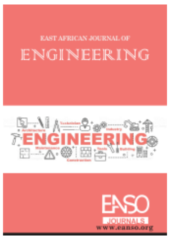

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Original Article

Effect of Bamboo Leaf Ash on The Properties of Geopolymer Concrete at Ambient Curing Temperature

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ABSTRACT

As a result of the growing environmental concerns in the cement industry and the rising cost of building materials, alternative cement technologies have become an area of increasing interest. In this study, geopolymer concrete containing fly ash class F and bamboo leaf ash was chosen as a cement substitute in concrete manufacturing. This research was an experimental study evaluating the effect of bamboo leaf ash (BLA) on geopolymer concrete by addition as a partial replacement of fly ash. The test samples were 100 x 100 x 100 mm cubes and 300 x 150 mm cylinders at the ambient curing temperature. The design mix of C25 was used for this study. This research aimed to explore the suitability of the use of bamboo leaf ash as a mixing material in geopolymer concrete in more environmentally friendly industries. The properties that were investigated in this study are the basic aggregate tests, XRF analyses of BLA and fly ash, and workability tests by evaluating slump and compaction factor tests. In addition, compressive strength and splitting tensile strength of 28, 56, and 90 days. Therefore, in this study, various levels of bamboo leaf ash were utilized, including 0%, 5%, 10%, 15%, and 20% BLA. The alkaline liquid-to-binder ratio for all mixes was constant at 0.6, while the Na_2SiO_3 to NaOH ratio was 2.5. The test results of the workability show that the increased amount of bamboo leaf ash gradually reduces the alkaline liquid. The result of compressive and splitting tensile showed that fly ash substitutes that contained 5% and 10% of the bamboo leaf had higher strengths of about 38.7 MPa, 40.8 MPa, 4 MPa, and 4.22 MPa, respectively than other mixtures. Therefore, bamboo leaf ash can be one of the constituent materials used to improve the mechanical properties of geopolymer concrete.

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INTRODUCTION

Cement production has increased worldwide, producing 3.6 billion tons of cement in 2011 (Armstrong, 2012). In 2020, carbon dioxide (CO_2) emissions increased by 50% due to Portland cement production (Andrew, 2018). One ton of cement produces about one ton of ambient carbon dioxide (Shaikh, 2016). Concerns about environmental conservation are frequently raised with regard to cement being used in concrete as a binder. Moreover, the cost of cementitious materials for the construction sector is continually rising. According to Andrew (2018), the global concrete industry is in dire need of binding materials, which is likely to lead to less cement usage. In light of these facts, the development of new sustainable materials is a very effective line of work for the modernisation of the construction industry. One of the most acceptable possibilities in this regard is the processing of geopolymer concrete. Thus, geopolymer materials represent a potential solution to minimise both the environmental effects and the cost of binding materials.

Geopolymers are inorganic polymeric materials that have a chemical composition similar to zeolites but contain an amorphous structure and possess ceramic-like structure and properties. In a simple definition, geopolymer is a "new" material that does not require the presence of Portland cement as a binder. Alternatively, pozzolanic materials with high silicon and aluminium content, such as industrial products (fly ash, slags, silica fume, etc.) or agricultural wastes (rice husk, bamboo leaf ash, etc.), are activated by alkaline liquids to generate the binder. Hence, geopolymers can provide the possibility of preparing inorganic bonds. Additionally, the silicon (Si) and aluminium (Al) are dissolved in an alkaline activating solution and subsequently polymerise into molecular chains and become the binder (Aleem et al., 2012). Furthermore, the ultimate structure of the geopolymer concrete greatly influences the ratio of silicon to aluminium (Si: Al), with the materials most often considered for use in transportation infrastructure generally having a Si: Al ratio of between 2 and 3.5 (Lloyd et al., 2009).

Accordingly, this study presented knowledge on fly ash-based geopolymer concrete with bamboo leaf ash. Instead of Portland cement, low-calcium fly ash (ASTM Class F) was used as the main source material when manufacturing the concrete. In terms of civil engineering applications, geopolymer concrete has shown a higher performance of mechanical properties, resisting weathering action, chemical attack, and lower creep effects than ordinary Portland cement (OPC), according to Bagheri et al. (2014) and Wallah (2010). The most common materials in geopolymer concrete are pozzolanic resources, whether natural pozzolanic or industrial by-products. Pozzolans comprise silica and alumina which could react with lime at room temperatures to form cementitious compounds like calcium silicate, calcium aluminate, and calcium sulphoaluminate hydrates in the presence of moisture (ASTM C 618). Moreover, the pozzolanic reaction is a simple acid-base reaction between calcium hydroxide Ca $(OH)_2$ and silicon oxide (SiO_2) to generate calcium silicate hydrate (C-S-H), as illustrated in equations (1) and (2).

$$3Ca\,(OH)_2 + 2SiO2 \rightarrow 3CaO.2SiO2.3H_2O \qquad \text{Eq 1}$$

Abbreviated form $3CH + 2S \rightarrow C_3S_2H$ Eq 2

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Pozzolanic materials containing less calcium oxide, such as calcined agricultural wastes and fly ash, do not react with normal water; they need an activator. The most common activators are alkaline liquid solutions comprising sodium hydroxide (NaOH), sodium silicate ($Na2SiO_3$), and potassium hydroxide (KOH). When comparing sodium hydroxide and potassium hydroxide, sodium hydroxide (NaOH) is preferred because it has a better capability to liberate silicate and aluminate monomers (Duxson et al., 2007).

This study also utilises one of the agricultural waste materials known as bamboo leaves. Bamboo leaf ash (BLA) is one of the new pozzolanic materials in geopolymer concrete, which has a high silicone content. Producing bamboo leaf ash requires drying, burning, and heating in the furnace before using it. Using additive materials such as bamboo leave ash (BLA) is one of the solutions that minimise environmental hazards and the total cost of concrete materials. Bamboo in East Africa is grown in tropical countries such as Kenya, Uganda, Malawi, and Tanzania (Poulsen et al., 2020). Therefore, this study is unique since it examines the effect of calcined bamboo leaf ash on geopolymer concrete concerning fresh properties of GPC (workability) and mechanical properties, such as compressive strength and splitting tensile strength.

MATERIAL AND METHODS

Bamboo Leaf Ash (BLA)

Twenty-seven kilograms of bamboo leaves were collected from Kenya's rainforests at the Mt. Kenya Forest with permission from Kenya Forest Service, Headquarters. The leaves were dried until they became folded and husky and then were burned in a kiln to produce ash and remove the organic substances. The ash was then taken to the University of Nairobi's Mechanical Department lab, where it was heated at 650–750 °C for two hours in order to eliminate extra carbon in the ash. After cooling the ash, it was sieved using a 75-micron sieve to obtain fine particles similar in size to cement particles.

Fly Ash Class F

The fly ash used in this study was low-calcium (ASTM Class F) as the main binding material for the production of geopolymer concrete. Furthermore, fly ash class F contains more than 70% aluminosilicate content. ASTM C-618 was used as the specification for fly ash with a specific gravity of 2.2. So, in this experimental study, the fly ash used was purchased at the Rangeela export market in Mumbai, India. The fly ash contained less than 10% calcium oxide content. Thereafter, the fly ash was taken into the geotechnical survey (Bruker) Laboratory in Nairobi to analyse chemical composition as well as to ensure compliance with standard requirements.

Alkaline Liquids

The primary binding agents for geopolymer concrete are alkaline liquids. The alkaline liquids used for polymerisation were the analytical-grade of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The ratio of activators for sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was 2.5. The alkaline liquid to fly ash ratio was chosen to 0.6 after trial mixing.

Aggregates

Sieve analysis of both fine and coarse aggregates was carried out in accordance with BS EN 12620 - (2022) to determine the different fractions of the size of taken aggregate samples and also to ensure standard specification requirements and the compliance of the mix design.

Test Methods

Grading of Aggregates

The sieve analysis of course and fine aggregates was carried out in compliance with BS EN 12620-2002 to ensure the design, production control, and compliance guidelines.

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Hydrometry Analysis of Bamboo Leaf Ash, OPC Cement, And Fly Ash

These tests were carried out following the BS 1377-2 standard to determine the particle size distribution of bamboo leaf ash, ordinary Portland cement (OPC) and fly ash for particles passing the N.200 (75 microns) sieve size. The apparatus included a 1000ml glass cylinder, beaker, time measure, mechanical stirrer, sedimentation cylinder, weight balance, and hydrometer. Hydrometer is an instrument that is designed to assess the relative density of a liquid which refers to the ratio of the actual density of the substance to the density of the water. First, a 50g dry sample of bamboo leaf ash, OPC, and fly ash was sieved at 0.075mm and tested on three different days.

The ash was poured into the mechanical stirrer with a small amount of water and mixed for 5 minutes. Then, the dispersion agents were added into the measuring cylinder in order to avoid the fine particles sticking together and allow every particle size to fall free. The dispersion agents used were a combination of 7 grams of sodium carbonate (Na_2O_3), 33 grams of sodium hexametaphosphate ($NaPO_3$)6 and 100ml of water. Later, the water was poured into the measuring cylinder up to 1000ml, and then a hydrometer was inserted inside gradually until it was stabilised. The scale of the hydrometer was then read and noted based on its submersion at an interval of 0.5 minutes up to 120 minutes.

Chemical Composition of Fly Ash, BLA, and OPC Cement

These tests were carried out following the requirements of the ASTM C618-12a standard. The chemical composition of fly ash (ASTM class F) and bamboo leaf ash (ASTM class N) and ordinary Portland cement (OPC) was analysed to get detailed information on the materials' characteristics and to ensure the resulting products are to the required standards. And also, the chemical composition of OPC cement was tested and obtained in order to see and compare the difference between the pozzolanic materials of GPC and OPC cement. For instance, variations of silicon dioxide (SiO2), aluminium oxide (AL2O3), ferric oxide (Fe2O3), calcium oxides (CaO), and magnesium oxide (MgO) contents. These are the common molecules that separates pozzolanic, non-pozzolanic, and cementitious materials. Two grams of fly ash, bamboo leaf ash, and OPC cement were tested using X-Ray Fluorescence (XRF).

Mixing Method of GPC

The mixing method of geopolymer concrete is similar to standard concrete and the process is carried out in the laboratory at room temperature. A lab pan mixer with a capacity of 70 litres was used to mix the geopolymer concrete. The mixing pan was properly cleaned to remove any leftovers from the previous batches. Furthermore, the inner surface of the pan was also lightly moistened to minimise water attraction from the mixtures. In the mixing pan, coarse aggregates were initially loaded, followed by sand, which was prepared in a saturated-surface-dry condition. After that, aggregates were thoroughly mixed for 2 to 3 minutes. Then, before applying the activator solution, fly ash and various amounts of calcined bamboo leaf ash were put into the mixing pan combined and properly mixed for another 2 or 3 minutes. While the mixing was going on, a premixed alkaline activator solution of sodium silicate and sodium hydroxide was added gradually.

Workability of Geopolymer Concrete

The workability of freshly prepared geopolymer concrete mixtures was measured by using a slump and compaction factor apparatus.

Mechanical Properties of Geopolymer Concrete

Compressive Strength

The compressive strength test of geopolymer concrete for this study was carried out to BS EN 12390-3 (2002). In this test, a cube size of 100 x 100 x 100 mm was used. The inner surface of the mould was cleaned and oiled to avoid sticking to the concrete. Then the moulds were filled with the prepared C25 geopolymer concrete mix. Once the mould was filled, the top surface of the mould was

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levelled using a trowel to make it smooth. Additionally, after the concrete hardened the cubes were demoulded and then taken into the curing at room temperature. 28-day, 56 days, and 90-day specimens were tested by a compression testing machine as shown in *Plate 1* by applying the load rate of 6.8 kN/s. The failure load divided by the cross-sectional area of the specimen gave the compressive strength as per Equation 3.

$$Compression\ strength\ \left(\mathrm{Fc}, \frac{\mathrm{N}}{\mathrm{mm2}}\right) = \frac{Maxmium\ load}{Cross-sectional\ area} \quad \text{Eq 3}$$

Plate 1: Compressive strength test

Splitting Tensile Strength

The splitting tensile strength test was carried out in accordance with BS EN 12390-6:2009. A cylindrical specimen size of 300 mm in length and 150 mm diameter was preprepared and cast. After curing for 5 days at room temperature, the samples were removed from the moulds. To ensure that the specimen's two ends are on the same axial position a diametrical line was drawn on them by using a marker. The geopolymer concrete cylinders were subsequently crushed by applying a compressive load without shock at a rate of around 14–21 kg/cm^2/minute throughout their entire length. The maximum breaking load (P) was then recorded. Splitting tensile strength was calculated by following Equation 4.

$$Splitting\ tensile\ strenght\ \left(\frac{N}{mm2}\right) = \frac{2P}{\pi DL} \quad \text{Eq 4}$$

RESULTS AND DISCUSSION

Grading of Coarse Aggregate

Figure 1 shows the average particle size distribution of coarse aggregate from the finest to the largest particle size. The cumulative passing percentage (%) of the 20 mm sieve size was 100%, whereas the 14 mm sieve size was 96.8%. The percentages for the 10- and 5-mm sieve sizes were 61.9% and 8.8%, respectively. The retained percentage mass of the 20 mm, 14 mm, and 10 mm sieve sizes were 0%, 3.2%, and 34.9%, respectively, while 5 mm and 2.36 mm sieve sizes were 53.1% and 8.8%, respectively. This result of sieve analysis passes the grading standard of BS 882: 1992. The purpose of this test was to determine the different fractions of coarse aggregates and the paste requirement for workable concrete. The distribution of various particle sizes affects the engineering properties of the concrete, such as strength and durability. For example, if the size of the coarse aggregate is

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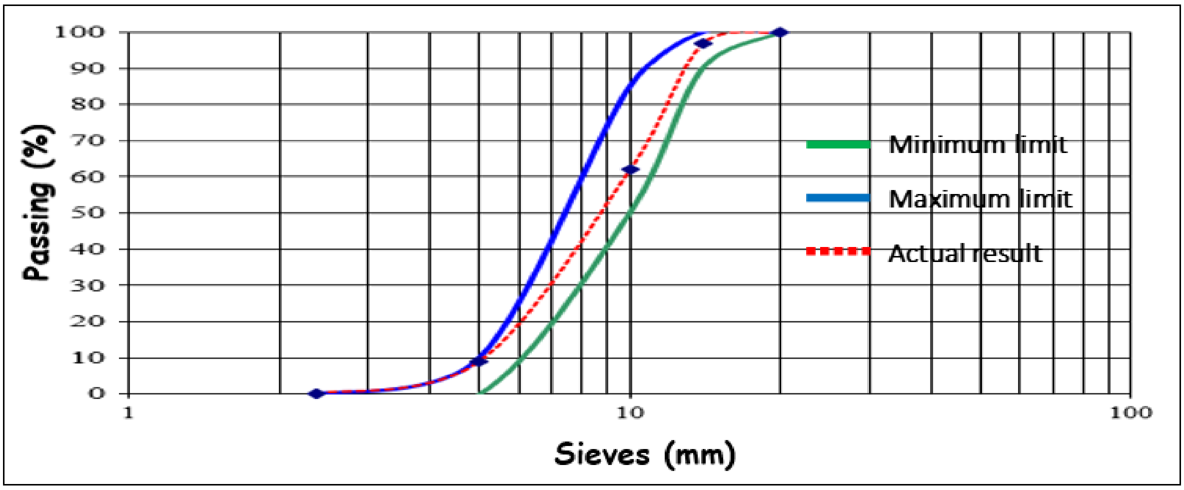
bigger or all uniform, it causes many gaps in the concrete mix which then will require more quantity of binding materials to fill up the extra spaces. So, the combination of all different sizes of coarse aggregate results is necessary to minimise voids in concrete

Figure 1: Grading curve of coarse aggregate

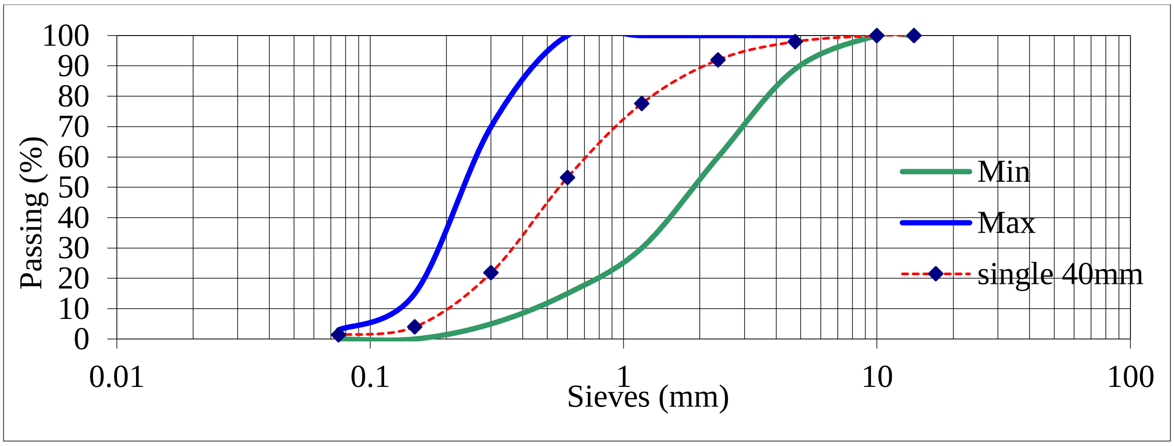


These findings are similar to the results of Ajamu and Ige (2015). They concluded that the coarse aggregate size is proportional to the workability (slump) of fresh concrete with a constant water-cement ratio and that the compressive strength of concrete increases as coarse aggregate size increases. Strange and Bryant (1979) also found that when aggregate size increases, the fracture toughness of the concrete also increases.

Grading of Fine Aggregate

Figure 2 illustrates the fine proportion of different grain sizes in river sand. According to *Figure 2*, the total retained percentage above 600 microns was 34.6%, while the retained percentage below 600 microns was 65.4%. Thus, the sand is categorised as zone 2 under B.S. 882-1992. This result shows that the sand was fine-graded with a fineness modulus of 2.53. Neville (1981) suggested that the number of particles smaller than 600 microns in size has a large effect on the workability of the mix ratio and gives a reasonably reliable index on the specific surface of fine aggregates. Good quality sand must have coarse, medium, and fine grain sizes, while poorly graded sand is composed of one or two of the three possible grain sizes. Meanwhile, in terms of workability well, graded sand minimises the demand for more liquid. Therefore, well-graded sand can lead to producing good quality geopolymer concrete.

Figure 2: Grading curve of river sand



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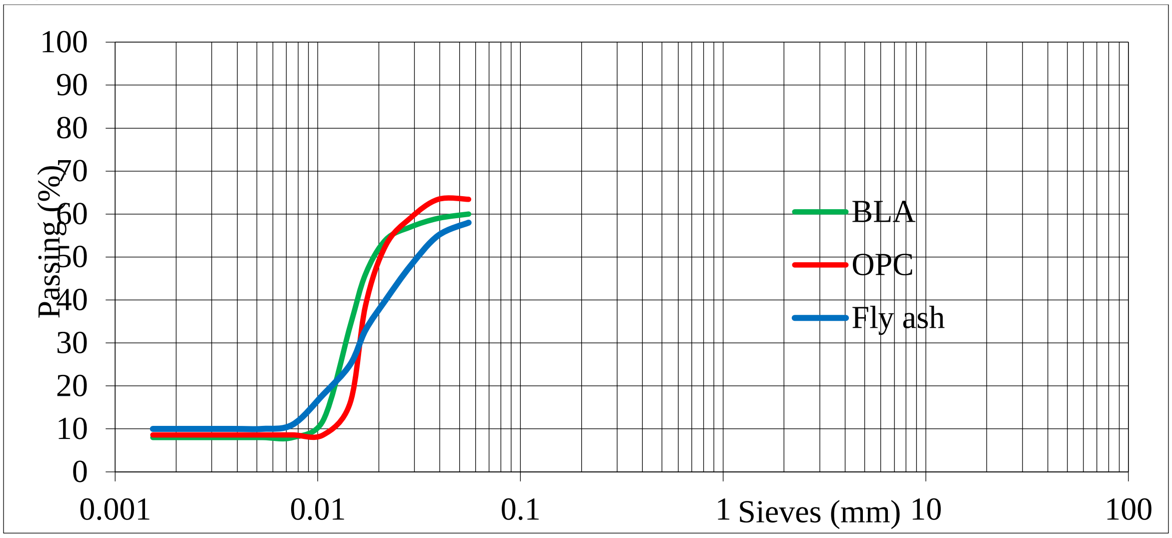
Particle Size Distribution of Bamboo Leaf Ash (BLA), OPC, and Fly Ash

Figure 3 shows the particle size distribution of bamboo leaf ash, ordinary Portland cement (OPC), and class F fly ash used in this study. The diameter of fine bamboo leaf ash particles ranged from 0.056 mm to 0.002 mm. While the particle size distribution of fly ash ranged from 0.061 mm to 0.002 mm. For OPC cement, particle size distribution varied from 0.055 mm to 0.003 mm. Based on *Figure 3*, the test results of BLA, OPC and Fly ash demonstrate that the particles were well-graded. This means particles in the sizes of 0.06 mm, 0.05 mm, 0.04 mm, 0.03 mm, and 0.02 were observed. The particles of fly ash and bamboo leaf ash have a significant effect on the engineering properties of geopolymer concrete, such as hardening properties, workability, and alkaline liquid-to-fly ash ratios (Assi et al., 2018). Many articles have been published on the performance and characteristics of bamboo leaf ash (BLA) blended in concrete. However, only limited information is available on the effect of BLA fineness.

Figure 3: Particle size distribution of BLA, OPC, and Fly Ash



This research suggests that the fineness of bamboo leaf ash and fly ash affects the rate of strength gain and enhances the workability of geopolymer concrete. For previous studies, Jamkar et al. (2013) concluded that the compressive strength results show that the fly ash fineness plays a vital role in the activation of geopolymer concrete. An increase in the fineness increased both workability and compressive strength.

Chemical composition of Fly Ash, BLA, and OPC

Table 1 shows the chemical composition of class F fly ash, bamboo leaf ash (BLA), and Ordinary Portland Cement OPC. For fly ash, the result of silicon dioxide (SiO2) was 61.16%, while the aluminium oxide (Al2O3) was 29.88%, and the calcium oxide (CaO) content was 1.452 per cent, which is less than 10%, indicating that class F fly ash (pozzolanic material) has a lower calcium oxide content when compared to ordinary Portland cement (62.04%). The SiO2, Al2O3, and CaO contents of OPC cement were 25.3%, 5%, and 62.04%, respectively. This shows the difference between pozzolanic materials and Cementous materials.

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Table 1: Chemical composition of fly ash, BLA, and ordinary Portland cement OPC cement

Chemical Compound	Abbreviation	Fly Ash Class F (%)	Bamboo Leaf Ash (BLA) (%)	(OPC) (%)
Silicon dioxide	SiO_2	61.6	82.03	25.3
Aluminium oxide	$Al2O_3$	29.88	2.65	5.0
Ferric oxide	Fe_2O_3	12.7	2.63	1.2
Calcium oxide	CaO	1.452	5.32	62.04
Magnesium oxides	MgO	2.0	1.67	0.03
Potassium oxides	K_2O	0.55	3.69	0.45
Sulphur	SO_3	0.5	0.95	2.47
Titanium dioxide	TiO_2	1.5	0.52	-
Manganese (II) oxide	MnO	-	0.17	-
Loss on ignition	LOI	1.61	-	1.27

For bamboo leaf ash (BLA), the main constituents were SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, and K_2O. TiO_2, MnO, and SO_3 have concentrations of less than 1%. The silicon dioxide percentage was 83.03 per cent, indicating that it had the highest concentration than cement and fly ash. Silica reacts with calcium hydroxide at normal temperatures to form compounds having cementitious characteristics that contribute to the hardening of geopolymer concrete. Aluminium oxide gives the concrete rapid setting time and has a high enough acidity to support the pozzolanic reaction. The ASM 618 specifies that pozzolanic materials, whether calcined ash or industrial products, should have less than 10% calcium oxide (CaO) content. This result shows a calcium oxide content of 5.32%, which is less than the 10% limit. This result for bamboo leaf ash is similar to that found by Silva et al. (2021). Oxides such as SO_3, TiO_2, Cl, and MnO also showed contents below 1%. This was also observed by Villar et al. (2011), who concluded that the silicone content of bamboo leaf ash ranges between 75.90% and 82.86%. Based on these test results of BLA, this study suggests that bamboo leaf ash can be used as a pozzolanic constituent of geopolymer concrete.

Workability Of Geopolymer Concrete

Slump

Figure 4 represents the workability of geopolymer concrete with different percentages of bamboo leaf ash (BLA). The slump values of 0% and 5% BLA were 72 and 65 mm, respectively. While 10% and 15% BLA were 55 and 42 mm, respectively, and for 20% BLA, it was 24 mm. Thus, the slump results show that the increased percentage of bamboo leaf ash gradually reduces the slump values. This is because geopolymer concrete, including bamboo leaf ash, requires more liquid for a given consistency. And also due to the absorbent characteristics of the cellular bamboo leaf ash particles and their high fineness, which increases their specific surface area, Dhinakaran et al. (2016). The workable mixture with the highest flow value was obtained when the ratio of activator to binder was 0.6 and 0% of bamboo leaf ash. Also, it was observed that the higher percentage of BLA as the partial replacement for fly ash class F required more alkaline liquid to achieve the desired slump.

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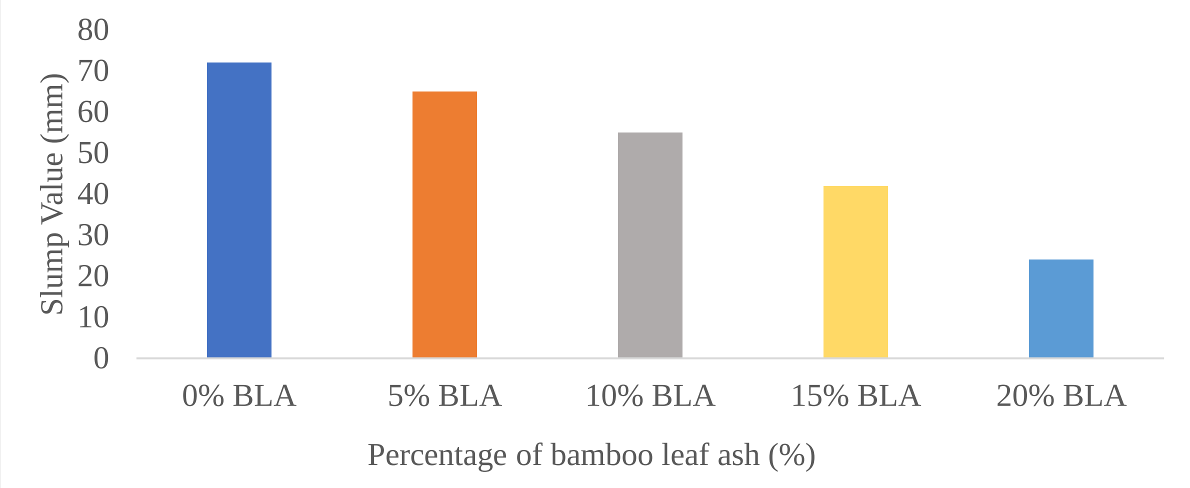
Figure 4: Effect of bamboo leaf ash on the slump of GPC



Based on limited studies on the fresh properties of geopolymer concrete, Saloma et al. (2017) carried out an experimental study using fly ash incorporated with rice husk ash. And the workability test results indicated that the effect of using fly ash and rice husk ash as a precursor on workability decreases the flow diameter along with an increase in rice husk ash (RHA) content. For this study, fly ash blended with bamboo leaf ash demonstrated that increasing the amount of bamboo leaf ash on the geopolymer concrete leads to it becoming harder and less workable. Considering this, using bamboo ash on the geopolymer concrete may require the use of superplasticisers to improve the workability. Adding superplasticisers or other admixtures that enhance the workability of geopolymer concrete containing bamboo ash represents a research opportunity and a possible research gap for further research.

Compaction Factor

Figure 5 shows the effect of bamboo leaf ash (BLA) on geopolymer concrete's compaction factor. The compaction factor value for 100% fly ash (FA) was 0.94, whereas 95%, 90% FA, plus 5%, and 10% (BLA) compaction factor values were 0.91 and 0.87, respectively. Additionally, the compacting values for 85%, 80 per cent FA, plus 15 and 20 per cent BLA were 0.82 and 0.79, respectively. When the percentage of bamboo leaf ash increases from 0% to 20%, the compaction values of geopolymer concrete decrease from 0.94 to 0.77 gradually. These findings of the compaction factor values demonstrate that 100% fly ash (FA) and 0% BLA have higher workability than mixes containing BLA. This could be due to the spherical-shaped particles of fly ash functioning as miniature ball bearings within the concrete mix, thereby providing a lubricant effect. It is also worth noting that this test aimed to assess how well fresh geopolymer concrete works about the external energy needed to suitably compact concrete. Mishra (2017) reported that the compaction factor test is more useful for concrete mixes which have low workability, for which the slump test is not suitable

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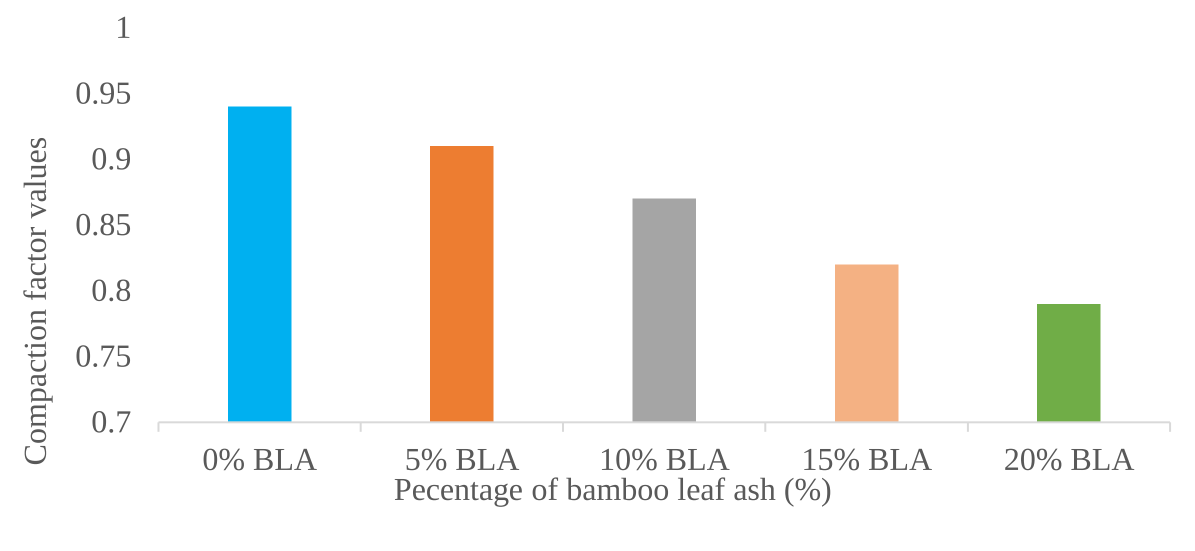
Figure 5: Effect of bamboo leaf ash on the compaction factor of GPC



Mechanical Properties of Geopolymer Concrete at Ambient Curing Temperature

Compressive Strength at Ambient Curing Temperature

Figure 6 shows the effect of bamboo leaf ash replacing fly ash on the compressive strength of geopolymer concrete at a 0.6 activator-to-binder ratio. Compressive strength for 0%, 5%, and 10% BLA at 28 days of room temperature curing was 26.3, 27.4, and 29.7 MPa, respectively, while 15% and 20% BLA were 25.8 and 24.1 MPa. Furthermore, at 56 days for 0%, 5%, and 10% BLA, the compressive strength was 29.2, 34.4, and 35.5 MPa, respectively, while 15% and 20% BLA were 27.5 and 26.7 MPa. At 90 days, the compressive strength for 0%, 5%, and 10% BLA was 36.6, 38.7, and 40.8 MPa, whereas, for 15% and 20% BLA, it was 35.3 and 29.1 MPa. The test results indicate that the compressive strength of geopolymer concrete increases with the increase in curing days at ambient temperature. The reason behind this is the polymerisation process between alumina and silica from the binder with the alkaline liquid solution (Deraman et al. 2017). This means that when alumina and silica react with an alkaline activator solution, NaOH and Na_2SiO_3 create a three-dimensional network, giving the geopolymer bonding capacity and hardening.

Additionally, the molarity of NaOH and the ratio of Na_2SiO_3/NaOH have a significant effect on the increment and reduction of the strength of geopolymer concrete. For instance, as reported in previous studies (Olivia et al. 2012) the higher molarity of NaOH between 12 to 16 molar exhibits an increase of strength due to the dissociation of the active species of raw material and yielding formation of more geopolymer gel network. While the lower molarity of NaOH indicates lower strength. On the other hand (Değirmenci, 2017) if the ratios of Na_2SiO_3/NaOH increase by 2.5 to 3, the strength tends to decrease due to the excessive alkali content which delays the polymerisation reaction. Ninety days of curing at room temperature, replacing 10% and 5% of bamboo leaf ash to fly ash, exhibits a higher compressive strength of 40.8 MPa and 38.7 MPa compared to the other mixes and curing days. Replacement of 0% and 20% BLA at 28 days had the smallest compressive strength, with values of 26.3 and 24.1, respectively. Therefore, the compressive strength progressively increased from 0% to 10% BLA, then declined when the bamboo ash reached 15% to 20% BLA. The main reason for this is that the large proportion of bamboo ash content in geopolymer concrete causes the absorption of more alkaline solutions, which decreases the compressive strength of GPC (Yin et al., 2022).

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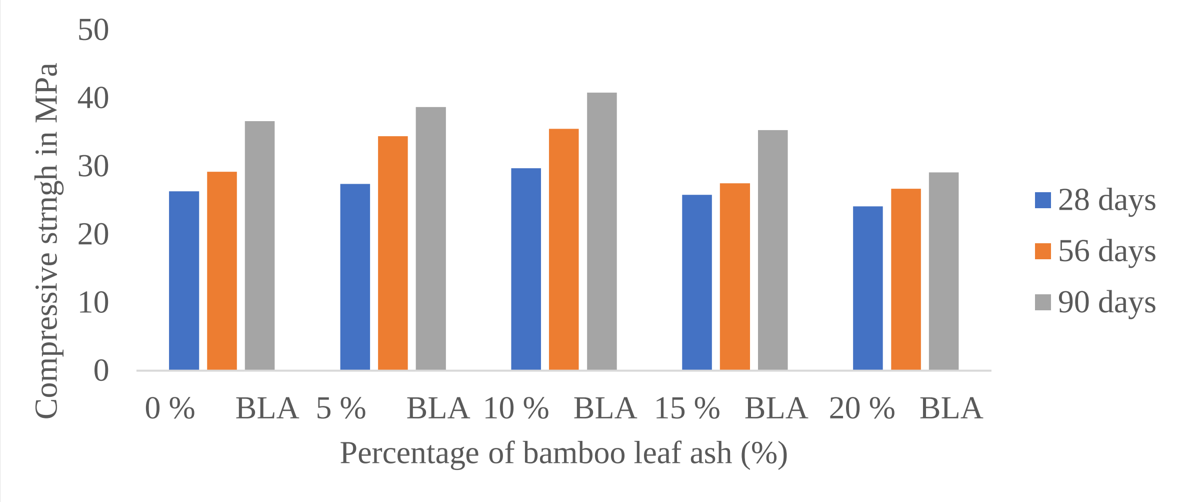
Figure 6: Effect of BLA on the compressive strength of geopolymer concrete



From previous studies on the compressive strength of geopolymer concrete, an investigation by Nath et al. (2015) concluded that geopolymer concrete mixtures prepared with low calcium fly ash as the primary binder resulted in very low early compressive strength at ambient curing temperatures. This is due to the low calcium fly ash (Class F) having a small composition of calcium oxide (CaO), which is important for the early development of strength (Hannesson et al., 2012). In this study, the lower calcium oxide (CaO) content of fly ash (1.43%) and calcined bamboo leaf ash (5.32%), curing takes place due to the polymerisation process with the presence of an alkaline solution to achieve the final product for the hardening and the strengthening of the geopolymer concrete. Geopolymer concrete contains pozzolanic materials with a high content of calcium oxide (CaO) such as grand granulated blast furnace slag (GGBS) mixed with fly ash. The curing occurs with both the heat of hydration and the polymerisation process to achieve the final product of geopolymer concrete (Patarea et al., 2019). This is how this research work on geopolymer concrete differs from geopolymer concrete for the previous studies.

In order to examine the response and behaviour of geopolymer concrete with low calcium content pozzolanic materials in terms of strength and hardening. In this research, geopolymer concrete containing low calcium fly ash and bamboo leaf ash were used as a binding material at normal curing temperature. The higher silicon contents of fly ash (61.6%) and bamboo leaf ash (82%) provided a significant increase in compressive strength due to the polycondensation of silica and alumina precursors with alkali content. This study suggests a maximum percentage of bamboo ash to replace a part of fly ash in geopolymer concrete not higher than 10%.

Plate 1 shows the failure modes for the compressive test cube samples. Firstly, inclined and vertical cracks appeared at the middle height of the specimens and then extended to the corners. Crushed cubes of geopolymer concrete with BLA show a similar failure behaviour to conventional concrete.

Plate 1: Failure modes for the cube samples

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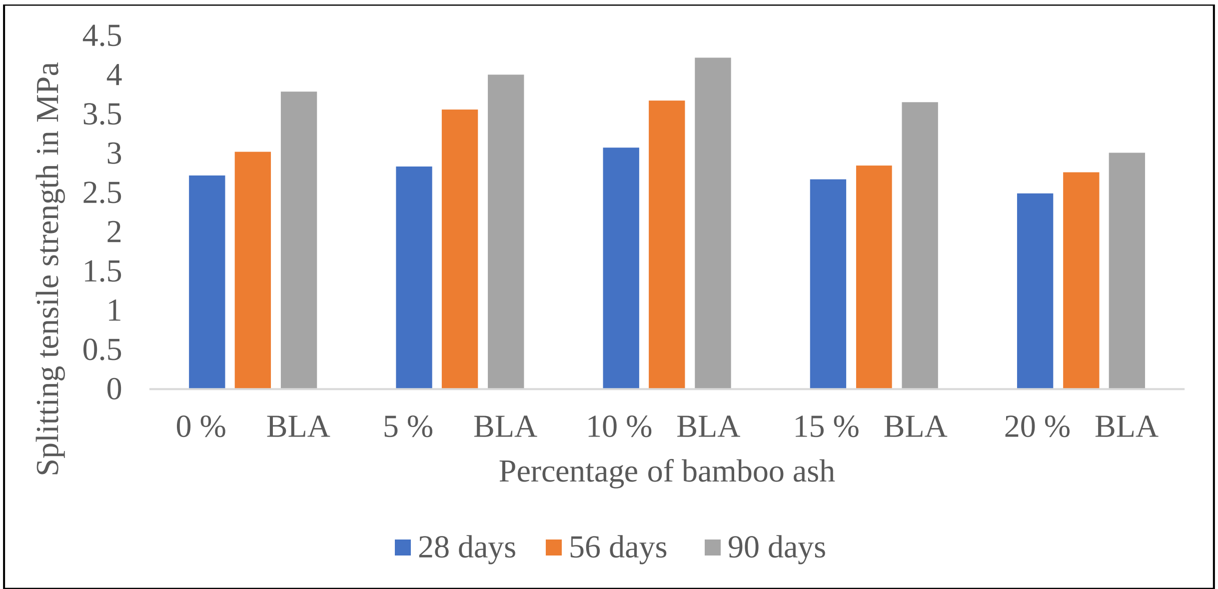
Splitting Tensile Strength

Figure 7 indicates the effect of bamboo leaf ash content on the splitting tensile strength of geopolymer concrete at a 2.5 $Na_2SiO_3/NaOH$ ratio. The optimum strength recorded was 4.2 MPa for 90% of fly ash and 10% of bamboo ash at 90 days of ambient curing temperature. The geopolymer splitting tensile strength increased with longer curing durations. This is due to the higher content of silicon dioxide (SiO_2) in the fly ash used in this study (61.6%) and bamboo leaf ash (82%) which delays the polymerisation process when it reacts with alkaline activators. Pozzolanic materials that are dissolved with alkaline activators and have low calcium (CaO) content require enough time for ambient curing temperature. This is why the pozzolanic reaction strength was improved gradually over a longer period of time (Saha, 2018). Even after 90 days, the strength keeps on increasing. This is the difference between OPC cement (62%, CaO) concrete and geopolymer concrete.

Figure 7: Effect of BLA on the splitting tensile strength of geopolymer concrete



Geopolymer concrete strength development depends on the chemical composition and physical properties of pozzolanic materials. From the result in *Figure 7*, the percentage increase at 90-day split tensile strength relative to the 5% and 10% BLA content was 5.5%, whereas the percentage decrease at 15% and 20% BLA was 17.8%. This is due to the high percentage of bamboo ash content in geopolymer concrete, which lead to the absorption of more alkaline liquid, resulting in lower strength (Yin et al., 2022). Thus, the mixtures containing 5% and 10% BLA attained the optimum tensile splitting strength of 4 and 4.22 MPa after 90 days, while the lowest splitting tensile strength was 2.4 Mpa for the 20% BLA content at 28 days.

Hardjito & Rangan (2005) and Shaikh (2014) reported that the strength of geopolymer concrete is increased when the sodium silicate (Na_2SiO_3) content is increased. For this research, the $Na_2SiO_3/NaOH$ ratio was 2.5 and exhibited a significant effect on the strengths of the geopolymer with bamboo leaf ash. There exists limited research on the effect of sodium silicate to sodium hydroxide ($Na_2SiO_3/NaOH$) ratio on the mechanical properties of geopolymer concretes based on fly ash incorporating bamboo leaf ash. A study of geopolymer concrete with bamboo leaf ash containing different $Na_2SiO_3/NaOH$ in varying ratios may be an opportunity for future study.

The failure modes for the splitting tensile strength specimens of geopolymer concrete with BLA are shown in *Plate*. A vertical crack was first formed at the middle height of the specimen. Then, after gradually increasing the split tensile strength

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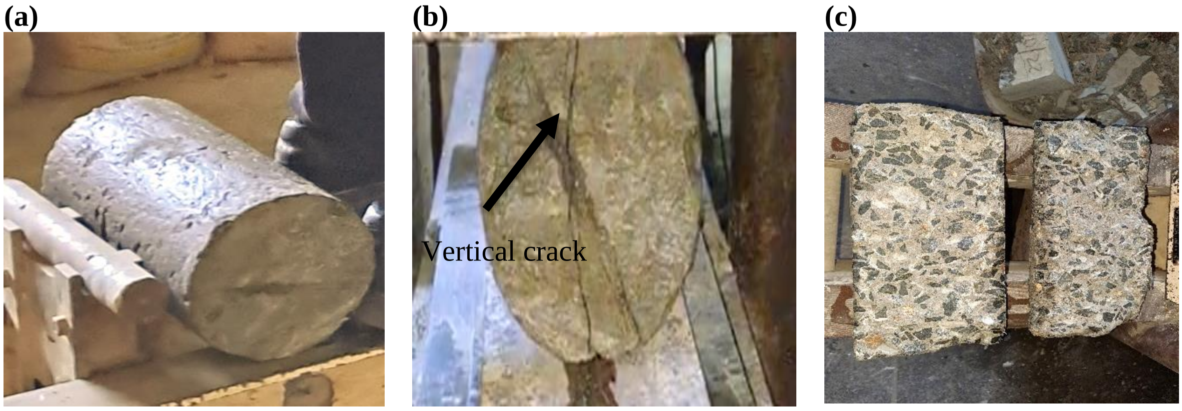
load, the cylinder was split into two parts as shown in *Plate 2c*.

Plate 2: Failure modes for the cylinder samples



CONCLUSION

Based on the study results, the following conclusions were made:

- Bamboo leaf ash has pozzolanic properties due to its high alumina and silica content and can be classified as Class N according to standard ASTM 618-12a classification.
- The fine particles of BLA have a significant effect on the fresh and hardened properties of geopolymer concrete.
- The strength of geopolymer concrete with bamboo leaf ash increases with the increase in curing days at ambient temperature. In addition, 5 and 10% BLA replacement of fly ash improves the compressive strength of geopolymer concrete. Therefore, bamboo leaf ash content exceeding 10% reduces the compressive and tensile strength of geopolymer concrete.

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