# Optimal Formulations of Eco-Friendly Lightweight Corn Cob-Geopolymer Composite Incorporating Class C and Class F Fly Ash Mixtures

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**Abstract**

In this study, an innovative approach to developing sustainable construction materials by formulating lightweight geopolymer concrete with corn cob aggregates is presented. Motivated by the need to reduce the environmental impacts of the construction industry, the research explores alternative materials that combine ecological benefits with practical performance. The primary objective is to assess the viability of corn cob aggregates as a partial replacement for traditional aggregates and to optimize mixtures of Class C and F fly ash to enhance the concrete's workability, setting times, and compressive strength. Through methodical experimentation, solid-to-liquid ratios (fly ash to alkali solution) were varied, and the integration of corn cob aggregates, aiming for a 50% volume replacement, was tested within the geopolymer matrix. Key findings highlighted Mix4 (solid-to-liquid ratio 1.67, fly ash Class C to Class F ratio 25:75) as the optimal formulation, significantly improving compressive strength from 15.70 MPa to 20.62 MPa over 28 days and offering superior workability suitable for practical applications. Mix4's initial setting time of 245 minutes and final setting time of 542 minutes, coupled with its enhanced mechanical strength, makes it ideal for incorporating corn cobs into the mix effectively. This process adhered to ASTM C332 and C129 standards for non-structural, moderate-strength concrete, ensuring the findings' practical applicability. The inclusion of corn cob aggregates into the geopolymer matrix resulted in a notable reduction in the bulk density while providing adequate compressive strength for non-structural applications. The findings validate the potential of lightweight corn cob geopolymer composite as a transformative solution for sustainable construction.

***Keywords***: *Lightweight Geopolymer, Corn Cob Aggregate, Fly Ash, Sustainable Construction, Agricultural Waste*

## 1. Introduction

Fly ash (FA) geopolymer concrete, recognized for its enhanced durability, superior strength, and reduced greenhouse gas emissions, has garnered significant interest for its early compressive strength, low permeability, and improved fire resistance, positioning it as a promising alternative to traditional concrete (Davidovits, 1991; Li et al., 2010). Geopolymers are materials made from aluminosilicate substances, which can be either natural or synthetic, or come from industrial waste products like fly ash, red mud, slag, metakaolin, glass, clay, rice husk ash, perlite, or a combination of these. The ASTM-618 classification system categorizes FA into two groups. Class F, with a calcium oxide ($CaO$) content of less than 18%, and class C, where the $CaO$ content exceeds 18% (Prannoy Suraneni, 2021). The type of fly ash used in geopolymer production significantly influences the setting time. Class F fly ash generally results in a longer setting time compared to Class C fly ash due to its lower calcium content and higher silica and alumina content (Hardjito & Rangan, 2005).

Corn cob aggregates have a natural tendency to absorb water, which can lead to a faster setting time when incorporated into the geopolymer matrix. The blending of Class F and Class C fly ashes in the development of geopolymer offers several advantages, such as suitable setting time and high compressive strength (Phavongkham et al., 2023). Fly ash geopolymer concrete production typically involves the use of sodium hydroxide ($NaOH$) and sodium silicate ($Na_2SiO_3$) solution. Higher concentrations of sodium hydroxide can reduce the workability and accelerate the setting time of the geopolymer concrete, making it difficult to place and compact the material (Patankar et al., 2014). Using lower concentrations of sodium hydroxide in geopolymer production can result in positive environmental impacts. Therefore, a sodium hydroxide solution concentration of 4M was utilized in this research.

Over the past three decades, many research studies have been conducted to explore the potential of plant fibers, including flax, sisal, and hemp, as a replacement for conventional synthetic fibers such as metallic, mineral, or polymeric materials in reinforcing building structures (Magniont et al., 2012). Corn cob is an agricultural waste material that is abundant and inexpensive, and corn cobs account for approximately 20% of the total weight of the remaining agricultural waste of corn plants (Santolini et al., 2021). Corn plantations are extensively present in provinces along the Thai-Myanmar and Thai-Lao borders, such as Myawaddy in Kayin State, Myanmar, and Huay Xai City in Laos, facilitating easy imports into Thailand (Pattanamongkol, 2023). Starting in 2014, the Thai government collaborated with agro conglomerates to encourage contract farming for large-scale maize cultivation as an additional source of income for rice farmers during the dry season (Pattanamongkol, 2023).

Corn cobs, composed of lignocellulosic materials such as cellulose, hemicellulose, and lignin, present valuable opportunities for circular processes that produce energy and bio-based products for agricultural and general construction applications (Santolini et al., 2021; Pinto et al., 2011). However, incorporating agricultural waste like palm oil clinker into ordinary Portland cement concrete as a substitute for natural aggregate can lead to a reduction in both compressive strength and abrasion resistance of the composite, regardless of the curing method used (Ibrahim et al., 2017). Historically, corn cobs have been found in the outer walls of old Portuguese structures (Pinto et al., 2011). Corn cobs in concrete composition have a significant effect on reducing density and thermal conductivity, while also being eco-friendly and sustainable (Grădinaru et al., 2021). Despite the potential benefits, there is limited research on the properties of fly ash geopolymer concrete incorporating corn cob aggregates, necessitating further investigation into the feasibility and mechanical, physical, and thermal properties of this material.

## 2. Objectives

1) **To identify the Optimal Fly Ash Mixture Ratio**: To determine the most effective mixture ratio of Class C and Class F fly ash for geopolymer concrete in terms of workability and structural integrity.
2) **To optimize the Solid-to-Liquid Ratio**: To establish the ideal ratio of fly ash (solid) to alkali solution (liquid) that achieves optimal workability, setting time, and compressive strength in the geopolymer paste.
3) **To incorporate Corn Cob for Lightweight Concrete**: After determining the optimum geopolymer paste, to incorporate corn cob aggregates at 50% by volume to create a non-structural, moderate strength, lightweight geopolymer concrete, aligning with a combination of ASTM standards C332 and C129 for nonloadbearing concrete masonry units.

## 3. Materials and Methods

### *3.1 Materials*

Corn cob sourced from Chiang Rai, Thailand, was utilized in this study. It underwent processing with a wood chipping machine (Nimut 2ECM 2, Thailand) and was subsequently sieved to achieve a consistent particle size ranging between 3.36 mm and 4.76 mm. This size range is consistent with the fine aggregate dimensions specified in the ASTM C332 grading requirements for lightweight aggregates for insulating concrete. The bulk density of the corn cob, measured using the pycnometer method, was determined to be 0.477 $gcm^{-3}$. In the literature, the reported bulk density of corn cob varies, with a range from 0.2121 $gcm^{-3}$(Pinto et al., 2012) to 0.497 $gcm^{-3}$(Laborel-Préneron et al., 2018). Corn cob's biochemical composition includes 39.1% cellulose, 42.1% hemicellulose, 9.1% lignin, 1.7% protein, and 1.2% ash (Ashour et al., 2013). SEM analysis of corn cob geopolymer composite: Figure 1d and 1e showcase the SEM images of the glume and pith of the corn cob, each exhibiting macrostructures indicative of their biological functions. The glume features a protective, smooth, layered surface with occasional pores. The pith presents a nutrient-transporting porous, sponge-like arrangement.

The Class C and Class F fly ashes used in this study were sourced from the Mae Moh Power Plant in Lampang, Thailand. The chemical composition of Class C (FAC) and Class F (FAF) fly ashes, as determined by X-ray fluorescence (XRF), is presented in Table 1b. Scanning electron microscopy (SEM) micrographs of the fly ashes used in this study, shown in Figure 1b and 1c, reveal that both FAs consist of predominantly spherical particles with minor surface variations and a consistent range of particle sizes.

The Laser Scattering Particle Size Distribution Analyzer (LA-960 - HORIBA, Japan) was utilized to measure fly ash particle sizes. The median particle sizes for FAC and FAF were 14.18 and 17.21 micrometers, respectively, while the mean sizes were 41.43 micrometers for FAC and 36.47 micrometers for FAF. This indicates that the particles of FAC are smaller compared to those of FAF. The standard deviation for FAC was 54.21 micrometers, suggesting a broader size range than FAF's 42.46 micrometers. $NaOH$ and $Na_2SiO_3$ were utilized as the chemicals for FAC and FAF-based geopolymer paste. Pellet forms of $NaOH$ with 99% purity (obtained from QReC, New Zealand) were used, while $Na_2SiO_3$ was commercially available in solution form from C. Thai Chemicals Co., Ltd., with a composition of 16.50% $Na_2O$, 35.25% $SiO_2$, and 48.25% $H_2O$.

### *3.2 Corn cob and geopolymer paste preparation*

Raw corn cobs were processed through a wood chipping machine (Nimut 2ECM 2, Thailand), breaking them down into smaller fragments. These pieces were subsequently sifted through two sieves, one with a size of 4.76 mm and another at 3.36 mm. The particles that were obtained, measuring between 3.36 mm and 4.76 mm in size, were used in this research. The alkali activator, a liquid mixture between 4 M $NaOH$ solution and $Na_2SiO_3$ at a weight ratio of 1.0, was mixed with FAC and FAF to create the geopolymer paste, resulting in six distinct mixes for evaluation: Mix1, Mix2, Mix3, Mix4, Mix5, and Mix6. These codes correspond to the proportions of Class F and Class C fly ashes and their respective solid-to-liquid (fly ash to alkali activator) weight ratios. Additionally, the total water content for each mix was factored into the calculations. Details for each mix, including the total water content, are outlined in Table 1a. Each mix was blended for 5 minutes, then cast into 5cm x 5cm x 5cm cubic molds and cured at ambient temperature (23 °C to 35 °C) for 14 days and 28 days, with a demolding period of 7 days, to align with practical application conditions.

### *3.3 Corn Cob-enhanced lightweight geopolymer concrete preparation*

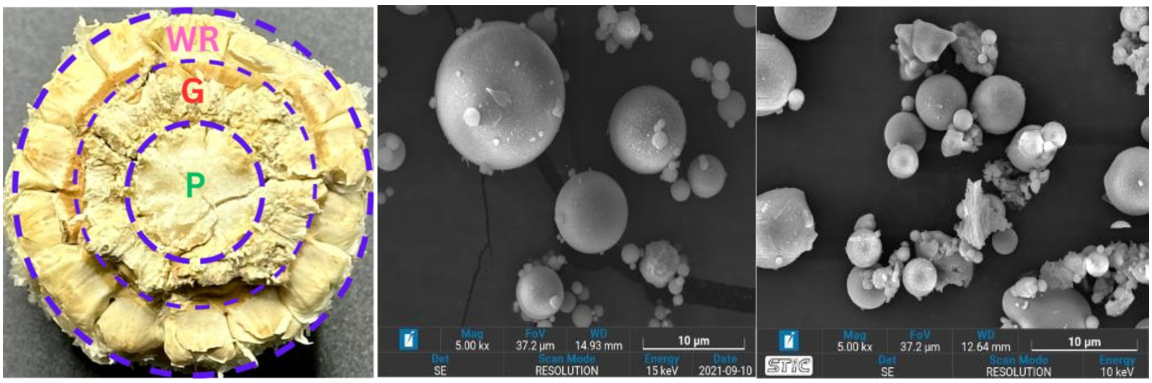
In the preparation of corn cob-enhanced lightweight geopolymer concrete, the bulk densities of corn cob, determined using the pycnometer method, 0.477 $gcm^{-3}$ and geopolymer paste (code Mix2) at 1.863 $gcm^{-3}$, as determined per ASTM C138, were utilized to calculate the respective weights of corn cob and geopolymer paste ingredients. Detailed calculations for these components are presented in Table 2. Initially, an alkali activator was prepared by mixing $NaOH$ and $Na_2SiO_3$. This activator was then combined with FAC and FAF and stirred for 5 minutes to form a geopolymer slurry. Following this, corn cob aggregates, making up 50% of the mixture by volume, were added to the slurry and stirred for an additional 3 minutes, resulting in a homogenous geopolymer-corn cob mixture. This mixture was poured into 5cm x 5cm x 5cm cubic molds and cured at ambient temperature or in an oven, leading to the production of the final geopolymer corn cob composite.

***3.4 Experimental methods***

The setting time of the geopolymer slurry was measured using a Vicat apparatus (Humboldt Mfg. Co., USA), as per ASTM C-191 (Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle, 2021) guidelines. The slurry was cast into a mold atop a glass sheet in order to track the initial and final setting times. Initial setting time was recorded at room temperature (25 °C) in 5-minute intervals until the needle's penetration did not exceed 25 mm. The final setting time was noted when the slurry hardened to the point where the needle failed to leave a full circular indentation on the surface. The compressive strength testing conformed to ASTM C109 standards (Standard Test Method for Compressive Strength of Hydraulic Cement Mortars using 2-in. or 50-mm Cube Specimens, 2017), utilizing a universal testing machine (600kN KC-HD600K, Thailand). Bulk density measurements of the geopolymer paste adhered to ASTM C138 (Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete, 2023) specifications, which provide an accurate reflection of the density of the freshly mixed concrete, thus ensuring relevance to practical applications. The bulk density of the corn cob-enhanced lightweight geopolymer concrete was determined by ASTM C642-97 (Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, 2017), appropriate for oven-dried samples. Cubic specimens measuring 5 cm × 5 cm × 5 cm were utilized to test compressive strength and bulk density.

Furthermore, the fire resistance of the geopolymer composites was assessed following RILEM TC129-MHT guidelines. Post-curing, the specimens, sized 5 cm × 5 cm × 5 cm, were subjected to heat treatment in an electric furnace (Nabertherm P330, Germany) at 200 °C, 400 °C and 600 °C for 1 hour, with a heating rate of 5 °C per minute. After heating, the specimens were permitted to cool to room temperature before the evaluation of their residual compressive strength.

a b c

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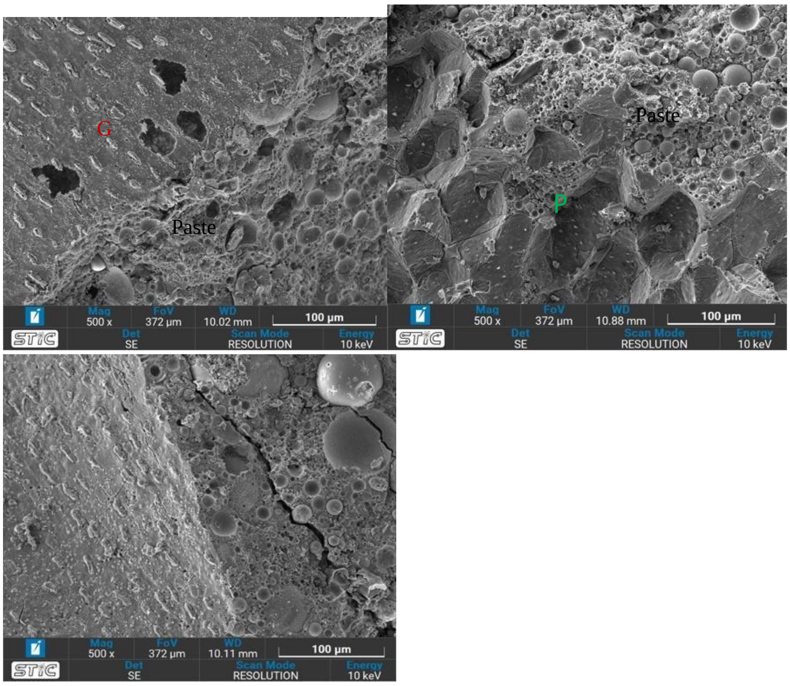


G

Paste

**Figure 1:** Microstructure of Corn Cob-Geopolymer Composite and Fly Ash **a)** Corn Cob Cross-Section (P = pith, G = glume, WR = woody ring) **b)** SEM image of FAC) **c)** SEM image of FAF **d)** Pre-heat treatment interfaces between geopolymer paste and glume **e)** geopolymer paste and pith **f)** interface between geopolymer-corn cob after heat treatment at 200 °C.

**Table 1: a)** Geopolymer paste mix design and calculated total water content (all in grams)

| Code | S/L ratio | Solid (FA) | FAC | FAF | Liquid sodium silicate ($Na_2SiO_3$) | Sodium hydroxide ($NaOH$) | Water ($H_2O$) |
|---|---|---|---|---|---|---|---|
| Mix1 | 1.67 | 100 | 50 | 50 | 30 | 30 | 25.2 |
| Mix2 | 1.43 | 100 | 50 | 50 | 35 | 35 | 29.4 |
| Mix3 | 1.25 | 100 | 50 | 50 | 40 | 40 | 33.6 |
| Mix4 | 1.67 | 100 | 25 | 75 | 30 | 30 | 25.2 |
| Mix5 | 1.43 | 100 | 25 | 75 | 35 | 35 | 29.4 |
| Mix6 | 1.25 | 100 | 25 | 75 | 40 | 40 | 33.6 |

**b)** Chemical composition of Class C (FAC) and Class F (FAF) fly ashes

| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $CaO$ | $K_2O$ | $MgO$ | $MnO$ | $Mn_2O_3$ | $TiO_2$ | $SO_3$ | $Na_2O$ | $ZrO_2$ | $LOI$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **FAC (%)** | 33.41 | 15.03 | 16.48 | 21.46 | 2.4 | 3.29 | - | 0.13 | 0.54 | 7.23 | - | - | 0.03 |
| **FAF (%)** | 72.44 | 17.23 | 5.33 | 1.07 | 1.4 | 0.39 | 0.12 | - | 0.94 | 0.39 | 0.29 | 0.12 | - |

**Table 2:** Quantitative composition for corn cob-enhanced geopolymer concrete mix (all in grams)

| Corn cob vol % | Geopolymer paste vol % | Corn cob mass | S/L ratio | Solid (FA) | FAC | FAF | Liquid sodium silicate ($Na_2SiO_3$) | Sodium hydroxide ($NaOH$) | Water ($H_2O$) |
|---|---|---|---|---|---|---|---|---|---|
| 50 | 50 | 41 | 1.67 | 100 | 25 | 75 | 30 | 30 | 25.2 |

## 4. Results and Discussion

### *4.1 Setting time of geopolymer paste*

The setting time of a geopolymer composite is an important parameter that influences the workability and the time frame within which the material can be manipulated (Siyal et al., 2016). In this study, the initial and final setting times of six geopolymer paste mix designs were investigated. The mixes varied in their solid-to-liquid (S/L) ratios, proportions of Class F and Class C fly ashes (FAC and FAF), and amounts of liquid components (sodium silicate and sodium hydroxide) and water. However, the molarity of NaOH was kept constant at 4 M. The initial and final setting times for these pastes are presented in Figure 2a.

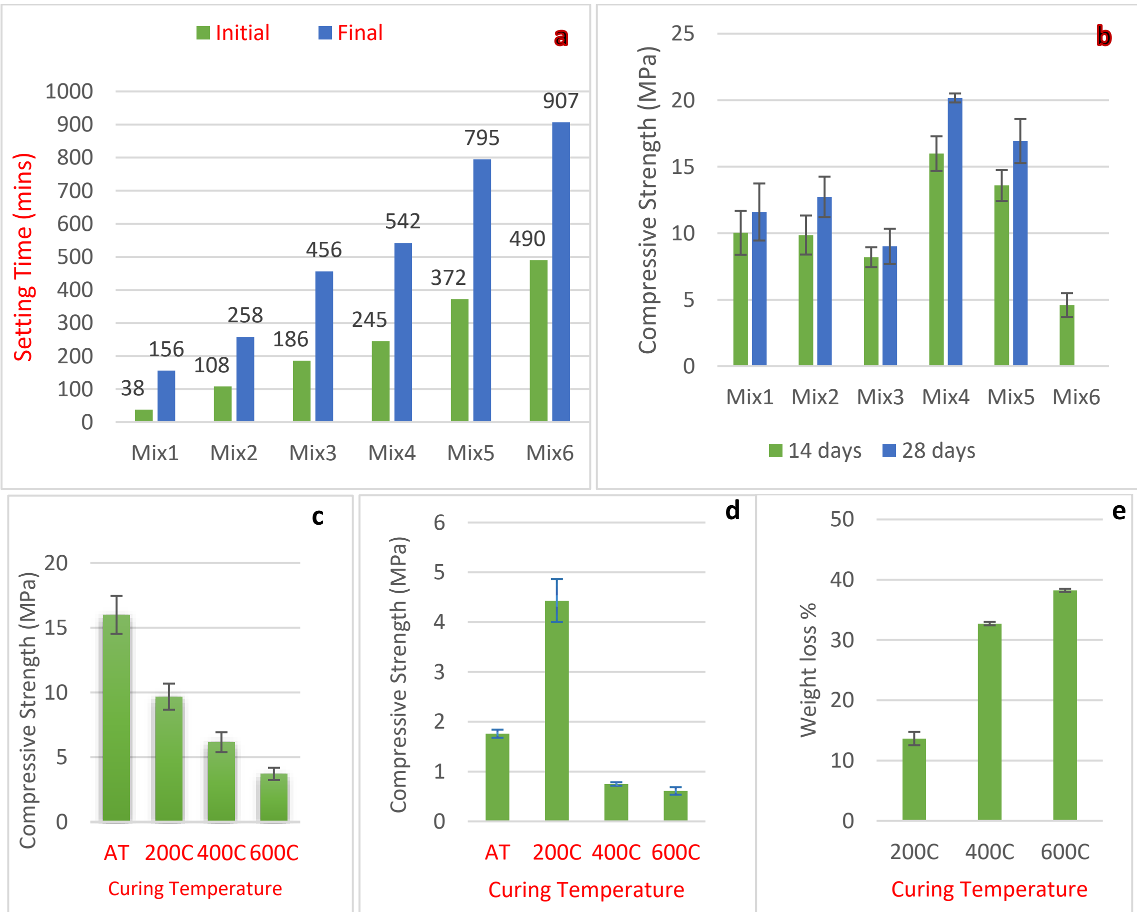


**Figure 2: a)** Setting times of geopolymer mixes with different S/L ratios and fly ash proportions

**b)** Compressive strength of different mixes of geopolymer paste **c - d)** Residual compressive strength of paste and 50% corn cob geopolymer composite, respectively, at ambient, 200 °C, 400 °C, and 600 °C curing temperatures (AT = 23 °C to 35 °C) **e)** The corresponding weight loss percentage of 50% corn cob geopolymer composite after thermal treatment.

Mix1, with equal amounts of FAC and FAF and a solid-to-liquid ratio of 1.67, hardened quickly. In contrast, Mix4, despite sharing the same S/L ratio of 1.67, had a higher proportion of FAF (75%) and a lower proportion of FAC (25%). It exhibited longer setting times with an initial set at 245 minutes and a final set at 542 minutes. This suggests that the higher $CaO$ content in the FAC can speed up the hardening process. Generally, fly ash with less calcium leads to a slower setting of the geopolymer (Nath & Sarker, 2014). Mix1, Mix2, and Mix3 maintained consistent fly ash ratios but displayed contrasting setting times due to different S/L ratios. Mix3, with a lower S/L ratio and thus a higher volume of alkali solution, actually exhibited a slower setting compared to Mix1. Likewise, Mix3 set more slowly than Mix2, indicating that increased alkali solution volumes, associated with lower S/L ratios, can extend the setting process. This observation aligns with findings from Nath and Sarker (2014), in which geopolymers with lower S/L ratios, and therefore higher alkali content, required more time to set.

Mix5 and Mix6, with a low S/L ratio of 1.25 and predominance of FAF (75%), demonstrated the most prolonged setting times. Mix5 required 372 minutes to begin setting and 795 minutes to fully set, while Mix6 took even longer, with 490 minutes to start setting and 907 minutes to completely set. These findings suggest that both a lower S/L ratio and a high proportion of FAF, with its reduced $CaO$ content, can markedly decelerate the geopolymerization process, resulting in extended setting times. This is in compliance with the Australian standard AS 3792 (Soomro et al., 2023), which mandates a minimum initial setting time of 45 minutes and a maximum final setting time of 360 minutes for general-purpose cement, Mix2 from this study aligns well with these parameters. With an initial setting time of 108 minutes and a final setting time of 258 minutes, Mix2 meets the AS 3792 criteria, demonstrating its suitability under these standards.

However, it is crucial to consider the workability of geopolymer corn cob concrete in practical applications. The elevated water absorption rate of corn cob, documented at 123% in the study (Laborel-Préneron et al., 2018), significantly influences the setting characteristics and workability of the mix. Despite Mix2's compliance with the setting time standards, its relatively quick initial setting time of 108 minutes poses challenges in terms of workability, particularly when incorporating corn cob. Given these considerations, Mix4 emerges as a more suitable option. While its initial setting time of 245 minutes and final setting time of 542 minutes do not align with the AS 3792 standard, these extended setting periods may be advantageous in the context of geopolymer corn cob concrete. The longer setting time provides a more manageable window for working with the mix, especially important given the high water absorption rate of the corn cob. This attribute makes Mix4 a preferable choice for applications where workability is a critical factor, despite its deviation from the standard setting time requirements.

### *4.2 Compressive strength and bulk density of geopolymer paste*

The compressive strength of six geopolymer paste mixes, cured at ambient temperature and assessed over 14-day and 28-day periods, is presented in Figure 2b. Mix4 and Mix5 demonstrated commendable strength growth, with Mix4, in particular, showcasing a robust increase from 15.70 MPa at 14 days to 20.62 MPa at 28 days. With the increase in the S/L ratio in Mix2, the interaction frequency between the precursor material and the alkaline activator intensifies due to a reduction in the fluid medium's volume. This elevated interaction enhances the dissolution of aluminosilicate materials, consequently leading to an uptick in the geopolymer's compressive strength (Tahir et al., 2022). Mix4 followed suit with a gain from 13.60 MPa to 16.94 MPa. Mix1, Mix3, and Mix5 also exhibited a progressive strength increase, with Mix3 improving from

9.86 MPa to 12.73 MPa, indicating effective long-term geopolymerization. Mix5's strength moderately rose from 8.19 MPa to 9.02 MPa. Mix6, with the lowest S/L ratio of 1.25, encountered issues as evidenced by the emergence of cracks by the 28-day mark, which led to the exclusion of its 28-day strength data. This issue may stem from an excess alkaline activator, yielding too many hydroxide ions ($OH^{-}$), which can weaken geopolymer structures (Tahir et al., 2022), highlighting the importance of a balanced S/L ratio.

Incorporating the nuances of S/L ratio effects on geopolymer characteristics, it is noted that while density typically rises with an increasing S/L ratio, peaking at around 2.5 $gcm^{-3}$, this trend inversely relates to the volume of the alkaline activator (Tahir et al., 2022). Despite this, the study observed that bulk density across the different geopolymer mixes maintained a consistent level, with values ranging between 1.65 and 1.8 $gcm^{-3}$. This narrow range suggests that the bulk density is not significantly affected by the variations in the mix designs that were investigated. The consistency in bulk density across the mixes is nonetheless a noteworthy observation, indicating a degree of homogeneity in the material structure that merits further investigation.

***4.3 Identifying the optimal binder mix for corn cob geopolymer composite***

While Mix2 conforms to the Australian standard AS 3792, with setting times well within the required range, its selection for practical applications, particularly when incorporating corn cob, is compromised due to workability issues. This is exemplified in the $5cm \times 5cm \times 5cm$ cube sample of Mix2, observed 28 days post-addition of 30% corn cob by volume. The cube, intended to be a perfect cubic shape, exhibited significant distortion and irregularity, indicative of the poor workability of the mix. The surface was uneven, with visible signs of crumbling and lack of cohesion, highlighting the challenges faced when integrating corn cob into the geopolymer mix. These workability concerns, despite the mix's compliance with setting time standards, underscore the necessity of considering practical handling and application properties in mix selection.
Contrastingly, Mix4 exhibits superior compressive strength, with a significant increase from 15.70 MPa to 20.62 MPa over 28 days, outperforming Mix2, which showed a rise from 9.86 MPa to 12.73 MPa. Mix4 also offers enhanced workability. With an initial setting time of 245 minutes and a final setting time of 542 minutes, Mix4 provides a more favorable working time, crucial for incorporating corn cobs effectively into the mix. Consequently, Mix4 was selected as the optimal mix for creating corn cob geopolymer composites, considering both mechanical strength and workability.

***4.4 Compressive strength and fire resistance of geopolymer paste mix4***

The fire resistance of geopolymer paste mix4 was evaluated by measuring its compressive strength after exposure to various high-temperature conditions. Initially, at 14 days of ambient temperature curing, mix4 exhibited a compressive strength of 15.99 MPa. When subjected to a temperature of 200 °C, the compressive strength decreased to 9.68 MPa (Figure 2c), indicating a reduction of approximately 39.5% from the initial strength. Further exposure to elevated temperatures of 400 °C and 600 °C resulted in a more pronounced decrease in strength, with values recorded at 6.16 MPa and 3.71 MPa, respectively.

The observable cracks after the 200 °C exposure (Figure 3b) provide a clear indication of the thermal damage sustained at a macro level. These findings are consistent with those reported in the literature, where geopolymers show visible cracks at temperatures below 300 °C, which become more pronounced with increased temperature (Zhao et al., 2021). At higher temperatures of 400 °C and 600 °C, the compressive strength further diminished to 6.16 MPa and 3.71 MPa, respectively, with the development of more pronounced surface cracking at these temperatures (Figure 3c and 3d).

Geopolymers made from low calcium fly ash are known for their thermal stability and minimal deterioration when exposed to high temperatures. This stability is due to the formation of a silicon and aluminum-rich geopolymeric gel with a low degree of crystallinity, which does not undergo significant phase changes under thermal stress (Davidovits, 1991). In contrast, the addition of high calcium fly ash can lead to the formation of calcium-based silica-alumina hydrate (C-A-S-H) gel (Payakaniti et al., 2020). While this gel contributes to initial strength gains, it is less thermally stable than the low-calcium fly ash-based geopolymer gel. Upon heating, the C-A-S-H gel can disintegrate due to the dehydration and breakdown of its more hydrated and amorphous phases (Çelikten et al., 2019). In the case of the geopolymer paste in which a mixture of FAC and FAF was used, the initial decrease in compressive strength after thermal curing at 200 °C is consistent with the expected behavior of materials containing high calcium content. The reduction in strength is attributed to the decomposition of the hydrated phases (Phavongkham et al., 2023), as indicated by the TGA results presented in Figure 4b.

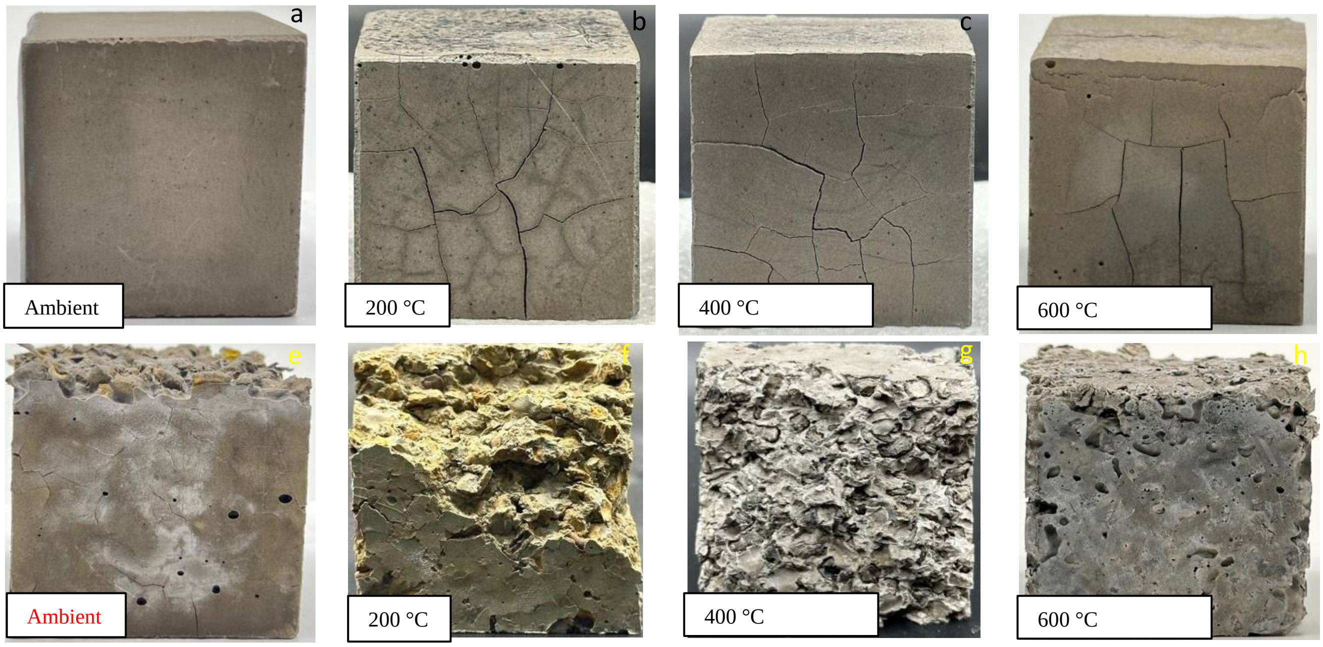


**Figure 3:** Mix4 Cubic geopolymer paste specimens **a)** after 14 days ambient temperature curing **b)** after heat treatment at 200 °C **c)** 400 °C **d)** 600 °C **e)** corn cob geopolymer composite (corn cob 50% by volume) after heat treatment at 200 °C **f)** fractured surface of the same sample **g)** fractured surface after 400 °C **h)** 600 °C

***4.5 Thermal curing and its impact on the mechanical properties of corn cob-geopolymer composites***

Contrastingly, as shown in Figure 2d, the corn cob geopolymer composite initially exhibited lower compressive strength at ambient conditions (1.76 MPa), but it showed a significant increase to 4.43 MPa after thermal curing at 200 °C and then decreased to 0.75 MPa and 0.61 MPa after curing at 400 °C and 600 °C

(Figure 2d). SEM analysis, as illustrated in Figure 1d and 1e, revealed the distribution of corn cob components—glume and pith—within the geopolymer matrix before heat treatment. These images highlight the good initial bonding between the corn cob inclusions and the geopolymer matrix. Following thermal curing at 200 °C, as depicted in Figure 3f, the images confirm that the structural integrity and the quality of bonding between the components and the matrix remained intact, indicating that the thermal treatment caused no damage to the composite's cohesive structure.

While the geopolymer exhibited remarkable thermal stability up to 1000 °C (Figure 4b), in contrast, the progressive weight loss in corn cob-geopolymer composites, indicated by 13.6% at 200 °C, around 30% at 400 °C, and nearly 40% at 600 °C (Figure 2e), suggests various degrees of thermal decomposition. This trend can be elucidated by the TGA and DTG results (Figure 4a), which indicate that the corn cob began to decompose significantly between 250 and 380 °C. At 200 °C, the heat treatment likely drove off moisture and some volatiles from the corn cob, leading to a stronger composite. However, as the temperature reached 400 °C and above, the organic components of the corn cob started to decompose extensively, compromising the integrity of the composite. The loss of structural organic matter at these elevated temperatures reduced the composite's ability to bear loads, resulting in lower compressive strength. This underlines the importance of temperature control in the thermal treatment of corn cob-geopolymer composites to enhance mechanical properties without triggering significant decomposition of the aggregate.

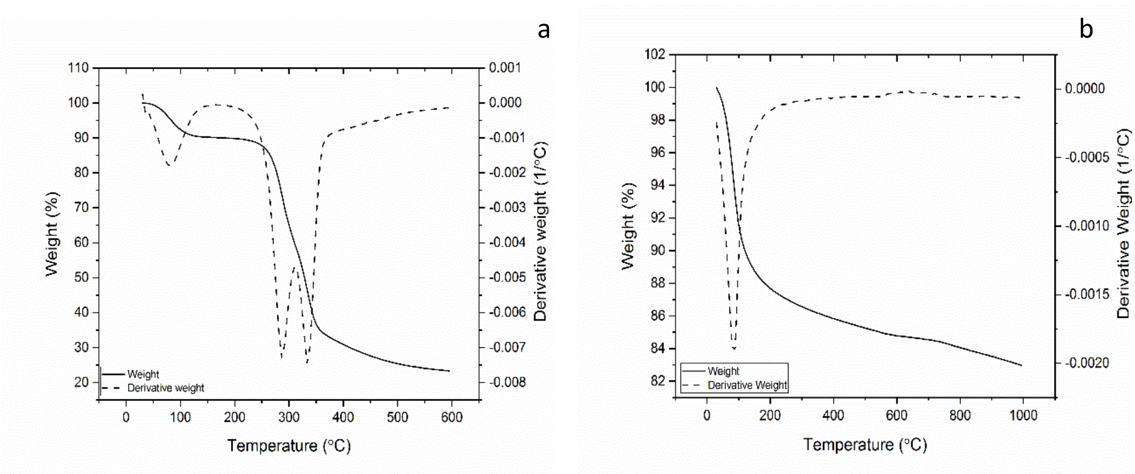


**Figure 4:** Thermogravimetric (TGA) and derivative thermogravimetric analysis (DTG) of
**a)** Corn Cob **b)** Mix4 geopolymer paste

***4.6 Compressive strength enhancement and ductility to brittleness transition in corn cob-geopolymer composite induced by thermal treatment at 200 °C***

The stress-strain curves for a geopolymer composite with and without heat treatment and for the geopolymer paste alone are shown in Figure 5. The geopolymer paste exhibits the highest stress capacity, indicative of the greatest compressive strength among the three samples tested. The corn cob-geopolymer composite subjected to heat treatment at 200 °C demonstrates an intermediate peak stress level, surpassing the composite in its ambient temperature (as-cured) state, which exhibits the lowest peak stress. This data reveals a distinct improvement in the compressive strength of the corn cob-geopolymer composite postthermal treatment. Remarkably, the slopes from the elastic region of the stress-strain curves for both the as-cured and the 200 °C heat-treated sample are nearly identical, indicating a similar elastic modulus.

However, the "composite as cured" reaches its breaking point at a significantly higher degree of deformation compared to the "composite after 200 °C," which suggests that the as-cured composite is more ductile. For the composites with 200 °C heat treatment, although the decrease in ductility is minimal, it indicates that the thermal curing process induces some level of brittleness in the material. Despite this, the overall mechanical integrity of the composite is enhanced, as evidenced by the increased compressive strength.

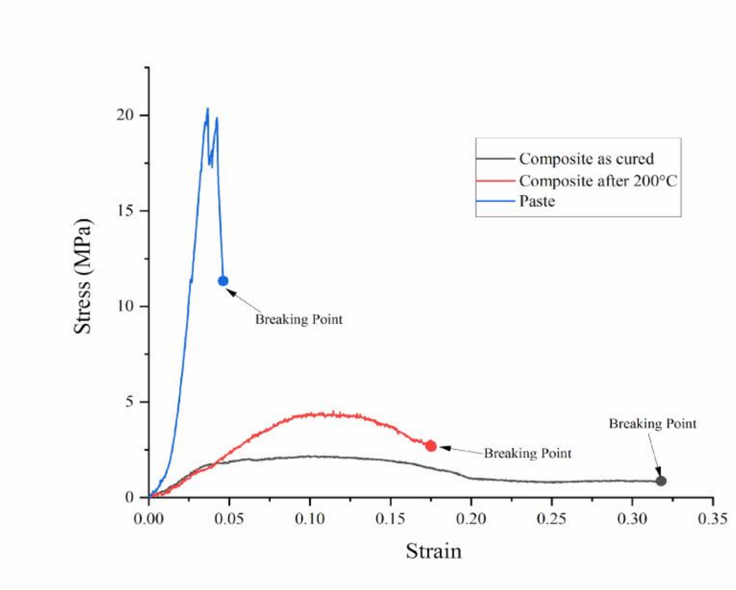


**Figure 5:** Stress-strain behavior of geopolymer paste cured at ambient temperature and corn cob geopolymer composite before and after exposure to 200 °C

### *4.7 Thermal Curing Optimization for Corn Cob-Geopolymer Composite in Compliance with ASTM Standards for Nonloadbearing Units*

In optimizing the thermal treatment process for corn cob-geopolymer composites, a tailored approach beyond the standard 14-day ambient temperature curing was investigated. The tailored thermal treatment of corn cob-geopolymer composites showed alignment with the specifications for non-structural, moderate strength, lightweight geopolymer concrete, conforming to ASTM standards C332 (Standard Specification for Lightweight Aggregates for Insulating Concrete, 2023) and C129 (Standard Specification for Nonloadbearing Concrete Masonry Units, 2023) for nonloadbearing concrete masonry units. This enhanced curing involved a sequence of controlled temperature exposures—90 °C for one day, 60 °C for the next day, a cooling period, and a final hour at 200 °C. This approach yielded an average compressive strength of 4.32 MPa with consistent results, as indicated by a low standard deviation of 0.19 MPa. Additionally, the composite's average bulk density reached 1.08 $gcm^{-3}$, with minimal variance among samples demonstrating material uniformity.

## 5. Conclusion

In conclusion, this study has successfully formulated a geopolymer composite that incorporates corn cob aggregates to produce non-structural, moderate-strength, lightweight concrete. The study pinpointed the optimal mix of Class C and F fly ash geopolymer paste that demonstrates superior compressive strength, alongside suitable setting times and workability at ambient temperature, specifically tailored for the integration of corn cob aggregates. The incorporation of corn cob aggregates to achieve a 50% volume replacement within the matrix has resulted in a composite that fulfills the requirements of ASTM standards C332 and C129 for non-structural, moderate-strength concrete, and nonloadbearing concrete masonry units. Moreover, it established a unique curing protocol involving sequential temperature exposures—initially at 90 °C for one day, followed by 60 °C for the subsequent day, a cooling period, and concluding with a final hour at 200 °C. This meticulous curing approach ensures the composite meets ASTM standards C332 and C129 for non-structural, moderate-strength concrete, and nonloadbearing concrete masonry units. It is recommended that future studies include thermal conductivity testing to fully comply with the relevant ASTM standards and to ensure a comprehensive understanding of the material's performance in terms of energy efficiency and insulation properties. The findings presented offer a promising direction for the development of eco-friendly construction materials that cater to the growing demand for sustainable and cost-effective building solutions.

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