 kg/m³ in 28 days. This infers that the addition of more corncob ash (CCA) marginally decreases the density in the GPC mix. This may be attributed to the specific gravity of CCA which is less than that of GGBFS.

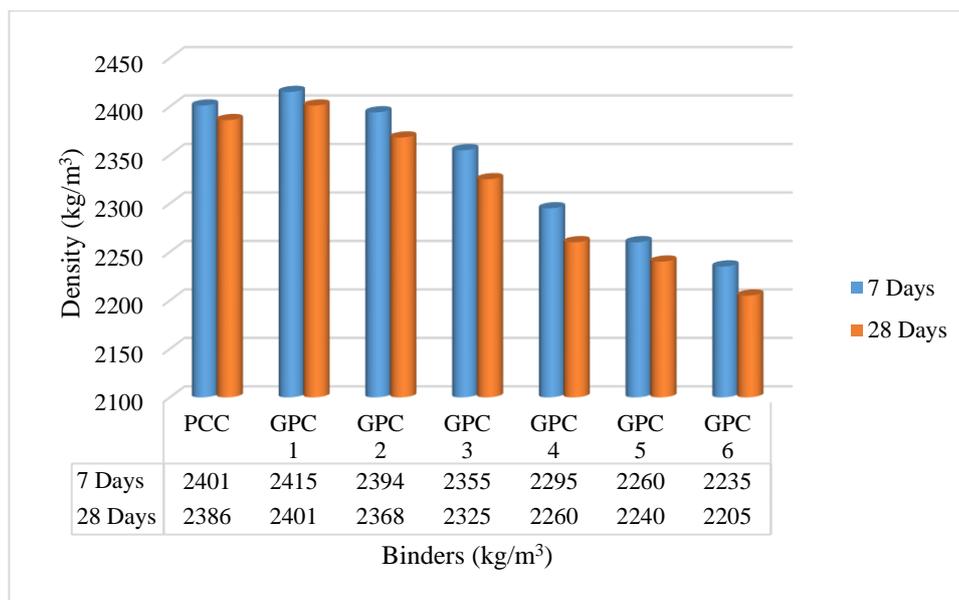


Fig. 3 Graph of density against the curing days

3.5 Compressive Strength

Comparing the compressive strengths of geopolymer concrete (GPC) to the compressive strengths of control mix (PCC) at 7 and 28 days curing in Figure 4, the results show that there is an increase in compressive strength of GPC up to 40% replacement levels over the PCC. Thus, 40% substitution of GGBFS with CCA seems to be the optimal limit for the Grade 30 mix design. The increase in both early and later strengths of GPC 1 to GPC 3 compare with the control mix (PCC) may be attributed to the reactive presence and formation of calcium-aluminate-silicate-hydrate (C-A-H-S) gels in the geopolymer paste, which compress the microstructure of geopolymer matrix, and reduce the void, and the continued-longer period of polymerization process of the GPC [33-34]. In addition, it is revealed that the compressive strength of the geopolymer concrete increased with the increased amount of ground granulated blast furnace slag in the mix. Furthermore, GPC 4, GPC 5, and GPC 6 exhibit relatively lower early age and later age strengths than the control mix (PCC) which may be imputed to the lower amount of reactive silica or aluminate in the matrix of the concrete to influence the formation of particle interaction that would yield better aluminosilicate bonds [35].

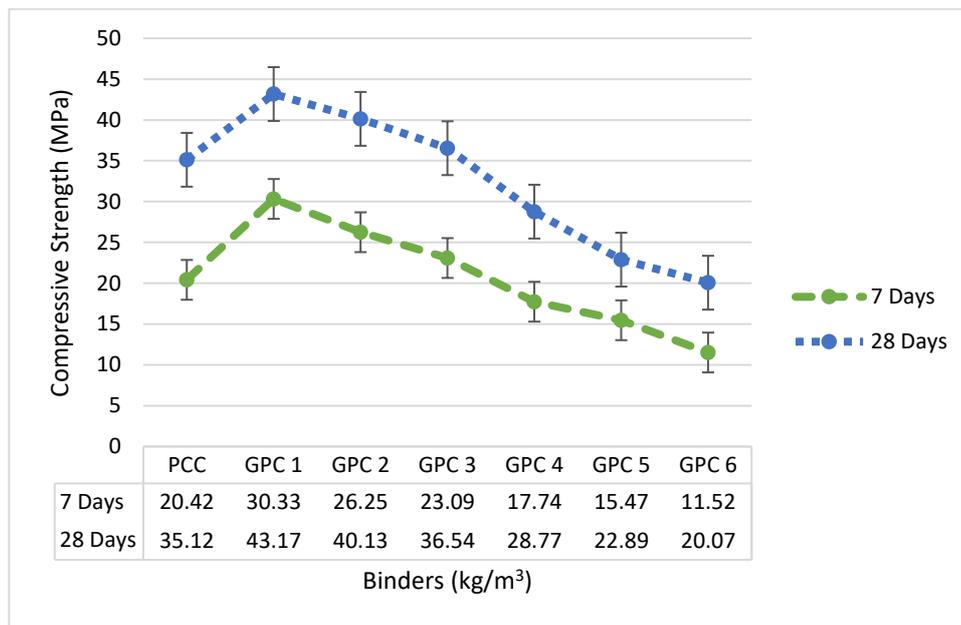


Fig. 4 Graph of compressive strength against the curing days

3.6 The relationship between the compressive strength and the density of the GPC

A standard statistical software tool (Matlab 2017a) was employed to determine the relationship that exists between the compressive strength and the density of the geopolymer concrete at both 7 and 28 days curing. The polynomial regression model at degree 2 was used. The regression equations are presented in Figure 5 and Figure 6 for 7 and 28 days respectively. With respect to compressive strength, the coefficients of determination (R^2) are 82.28% and 92.19% for density at 7 and 28 days respectively. These infer that the models are 82% and 92% significantly fit to predict the 7 and 28 relationships respectively and also, compressive strength largely depends on the density at 95% confidence bounds.

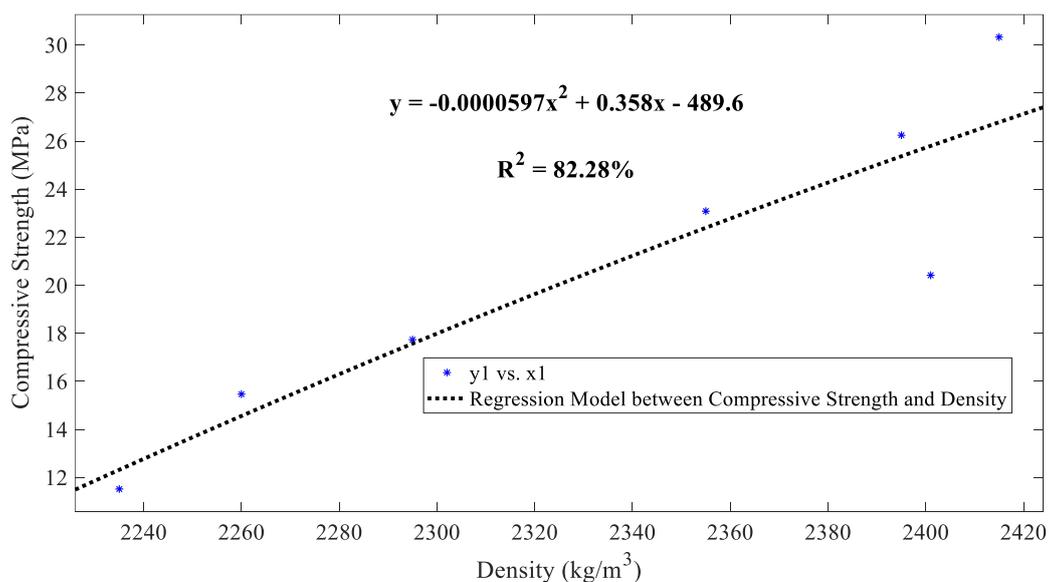


Fig.5: Relationship between the compressive strength and the density at 7 days

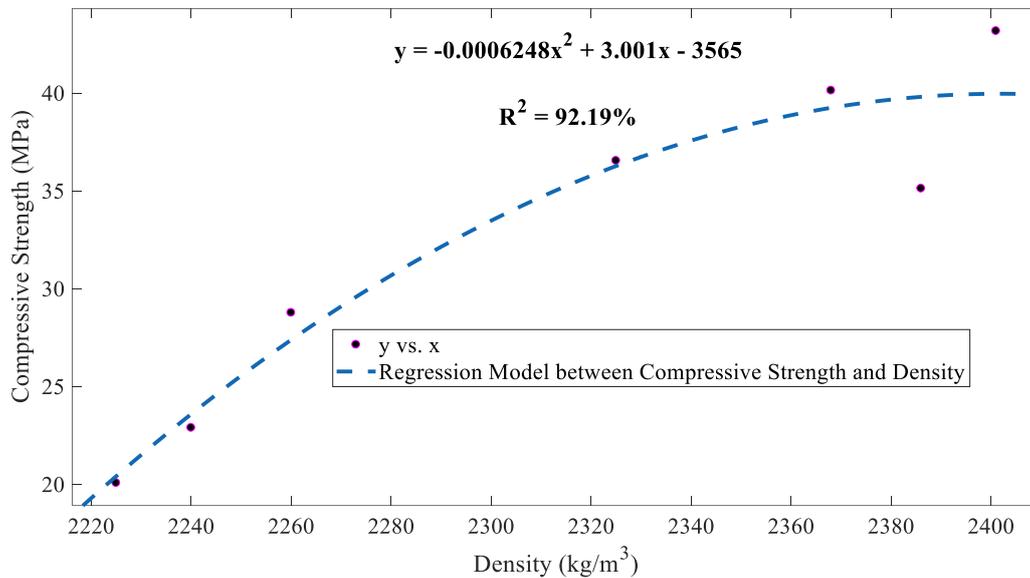


Fig.6 Relationship between the compressive strength and the density at 28 days

4. Conclusions

Geopolymer concrete shows a higher compressive strength when compared with the Portland cement concrete. Comparing with the PCC, the optimal replacement level of both GGBFS and CCA for optimum strength is obtained at 60% and 40% respectively. GGBFS and CCA-based GPC shows an emerging sustainability in place of PCC which can be utilized in general construction as a structural and non-load bearing concretes. Therefore, it is of great realistic importance to state that this study contributed to the engineering and emerging innovation for a sustainability world. It utilized the chemistry of materials for sustainable buildings, cities, and communities. Also, it established model equations to predict the compressive strength with respect to the density of the concrete.

Acknowledgements

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

References

- [1] Davidovits J. High-alkali cements for 21st century concretes. In concrete technology, past, present and future. Proceedings of V. Mohan Malhotra Symposium (pp.383-397). Editor: P. Kumar Metha, ACI SP- 144, 1994.
- [2] Stewart M, Wang X, Nguyen M. Climate change impact and risks of concrete infrastructure deterioration. *Engineering Structures*, 2011, 33(4): 1326-1337.
- [3] Saha M, Eckelman M. Urban scale mapping of concrete degradation from projected climate change. *Urban Climate*, 2014, 9: 101-114.
- [4] Malhotra V M. Introduction: Sustainable Development and Concrete technology, *ACI Concrete Journal*, 2002: 1147-1165.
- [5] Davidovits J. Geopolymer cement: A review. [Online], 2013. Available at <http://www.geopolymer.org/library/technical-papers/21-geopolymer-cement-review> 2013.
- [6] The United Nations Statistics Division Sustainable Development Goals. The sustainable development goals report. United Nations publication issued by the Department of Economic and Social Affairs (DESA), New York, NY, 2017: 10017.

- [7] Ede A N, Adebayo S O, Ugwu E I, Emenike C P. Life cycle assessment of environmental impacts of using concrete or timber to construct a duplex residential building. *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 2014, 11(2): 67-72.
- [8] Akinwumi I I, Aidomojie O I. Effect of corncob ash on the geotechnical properties of lateritic soil stabilized with Portland cement. *International Journal of Geomatics and Geosciences*, 2015, 5(3): 375-392.
- [9] Hardjito D, Rangan B V. Development and properties of low-calcium fly ash-based geopolymer concrete Research Report GC 1, Faculty of Engineering, Curtin University of Technology, Perth, Australia, 2005.
- [10] Oyebisi S O, Olutoge F A, Ofuyatan M O, Abioye A A. Effect of corncob ash blended cement on the properties of lateritic interlocking blocks. *Progress in Industrial Ecology-An International Journal*, 2017, 11(4): 373-387.
- [11] Oyebisi S O, Ede A N, Ofuyatan M O, Oluwafemi J O, Akinwumi I I. Comparative study of corncob ash –based lateritic interlocking and sandcrete hollow blocks. *International Journal of Geomate*, 2018, 15(51): 209-216.
- [12] Raheem A A, Oyebisi S O, Akintayo S O, Oyeniran M O. Effects of admixtures on the properties of corncob ash cement concrete. *Leonardo Electronic Journal of Practices and Technologies*, 2010, 16: 13-20. ISSN 1583-1078.
- [13] Fernández-Jiménez A, Palomo A., Sobrados I, Sanz J. The role played by the reactive alumina content in the alkaline activation of fly ashes. *Microporous and Mesoporous Materials*, 2006, 91(1-3): 111-119.
- [14] Nath P, Sarker P K. Effect of GGBS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. *Construction Building Materials*, 2014, 66: 163-171.
- [15] Parthiban K, Saravanaramohan K, Shobana S, Bhaskar A A. Effect of replacement of slag on the mechanical properties of fly ash based geopolymer concrete. *International Journal of Engineering Technology (IJET)*, 2013, 5 (3): 2555–2559.
- [16] Puligilla S, Mondal P. Role of slag in microstructural development and hardening of fly ash-slag geopolymer. *Cement and Concrete Research*, 2013, 43: 70–80.
- [17] Lloyd N, Rangan V. Geopolymer concrete-sustainable cement less concrete. *ACI Special Publication SP-261, 10th ACI International Conference on Recent Advances in Concrete Technology and Sustainability Issues*. American Concrete Institute, Farmington Hills, MI, 2009.
- [18] Rajini B, Narasimha Rao A V. Mechanical properties of geopolymer concrete with fly ash and ggbs as source materials. *International Journal of Innovative Research in Science, Engineering and Technology*, 2014, 3(9): 15944-15953.
- [19] Fang G, Ho W K, Tu W, Zhang M. (2018). Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature. *Construction and Building Materials*, 2018, 172: 476–487.
- [20] American Society for Testing and Materials C 128. Standard test method for relative density (specific gravity) and absorption of fine aggregate, ASTM International, West Conshohocken, PA, 2015.
- [21] American Society for Testing and Materials C 127. Standard test method for relative density (specific gravity) and absorption of coarse aggregate, ASTM International, West Conshohocken, PA, 2015.
- [22] Okoye F N, Durgaprasad J, Singh N B. Mechanical properties of alkali activated flyash/Kaolin based geopolymer concrete. *Construction and Building Materials*, 2015, 98: 685–691.
- [23] British Standard EN 206- 1. Concrete specifications, performance, production and conformity. BSI, 389 Chiswick High Road, London, 2001.
- [24] British Standard 8500- 1. Concrete: Complementary British Standard to BS EN 206-1- Part-1. Method of specifying and guidance for the specifier. BSI, 389 Chiswick High Road London, 2002.

- [25] Rajamane N P, Jeyalakshmi R. Quantities of sodium hydroxide solids and water to prepare sodium hydroxide solution of given molarity for geopolymer concrete mixes. Indian Concrete Institute Technical Paper, SRM University, India, 2014.
- [26] British Standard EN 12350-2. Testing fresh concrete: Method for determination of slump. British Standard Institution, 2 Park Street, London, 2009.
- [27] British Standard EN 12390 -7. Testing hardened concrete: Density of hardened concrete. British Standard Institution, 2 Park Street, London, 2000.
- [28] British Standard EN 12390 -3. Testing hardened concrete: Compressive strength of test specimens. British Standard Institution, 2 Park Street, London, 2000.
- [29] American Society for Testing and Materials C 618. Standard specification for coal fly ash and raw or calcined natural pozzolan for use as a mineral admixture in concrete. Annual book of ASTM standards: Philadelphia, PA, 2005
- [30] American concrete Institute 233R. Ground granulated blast furnace slag. American concrete Institute Committee, Farmington Hills, Michigan, 2002.
- [31] Deb P S, Nath P, Sarker P K. The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. *Materials and Design*, 2014, 62: 32-39.
- [32] Junaid M T, Kayali O, Khennane A, Black J. A mix design procedure for low calcium alkali activated fly ash-based concretes. *Construction and Building Materials*. 2015, 79: 301–310.
- [33] Oh J E, Monteiro P J M, Jun S S, Choi S, Clark S M. The evolution of strength and crystalline phases of alkali-activated ground blast furnace slag and fly ash-based geopolymers. *Cement Concrete Resources*, 2010, 40 (2): 189-196.
- [34] Wan X, Hou D, Zhao T, Wang L. Insights on molecular structure and microproperties of alkali-activated slag materials: A Reactive Molecular Dynamics Study. *Construction and Building Materials*, 2017, 139: 430–437.
- [35] Yip C K, Lukey G C, van Deventer J S J. The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation. *Cement and Concrete Research*, 2005, 35 (9): 1688–1697.