Investigation of Compressive Strength of Slag-based Geopolymer Concrete Incorporated with Palm Oil Fuel Ash

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Abstract: *The paper investigated the compressive strength of ground granulated blast furnace slag-based geopolymer concrete incorporated with palm oil fuel ash compared to portland limestone cement concrete. An appropriate geopolymer mix design was first determined. This mix entailed fine aggregates: coarse aggregates: cementitious material: liquid ratio of 2: 2.5: 1: 0.5, respectively, with 100% replacement of portland cement with ground granulated blast furnace slag (GGBS) incorporated with palm oil fuel ash (POFA). An alkaline solution was used in place of water containing sodium hydroxide and sodium silicate. Following this design, five geopolymer mixes were prepared, each of varying POFA-GGBS ratios of 0:100, 25:75, 50:50, 75:25, and 100:0, and a 14M alkaline solution was used. In addition, a control mix was determined, comprising 100% portland limestone cement (PLC) as the cementitious material and 100% water. Three cubic samples were casted for each geopolymer mix with the control mix, and then the geopolymer mixes were thermally cured for 24 hours. The compressive strength test was conducted on the test samples after ambient curing of 7 days and 28 days, and values for compressive strength (MPa) and failure load (KN) were recorded. Through comparative analysis, it was determined that the most efficient geopolymer mix was mix 2 of GGBS: POFA ratio of 75:25 with 14M alkaline solution. Mix 2 achieved the highest compressive strength of 65.41MPa, approximately 21.99% higher than the strength attained by portland cement concrete samples, measured to be 53.62MPa. Thus, geopolymer concrete can achieve greater strength than portland cement concrete.*

Keywords: *Alkaline solution, Geopolymer concrete, cementitious material, ground granulated blast furnace slag, compressive strength, palm oil fuel ash*

1. Introduction

The most common type of cement used globally is portland limestone cement (PLC). PLC has become a major environmental threat because of the large quantities of CO_2 released during its production. Consequently, the vast quantities of CO_2 released into the environment deplete the ozone layer (Kamaldeep and Chamberlin, 2019). However, researchers such as Mehta et al. (1982), Poon et al. (2006), Shannag and Shaia (2003), Toutanji and El-Korchi (1995), and Wang et al. (2008) have proved that certain waste materials can improve concrete and mortar's strength and durability. The waste materials include rice husk ash (RHA), silica fume, ground granulated blast furnace slag (GGBS), fly ash (FA), and metakaolin, among others.

Palm oil fuel is one of the significant contaminants of water, air, soil, and surrounding ecosystems. Therefore, the need to focus more on geopolymer concrete which is an alternative way to reuse palm oil fuel and palm oil fuel ash (Zarina et al., 2013). Prabu, Shalini, and Kumar (2014) defined geopolymer concrete (GPC) as a hardened cementitious paste made from alkaline solutions and geologically sourced materials. These source materials include palm oil fuel ash, palm kernel shell ash (PKSA), rice husk ash, ground granulated blast furnace slag, and fly ash.

The two main constituents of GPC are alkaline activators and source materials. These two constituents of GPC influence the properties of geopolymer binders (Nurruddin et al., 2016). Saafi et al. (2013) opined that GPC production has significant advantages over PLC production, with the primary benefit being the relatively low production cost with energy-efficient processes. Further, GPC resists acid attacks and exposure to high heat and has a low shrinkage speed.

Davidovits (2013) also stated that the reaction type between a source material containing aluminium (Al) and silicon (Si) and an alkaline liquid is polymerisation reaction, which produces a family of mineral binders called geopolymers. Contrasting to portland limestone cement concrete, calcium-silicate hydrates is not the primary binder in GPC. Instead, the primary binder is an

alumino-silicate polymeric gel formed by tetrahedral-bonded silicon and aluminium with oxygen atoms shared in between. Several studies suggested that when a source material like GGBFS containing large amounts of soluble silicate is added to the geopolymeric gel, a new C-S-H gel is formed due to calcium dissolution occurring at low alkalinity. Thus, this gel is the primary binder phase with small calcium precipitate scattered inside, and the GPC's mechanical strength is improved by the coexistence of the two binder phases (Yip et al., 2005).

Several researchers have also studied the feasibility of partially replacing cement with POFA. For example, Tay (1990) partially replaced cement with shell and fibre palm oil ash in concrete. His results proved that it is possible to replace up to 10% of cement with shell and fibre ash to produce GPC. Subsequently, Tay and Show (1995) reported the feasibility of partially replacing cement with oil-palm bunch ash without adverse effects on the concrete's strength and durability. Chindaprasirt et al. (2008) also reported that the introduction of POFA improved the resistance of mortar to chloride penetration.

For geopolymer concrete, compressive strength depends on the curing conditions, the concentration of alkaline liquids, age, and the ratio of binder contents. Curing in portland limestone cement concrete is conventional, which entails curing in water and ambient curing. However, the curing for GPC is quite different as many studies such as Kumaravel (2014) and Singh et al. (2015) determined that higher temperature is a vital parameter in achieving optimum compressive strength of GPC, suggesting oven or thermal curing at 60 - 80°C.

Nurruddin et al. (2018) also proved by an investigation that oven curing is most efficient for curing geopolymer concrete. The curing principle is that water is produced during the polymerisation of GPC, which is vaporised during thermal curing. This water vaporisation hardens the concrete, minimises drying shrinkage, and greatly increases compressive strength. This resulted in concluding that thermal curing is the most suitable for GPC. It was also observed by Nurruddin et al. (2018) that the longer the period of curing, the more the increase in strength. However, for optimum compressive strength, the period of curing had to be at least 20 hours and curing periods longer than 24 hours had no significant increase in compressive strength.

Many researchers, such as Yewale et al. (2016), have found that the optimum strength of GPC occurs at a curing temperature of 60°C. Similarly, several other researchers have shown through their studies on concrete and mortar that POFA improves compressive strength and sulphate resistance when it partially replaces cement. (Jaturapitakkul et al., 2007; Weerachart et al., 2007; Rukzon and Chindaprasirt, 2009; Weerachart et al., 2009). Further, an increase in water demand to achieve preferred workability for concrete when POFA partially replaced PLC was reported by Chindaprasirt et al. (2007). In contrast, the strength of concrete improved when PLC was replaced with 20% POFA, while concrete strength reduced when POFA content exceeded 20%.

Bamaga et al. (2013) also conducted a study on concrete where about 40% ground POFA was used. The study results showed that the properties of the hardened concrete, such as elasticity modulus, creep, poisson's ratio, shrinkage, and strength are similar to reference samples with as much as 30% POFA. Lastly, several researchers have concluded from their respective research that POFA has the potential to be utilised in concrete production because of its pozzolanic characteristics (Bamaga et al., 2013).

The present study investigated the compressive strength of slag-based geopolymer concrete produced with varying proportions of GGBS and POFA in comparison to portland limestone cement concrete. This is to assess the sustainability of using geopolymer concrete utilising GGBS and POFA.

2. Materials and Methods

2.1 Materials

The materials used for this research are sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), portland limestone cement (PLC), fine and coarse aggregates, palm oil fuel ash (POFA), ground granulated blast furnace slag (GGBS), and water. The NaOH and Na_2SiO_3 were purchased from a chemical supplies company in Oyo State, Nigeria. Likewise, PLC — Dangote of cement grade 42.5R — was purchased from a local cement store within Oyo State, and GGBS was sourced through Engr. Oyakhire from a steel company in Port Harcourt, Nigeria. 19mm angular and well-graded coarse aggregate material were used, while natural river sand as fine aggregates. Further, both aggregates used were sourced locally within Oyo State, Nigeria. Finally, palm oil fuel was sourced locally from a palm oil mill within Ekiti State, Nigeria.

2.2 Materials Characterisation

2.2.1 Chemical Compositions

X-ray fluorescence (XRF) spectrometry analysis was conducted to determine the oxides compositions of the POFA, GGBS, and PLC materials used, with the results shown in Table 1.

Table 1. Oxides Composition of POFA, GGBS and PLC

Oxides	POFA (%)	GGBS (%)	PLC (%)	POFA (%)
SiO_2	64.47	35.77	21.60	64.47
Al_2O_3	2.63	14.11	5.85	2.63
Fe_2O_3	5.23	0.92	2.78	5.23
CaO	4.70	36.52	64.30	4.70
MgO	3.67	9.45	1.42	3.67
Na_2O	0.18	0.30	0.14	0.18
K_2O	7.55	0.52	0.72	7.55
SO_3	0.82	1.08	2.03	0.82
LOI	15.8	1.45	1.38	15.8

According to BS EN 450-1 (BSI, 2012) and BS EN 8615-2 (BSI, 2019), a suitable material as a pozzolanic binder must have the addition of its SiO_2, Al_2O_3 and Fe_2O_3 constituents equal at least 70% of its % composition. The POFA material satisfied this chemical pozzolanic requirement, as the sum of its SiO_2, Al_2O_3 and Fe_2O_3 equals 72.33%. Thus, it can be used as a binder in GPC production. Further, the chemical composition of the POFA material used is similar to that obtained from a study by Ranjbar et al. (2014).

Likewise, the GGBS used satisfied the requirements of BS EN 15167-1 (BSI, 2006), which states a range of 32 - 40% for SiO_2 (35.77%) and CaO (36.52%) contents in GGBS. In addition, the composition of the GGBS material is similar to that obtained in a previous study by Oyebisi et al. (2022). Thus, it can be deduced that the GPC material exhibited cementitious reactivity and is suitable for GPC production. Similarly, the PLC used satisfied the chemical requirements stated in BS EN 196-2 (BSI, 2016).

2.2.2 Microstructural behaviours

Figures 1 (a), (b), and (c) show the Scanning Electron Microscopy (SEM) images of POFA, GGBS, and PLC. From the SEM images, it can be deduced that POFA has a large and irregular shape with a porous structure, while PLC has an angular shape with its internal structure wrinkled to a limited extent. Further, GGBFS has an amorphous shape with uneven surfaces. Thus, the structure and shape of the particles of POFA and GGBS significantly contribute to the geopolymer concrete's properties, as Thomas (2007) established.
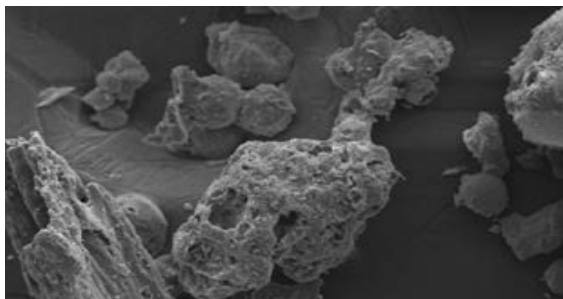

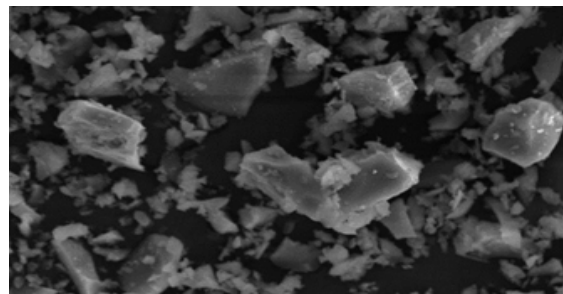**Figure 1(a).** SEM of POFA (Tonduba and Mirza, 2017)

Figure 1(b). SEM of GGBS (Adam et al., 2009)

Figure 1(c). SEM of PLC (Oyebisi et al., 2022)

2.3 Preparation of POFA

The sourced palm oil fuel was burnt and calcinated in a foundry workshop. Firstly, the palm oil fuel was burnt in the open air to ashes, and after that, a 300μm sieve sieved the ashes to remove undesired particles. Next, batches of the POFA material were calcinated in a closed furnace under a maximum temperature of 500°C for approximately 7 - 8 hours. Finally, the palm oil fuel ash was left to cool. After cooling, a miller ground the ash to obtain it in its finest form, having a maximum particle size of 45μm, as shown in Figure 2.


Figure 2. Calcinated Palm Oil Fuel Ash

2.4 Preparation of Alkaline Solution

The alkaline solution was prepared 24 hours in advance under standard laboratory conditions, as suggested by Kumar (2015). A 14 molar concentration of the alkaline activator with a ratio of 1: 2.5, as recommended by Venkatesan and Pazhani (2016), was formed from the reaction of sodium silicate (Na_2SiO_3) with liquid sodium hydroxide (NaOH).

2.5 Geopolymerisation Reaction and Mechanism

Geopolymerisation is a complex process that involves a rapid chemical reaction between a source material containing aluminosilicate and an alkaline solution. This chemical reaction produces a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Abdullah et al., 2011). Further, the composition of the product of a typical geopolymerisation process is expressed as $nM_2O \circ Al_2O_3 \circ xSiO_2 \circ yH_2O$, where "M" is an alkaline element and "n" is the degree of polycondensation (Davidovits, 1994).
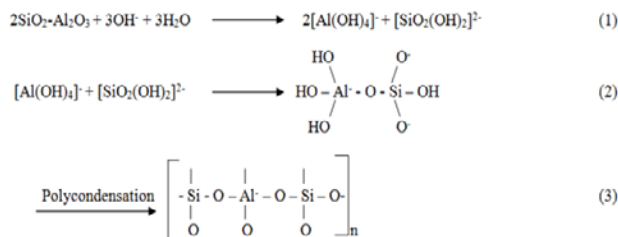
In addition, Davidovits (2008) stated that Si to Al ratio significantly influences a geopolymer's ultimate structure. Thus, geopolymer materials with a Si to Al ratio of 2 to 3.5 have very rigid structures and are suitable for constructing infrastructure projects. Davidovits (2008) also stated that polysialates (-Si-O-Al-O-), polysiloxo sialates (-Si-O-Al-O-Si-O-), and poly-disiloxo sialates (-Si-O-Al-O-Si-O-Si-O) are the three types of polysialates present in geopolymers. The chemical structures of the three polysialates are shown in Figure 3.
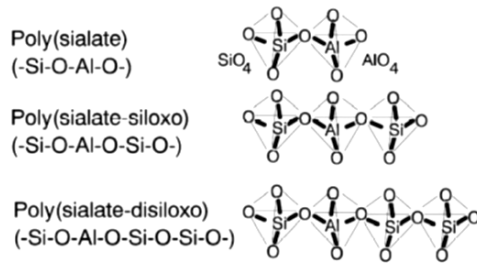
Figure 3. Chemical Structures of Polysialates
Source: Abstracted from Abdul Aleem et al. (2013)

Aziz et al. (2016) opined that the formation mechanism of the setting and hardening of a geopolymer material involves a chemical reaction with the three steps listed below and depicted by Eq. 1-3, as shown in Figure 4.
1) Dissolution of Si and Al atoms in the alkaline solution.
2) Reorganisation and diffusion of dissolved ions into monomers.
3) Polymerisation of monomers into polymeric or hydrated products.

$$2SiO_2 \cdot Al_2O_3 + 3OH^- + 3H_2O \longrightarrow 2[Al(OH)_4]^- + [SiO_2(OH)_2]^{2-} \quad (1)$$

$$[Al(OH)_4]^- + [SiO_2(OH)_2]^{2-} \longrightarrow HO-\overset{HO}{\underset{HO}{Al^-}}\cdot O \cdot \overset{O^-}{\underset{O^-}{Si}}-OH \quad (2)$$

$$\xrightarrow{Polycondensation} \left[-Si-O-Al^--O-Si-O- \right]_n \quad (3)$$

Figure 4. Three Steps of a Geopolymerisation Process
Source: Abstracted from Aziz et al. (2016)

During the formation of geopolymer concrete, water is usually released while curing the concrete. However, water is usually absorbed due to hydration during the curing process of PLC concrete. Thus, the difference in the curing processes due to the heat applied to facilitate polymerisation in geopolymer concrete significantly influences its mechanical and chemical properties and resistance to chemical attacks, water ingress, alkali–aggregate reactivity, and heat (Abdul Aleem et al., 2013).

2.6 Life Cycle Analysis (LCA) of Materials

GPC is an efficient alternative to PLC concrete because of its excellent durability properties and resistance against sulphate and acid attacks, higher mechanical strength, and lower heat of hydration (Hardjito and Rangan, 2005). Other beneficial outcomes of GPC production include environmental preservation, conservation of natural resources, and reduced disposal of waste materials into landfills (Venkatesan and Pazhani, 2016). While vast amounts of waste from agricultural and industrial processes such as POFA and GGBS are generated globally and usually disposed of in landfills, these wastes can be utilised in GPC production as cementitious materials (Malkawi et al., 2018; Mannan and Ganapathy, 2004).

In addition, for every 1Kg of PLC produced, 1Kg of CO_2 is emitted into the surroundings (Hardjito and Rangan 2005). Davidovits (2013) further broke this one-to-one ratio by explaining that 1 tonne of PLC generates 0.55 tonnes of CO_2 and an additional 0.40 tonnes when combusting carbon fuel. Therefore, sustainable alternatives to PLC concrete production are essential to reduce potential health hazards and environmental pollution problems.

2.6.1 LCA of POFA

The palm oil industry is one of the world's most essential industries; the by-products of a palm oil plantation are shown in Figure 5. According to UNDP (2007), the world is estimated to produce more than 295 million tonnes of waste annually, with about 90% produced in Malaysia and Indonesia and both countries accounting for 90% of global production and trade in palm oil. Thus, it becomes crucial to make sustainable use of the vast amounts of waste generated from palm oil plantations and related industries (Ofuyatan et al., 2021).
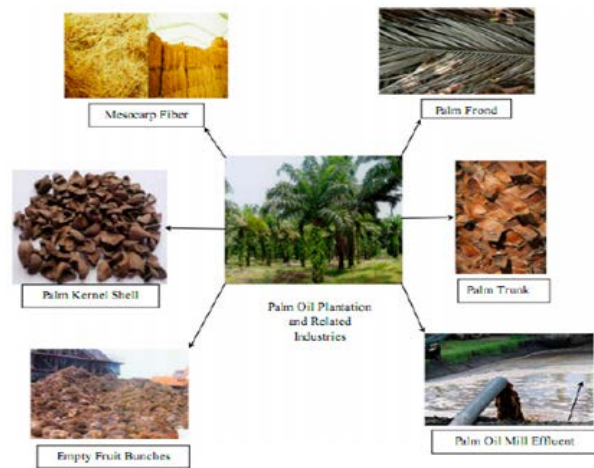
Figure 5. By-products of a Palm Oil Plantation

POFA is a solid waste produced from power plants in palm oil mills. It is usually obtained by burning empty

fruit bunches and shell and palm oil fibres as fuel in boilers. Further, palm oil mill operators often dump POFA around the mill area or in open areas without control (Bamaga et al., 2013). As a result, the increasing amount of POFA has become a contamination source to surrounding ecosystems, and therefore needs attention to prevent further harm to the environment (Zarina et al., 2013).

Additionally, several researchers have investigated the feasibility of using POFA as a partial cement replacement to produce high-performance concretes and reduce the environmental challenges caused by POFA (Thomas et al., 2017). Finally, the findings support the potential utilisation of ground POFA as supplementary cementing material in normal and high-strength concrete production due to its significant pozzolanic characteristics (Bamaga et al., 2013).

2.6.2 LCA of GGBS

Over 400 million tons of slag are produced each year globally (Kumar et al., 2019). Thus, several researchers have also studied slag due to the possibility of recycling steel production residues to produce new resource-efficient and low-carbon pozzolanic binders for concrete production (Di Maria et al., 2018). Slag is a very popular by-product of iron and steel production, commonly used as a cementitious material today. It is formed by running molten slag produced in a blast furnace directly into a pit of water or steam, or a combination of both. This quenches the molten slag, producing a glassy granular substance, which can then be ground into a fine powder to form GGBS (Prabu, Shalini and Kumar, 2014).

According to a study by Di Maria et al. (2018), it was proved that the binder properties of GPC can be activated by carbonation and alkali activation processes. Further, the study stated that utilising GGBS through alkali activation and carbonation to produce new cementitious construction materials would help reduce the environmental challenges and threats posed by cement and concrete industries. It has also been proved by Maghool et al. (2017) that GGBS poses no environmental threat for use in construction, and its use will result in a feasible and sustainable alternative for reuse of the vast amounts of slag in landfills.

Concerning CO_2 emissions, there is a considerable reduction of 80% of CO_2 emissions compared to that of PLC (Davidovits, 2013). The study also indicated that the energy needed for every 1 tonne of PLC requires approximately 4700 MJ of electric power. In comparison,

there is a significant reduction of 59% in the energy requirements for GGBS as a by-product of steel. Consequently, using GGBS will considerably decrease the comprehensive environmental issues of PLC production and improve the benefits of land resources and energy and materials conservation. However, global warming and acidification potential remain slag production's most significant environmental impacts (Li et al., 2016).

2.7 Mix Design of Test Samples

Various trial mixes were performed until the control mix of PLC resulted in 50MPa, as shown in Table 2. Five (5) mixes were considered whereby GGBS was replaced with POFA by 0, 25, 50, 75, and 100%, denoted as Mix 1, Mix 2, Mix 3, Mix 4, and Mix 5, respectively. Table 3 shows the varying quantities of GGBS and POFA in each mix.

Table 2. Mix Design of Grade 50 Geopolymer Concrete

Raw material	Ratio	Quantity per 100 mm cube
Coarse aggregates	2.5	1.0 kg
Fine aggregates	2.0	0.8 kg
Cement (PLC) / Cementitious materials (GGBS and POFA)	1.0	0.4 kg
Liquid (Water/Alkaline solution)	0.5	200 ml

2.8 Mixing and Casting of Samples

Before mixing and casting, moulds were cleaned with a clean, moist cloth to remove dust. After that, the moulds were lubricated with oil. The sandwich mixing method was adopted to minimise errors and encourage a more homogenous mix. Further, the required volume of the prepared alkaline solution was measured using a measuring cylinder and mixed with the solid components to form a homogenous mix. Immediately after mixing the freshly prepared concrete, it was filled into the moulds and vibrated. The vibration was crucial to ensure the concrete was properly compacted and reduce air voids. In addition, the resulting cubes were left to set for 24 hours to allow for adequate polymerisation and enhancement of mechanical properties. The cast test samples are shown in Figure 6.

2.9 Curing and Testing of Samples

The cubes were demoulded after 24 hours of proper polymerisation and enhancement of mechanical properties. After that, the test samples were thermally cured in an oven for 24 hours at a temperature of 60±3°C.

Table 3. Composition of Mixes 1-5 per 100mm Cube

Mix	Coarse Aggregates (kg)	Fine Aggregates (kg)	GGBS (%)	GGBS (kg)	POFA (%)	POFA (kg)	NaOH Solution (ml)	Na₂SiO₃ Solution (ml)
1	1	0.8	100	0.4	0	0	57	143
2	1	0.8	75	0.3	25	0.08	57	143
3	1	0.8	50	0.2	50	0.16	57	143
4	1	0.8	25	0.1	75	0.24	57	143
5	1	0.8	0	0	100	0.32	57	143

Figure 6. Test Samples

Afterward, the test samples were cooled to room temperature to avoid a sudden temperature change. They were later laid out in an area within the laboratory untouched for two test periods of 7 and 28 days at room temperature (approximately 30°C).

At the end of the 7 and 28 days of curing the test samples, a density test was conducted. Afterward, the compressive strength of the test samples was performed using BS 1881-116 (BSI, 1983). Therefore, the PLC and GPC samples were crushed using a compressive strength-testing machine. The machine applied loads on the samples, as shown in Figures 7(a) and (b), and the compressive strengths were recorded. From the latter, the failure load values were calculated and recorded.
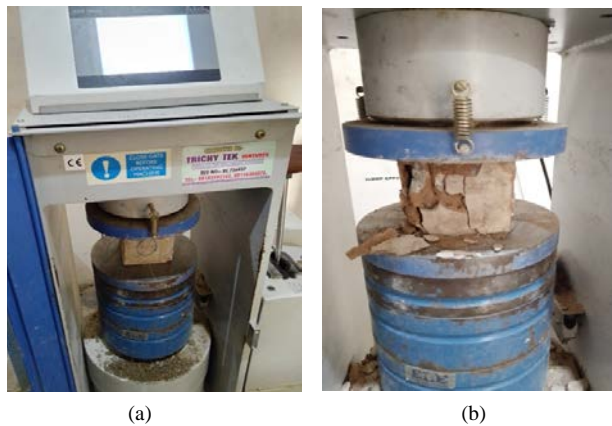

(a)   (b)

Figure 7. Compressive Strength Test on Samples

3. Results and Discussion
3.1 Density Test

The average densities of the test samples after 7 and 28 days of curing are presented in Table 4. Figure 8 shows that the average density of the GPC mixes decreased with increasing POFA content. When compared with the

control PLC mix, the decrease in average density at 7 days is 1.15%, 2.13%, 4.01%, and 9.54% for Mix 1, Mix 2, Mix 3, and Mix 4, respectively, while it is 0.87%, 1.30%, 3.17% and 6.51% at 28 days for Mix 1, Mix 2, Mix 3 and Mix 4 respectively. By comparing only the average densities of the GPC mixes, the results above show why Mix 1 and Mix 2 have better compressive strengths than Mix 3 and Mix 4. This is because density highly influences the mechanical properties of concrete, and denser concrete can more easily achieve fewer voids, low water absorption, low permeability to soluble substances and water, higher strength, and better durability.

Table 4. 7 and 28 Days Average Densities of Test Samples

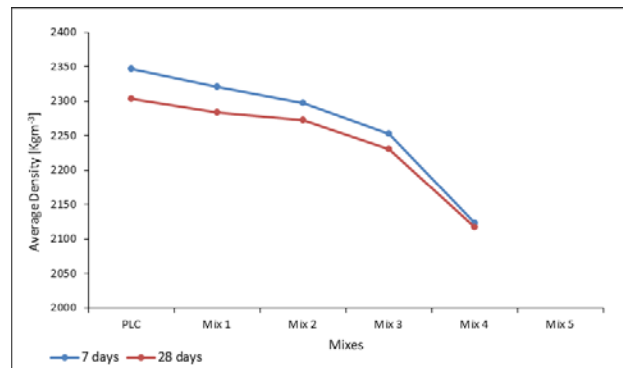| Mix	Average density (kgm^{-3}) at 7 days	Average density (kgm^{-3}) at 28 days
PLC	2347	2303
GPC Mix 1	2320	2283
GPC Mix 2	2297	2273
GPC Mix 3	2253	2230
GPC Mix 4	2123	2117
GPC Mix 5	-	-

Figure 8. Average Densities of GPC and PLC Mixes at 7 and 28 Days

3.2 Compressive Strength Test

The average compressive strengths of the test samples after 7 and 28 days of curing are presented in Table 5. Figures 9 and 10 show that average compressive strength increases for the first two mixes with 100% GGBS – 0% POFA and 75% GGBS – 25% POFA respectively, while it decreased for the last two mixes with 50% GGFBS – 50% POFA and 25% GGBS – 75% POFA respectively. In addition, the average compressive strength of Mix 1 and Mix 2 at 28 days are 8.28% and 21.99% greater than that of the control mix of PLC, respectively, while that of Mix 3 and Mix 4 are 59.12% and 81.15% lower than that of the control mix of PLC respectively. For Mix 5, specimens did not set nor harden as they collapsed upon demoulding. The results above imply that Mix 1 and Mix 2 can withstand and resist more compressive loading without any crack or deflection than the control mix of PLC, hence, suitable for commercial and industrial structures

and in cases where high thermal and chemical resistance are required. On the other hand, Mix 3 and Mix 4 are suitable for domestic use.

**Table 5.** 7 and 28 Days Average Compressive Strength of Test Samples

Mix	Average compressive strength (MPa) at 7 days	Average compressive strength (MPa) at 28 days
PLC	32.79	53.62
GPC Mix 1	34.83	58.06
GPC Mix 2	42.11	65.41
GPC Mix 3	15.23	21.92
GPC Mix 4	6.46	10.11
GPC Mix 5	-	-

3.3 Optimum Percentage Substitution of GGBS and POFA

Figures 8, 9, and 10 show that the mix with the optimum percentage substitution of GGBS and POFA is Mix 2, which corresponds to 75% GGBS – 25% POFA and has its average density and compressive strength at 28 days to be $2273 Kgm^{-3}$ and 65.41MPa, respectively. Therefore, the optimum percentage substitution of GGBS and POFA recommended is 75% GGBS – 25% POFA.
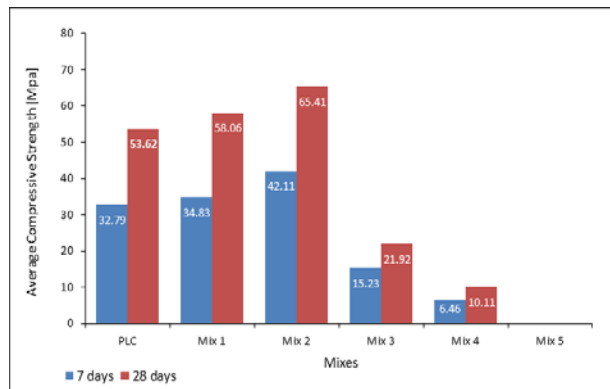
Figure 9. Average Compressive Strength of GPC and PLC Mixes at 7 and 28 Days
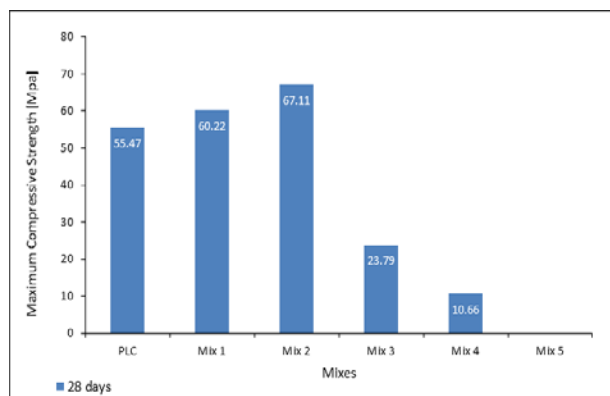
Figure 10. Maximum Compressive Strength of GPC and PLC Mixes at 28 Days

4. Conclusions

Geopolymer concrete is highly efficient in reducing portland limestone cement production and, thus, carbon footprints in the construction industry. The following can be deduced from the findings of this study:

1) GPC Mix 1 and GPC Mix 2 obtained the highest compressive strengths, which were 8.28% and 21.99% higher than the control PLC mix after 7 and 28 days, respectively.

2) GPC Mix 2 (75% GGBS – 25% POFA) achieved the highest compressive strength of 65.41MPa because of the reasonably high fineness of POFA particles, high packing factor, and increased pozzolanic reactivity in the geopolymer process.

3) The GPC Mix 5 containing 0% GGBS – 100% POFA cannot be considered an alternative to conventional concrete because the test specimens did not harden. The specimens did not harden because of the absence of GGBS to contribute more SiO_2 and Al_2O_3 contents and aid calcium dissolution to enhance the compressive strength of the mix.

4) The GPC mixes blended with POFA demonstrated low workability because of the increased alkaline solution demand due to the porous structure and large surface area of the ground POFA particles.

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