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HIGH-STRENGTH CEMENT-FREE CONCRETE MADE FROM FLY ASH AND PALM OIL FUEL ASH

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ABSTRACT: This study investigated palm oil fuel ash as a partial replacement for fly ash in binders. As fly ash is a limited resource, incorporating renewable materials like palm oil fuel ash is crucial. The research assessed the effects of adding 5% and 10% palm oil fuel ash to fly ash-based geopolymer concrete. Samples were cured at room temperature and heated at 60°C for 24 hours. Compressive strength tests were performed at 1, 7, and 56 days. The results showed that adding palm oil fuel ash increased compressive strength by 5% to 12% at 5% addition and 10% to 33% at 10% addition. The heated curing method significantly boosted compressive strength by 74% to 79% after one day, 139% to 196% after seven days, 13% to 28% at 28 days, and 6% to 14% after 56 days. Scanning electron microscope (SEM) analysis revealed that heated specimens exhibited more interaction between palm oil fuel ash and fly ash, with fewer cracks at the 7-day curing period. However, there was no significant difference in the SEM results between heated and room temperature specimens after 56 days. The study concluded that palm oil fuel ash has excellent potential to replace fly ash partially, and after 56 days of curing, elevated and room temperature curing geopolymer concrete has approximately the same compressive strength, which is the novelty of this research.

Keywords: Geopolymer concrete, Palm oil fuel ash, Fly ash, Scanning electron microscope, Elevated temperature

1. INTRODUCTION

In recent years, construction material technology has advanced significantly, driven by the demand for sustainable, durable, and cost-effective solutions [1]. Utilizing resilient construction materials is essential for minimizing the environmental impact of projects and ensuring long-lasting buildings. Research shows that incorporating waste materials with pozzolanic properties leads to high-quality, eco-friendly, and economically viable construction materials, fostering a more responsible and innovative industry [1].

The building materials market grows yearly, introducing new materials that improve quality. People choose materials that save resources during tough times when building infrastructure and buildings. A major issue today is rising carbon dioxide levels from cement production, which contributes to climate change and harms the environment [1].

To address this, studies have focused on pozzolanic materials, known for their adhesive properties, as potential replacements for cement. One widely studied pozzolan is fly ash (FA), which is favored due to its rich composition of aluminum (Al), silica (Si), iron (Fe), and calcium (Ca) [2]. Other pozzolanic materials, such as volcanic ash, rice husk ash, mining tailings, bamboo leaf ash, palm oil fuel ash (POFA), can also be used in the production of geopolymer concrete [3,4]

Thermal power plants and coal-fired power stations produce fly ash, which is generated when coal is burned in the boiler and rises above it. Fly ash can be categorized into two categories: Class F, which has less than 18% calcium oxide, and Class C, which has more than 18% calcium oxide [5].

In 2025, about 10 million tons of fly ash and solid ash (collectively FABA) were produced from coal combustion [6], but only 3.4 million tons were utilized, with the remainder in landfills [7]. This can lead to environmental issues, including heavy metals leaching into soil and groundwater [8]. Finding alternative uses for fly ash, such as geopolymer concrete, is essential [2,8]. With the limited future of coal due to the SDG agenda and its non-renewable nature, a renewable alternative for fly ash is needed.

In 2024/2025, palm oil production reached 78.23 million tons, with Indonesia accounting for 59% of the total [9]. Fresh palm oil includes palm oil, kernels, fibers, shells, and empty fruit bunches. Although various studies have examined the potential uses of palm oil waste, only 25% is currently used for electricity generation through combustion [10].

Based on our study, we found that the combustion process generated approximately 7% POFA, a result similar to findings in another study [4]. If POFA is not disposed of properly, it can pose health risks related to bronchial and lung conditions [10]. In 2025, Indonesia is projected to consume 26.1 million tons of palm oil [11], which could result in approximately 1.83 million tons of POFA. Given that this waste material can be detrimental to human health, it is crucial to find useful applications instead of allowing it to be discharged into the environment.

POFA consists of more than 50% SiO_2, along with minor amounts of Al_2O_3 and Fe_2O_3 [12,13]. As a result, POFA exhibits pozzolanic properties and can serve as a partial substitute for cement. When incorporated as a partial replacement for cement in concrete mixes, POFA demonstrates strong resistance to chemical attacks, including sulfate [14], acid [12], chloride [13] and high temperature [15].

The acid resistance of mortars made from geopolymer fly ash and POFA in acidic peat water was examined [12]. Using a Na_2SiO_3 to NaOH ratio of 2.34; both samples had an initial strength of 18.40 MPa. The POFA-based geopolymer lost 80% of its strength after 180 days. The fly ash-based geopolymer initially lost 10% strength at 7 days, gained 15% by 28 days, then decreased by 10% to 120 days, before gradually returning to its original strength after 180 days.

Patah et al. (2025) studied POFA in concrete, using 10%, 20%, and 30% proportions mixed with seawater and sea sand [13]. Their study indicated a significant improvement in the mechanical properties of concrete containing 10% ultrafine POFA when seawater was used for mixing, with the highest compressive strength of 37.95 MPa at 28 days, representing a 39.90 % increase compared to normal concrete. These samples also showed reduced water absorption and chloride penetration depth but exhibited increased porosity. They found that 10% ultrafine POFA significantly improved mechanical properties, achieving a compressive strength of 37.95 MPa at 28 days, with reduced water absorption and chloride penetration but increased porosity. Another study indicated that 10% micro POFA and 0.5% nano POFA provided the highest carbonation resistance [16].

Putra et al. (2021) [17] studied the combination of fly ash and POFA to create geopolymer concrete. They tested three variations of fly ash to POFA ratio of 3, 1 and 1/3 and explored ratios of Na_2SiO_3 to NaOH 1.5, 2.0 and 2.5. The maximum compressive strength achieved in 28 days was 22.08 MPa using ratio Na_2SiO_3 to NaOH of 2.5 and fly ash to POFA ratio of 3.

Research by How et al. (2024) highlighted the trade-offs between strength and workability when using POFA and fly ash in concrete [18]. The optimal compressive strength of 27.46 MPa was achieved with 30% POFA, 30% fly ash, and 2% silica fume, reaching 80% of its strength at 7 days. In contrast, mixes with 60% fly ash showed low early-age strength, at only 50% of the 28-day strength. Replacing 30% of cement with POFA and fly ash reduced tensile strength by 24.75% and flexural strength by 61.48% compared to the control. Workability decreased, with the highest slump of 130 mm for 60% fly ash and 2% silica fume and the lowest slump of 20 mm for the 30% POFA and 30% fly ash mix, compared to 190 mm for normal concrete.

Altwair et al. (2024) indicate that incorporating POFA into concrete can enhance its self-healing properties [19]. Specifically, replacing 10% of the concrete mix with POFA significantly improves the self-healing capability of pre-cracked POFA concrete when subjected to water curing conditions.

While numerous studies have explored POFA as a cement substitute [12,18,19], our research focuses on its potential as a fly ash substitute in the formulation of high-strength cement-free geopolymer concrete. As a sustainable material, POFA shows significant promise as a replacement for fly ash. The primary aim of this paper is to fill this research void by creating high-strength geopolymer concrete that integrates fly ash and POFA. The microstructure of this geopolymer will be examined through scanning electron microscopy (SEM). The second aim is to identify the optimal mix proportions of geopolymer concrete containing a combination of fly ash and POFA through compression testing. This research stimulates further investigation into new materials sourced from solid waste, such as fly ash and POFA. It propels concrete technology towards more eco-friendly alternatives by incorporating by-products from agricultural and industrial processes.

2. RESEARCH SIGNIFICANCE

This research explores using fly ash and POFA to create high-strength geopolymer concrete as a sustainable alternative to Portland cement concrete. It provides engineers with guidelines for mixed designs and curing methods. The findings show no significant difference in strength between concrete cured at ambient and elevated temperatures after 56 days. This suggests that geopolymer concrete is a practical option for construction. Overall, the study promotes environmental sustainability by reducing CO_2 emissions and encourages greener practices in the construction and palm oil industries while ensuring reliable building materials.

3. MATERIAL AND METHOD

The palm oil used in this study was harvested from Kandis Village near Pekanbaru in Riau province. It was burned at 600°C, reaching this temperature in 20 minutes, and maintained at that temperature for 2 hours. The palm oil shells were automatically incinerated and cooled over two days. The resulting palm oil fuel ash (POFA) was processed in a Los Angeles machine at 30 revolutions per minute for 2 hours to achieve a fine, dust-like consistency, as shown in Fig. 1. This study used POFA that passed through a #200 sieve.

According to the X-ray fluorescence test, the chemical composition of the POFA in this study was as follows: 36.9% SiO_2, 2% Al_2O_3, 9.2% Fe_2O_3, and 25.6% CaO. The density of POFA was 1720 kg/m^3

Fig. 1 POFA

Fly ash is made of fine particles created when coal is burned in power plants (Fig. 2). The fly ash used in this research was sourced from the Paiton electric steam power plant in Probolinggo. According to the X-ray fluorescence test results, the chemical composition of the fly ash consisted of 34.7% SiO_2, 23.6% Al_2O_3, 14.2% Fe_2O_3, and 15.1% CaO. The density of the fly ash is measured at 2560 kg/m^3.

Fig. 2 Fly ash

The fine aggregate used in this study was sourced from Bangka Belitung Island and had a density of 2405 kg/m3. The sodium hydroxide employed in the study was 98% concentrated and in flake form. Additionally, the sodium silicate used was 55% concentrated and liquid.

The primary objective of this research is to develop high-strength concrete. Previous studies have shown that excluding coarse aggregates from the concrete mix design can result in high-strength concrete [20].

The slump value of a sodium hydroxide solution with a molarity of 12 ranges between 6 cm and 8 cm (2.36 inches to 3.14 inches), which meets the requirements for beam and column structures according to ACI 211.1.9. Therefore, this research utilizes a sodium hydroxide solution with a molarity of 12.

Increasing the amount of POFA in a cement mixture leads to a reduction in compressive strength [12,13]. A higher ratio of POFA to fly ash further decreases the compressive strength of concrete mixtures that contain both materials [17,18]. POFA has limited pozzolanic capabilities compared to fly ash. Research indicates that a POFA content of 10% provides the best resistance to carbonation [16] and exhibits optimal self-healing properties [19]. This study set the amount of added POFA at 5% and 10%.

The ratio of the alkali activator is crucial in determining both the setting time and the strength of the specimens. Increasing this ratio results in higher compressive strength but also leads to a shorter setting time. However, there is an optimal alkali activator ratio beyond which compressive strength decreases. This decrease occurs because excess pozzolanic material cannot be activated if the optimal ratio is surpassed. Numerous studies [8,17] indicated that a Na_2SiO_3 to NaOH ratio of approximately 2.5 yielded the best compressive strength in concrete. For this study, however, a ratio of 2.67 was used.

The ratio of material mass compared to fly ash mass is presented in Table 1.

Table 1. Ratio of material mass

Material	Amount of POFA addition		
	0%	5%	10%
Fine aggregate	1.75	1.75	1.75
FA	1	1	1
POFA	0	0.05	0.10
Sodium silicate (Na_2SiO_3)	0.4	0.4	0.4
Sodium hydroxide (NaOH)	0.15	0.15	0.15

The test object was developed using a 12 molarity sodium hydroxide solution, which was left to stabilize for one day before being mixed with sodium silicate to form an alkali activator. Next, fly ash (FA) and palm oil fuel ash (POFA) were added to create a geopolymer paste, which was then transformed into geopolymer concrete by mixing in fine aggregate. This research tested two curing methods: at room temperature and 60°C for 24 hours. Heat curing at 60°C for 24 hours is the most effective for enhancing compressive strength, while higher temperatures or longer curing times do not yield additional benefits

[21].

The specimen measures 10 cm in diameter and 20 cm in height, with six pieces for each variable. Three specimens were heated in an oven at 60°C for 24 hours and then cured at room temperature. Compression tests will be conducted on the specimens after 1, 7, 28, and 56 days of curing**.**

4. RESULT OF THE RESEARCH

4.1 Compressive Strength Test

Table 2 and Fig. 3 compellingly illustrate the development of compressive strength in geopolymer concrete cured at ambient temperatures for 1 to 56 days, highlighting the significant potential of the POFA. Table 2 shows the average value (Avg) and standard deviation (SD).

Table 2. Effect of POFA addition on compressive strength of 12 molarity specimens cured at ambient temperature.

Time of curing (day)	Amount of POFA addition					
	0%		5%		10%	
	Avg	SD	Avg	SD	Avg	SD
1	11.47	1.01	12.27	1.62	15.6	1.83
7	15.66	2.56	17.53	0.08	21.39	0.80
28	37.77	3.08	41.08	0.81	48.89	0.88
56	43.72	0.27	47.87	2.22	53.65	1.07

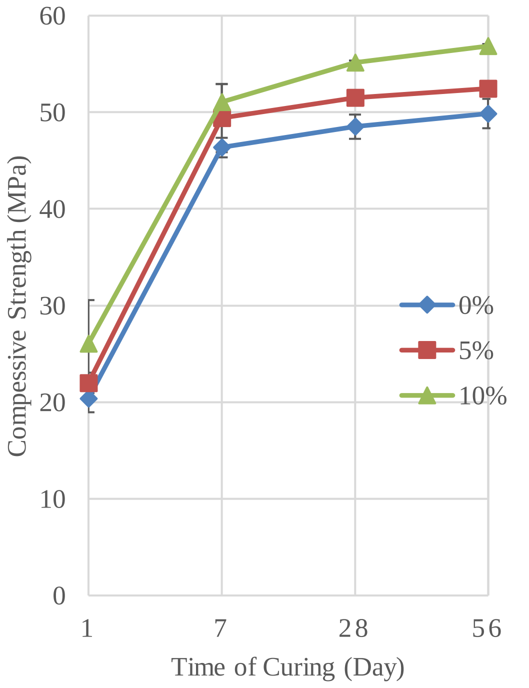

Fig. 3 Relationship between compressive strength and curing time at ambient temperature.

All specimens incorporating POFA and those without gradually increased strength when cured at ambient temperature over 56 days (Fig. 3).

This remarkable enhancement in compressive strength can be attributed to a continuous polymerization process [22]. Compared to specimens without POFA, the compressive strength increased by 7-12% with the addition of 5% POFA (Table 2). Adding 10% POFA resulted in a 23-37% increase (Table 2). These results demonstrate the benefits of POFA in enhancing material performance.

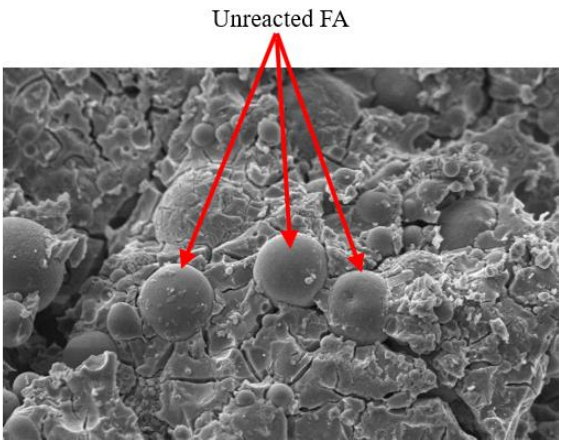

Fig. 4 SEM result for the specimen without POFA addition, cured at ambient temperature for **7** days

A close analysis of the micrographs (Fig. 4 and Fig. 5) of two geopolymer concrete specimens, cured at the same ambient temperature for 7 days, reveals that the specimen with 10% POFA demonstrated a superior agglomeration of powder materials due to its elevated silica content.

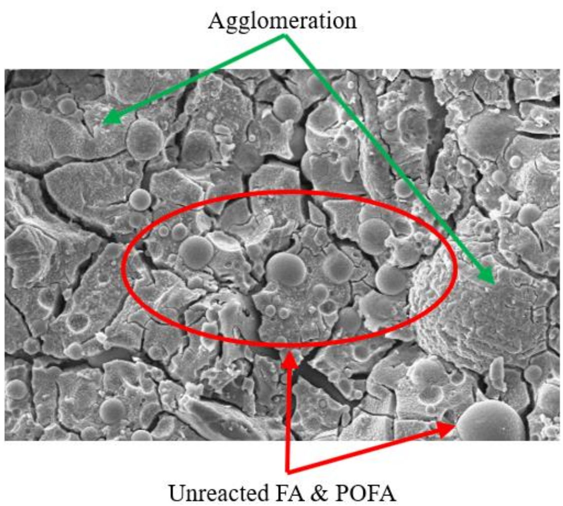

Fig. 5 SEM result for the specimen with 10% POFA addition, cured at ambient temperature for **7** days.

This key factor demonstrates why the specimen incorporating 10% POFA exhibited remarkably higher compressive strength than the control specimen without POFA, reinforcing findings from multiple studies [23,24].

The SEM micrographs (Fig. 5 and Fig. 6) demonstrate a notable change from irregular spherical shapes to a densely compacted mass, resulting in agglomeration. This transformation is driven by the polymeric changes that occur with extended curing time. It is closely associated with improved mechanical properties, especially increased compressive strength.

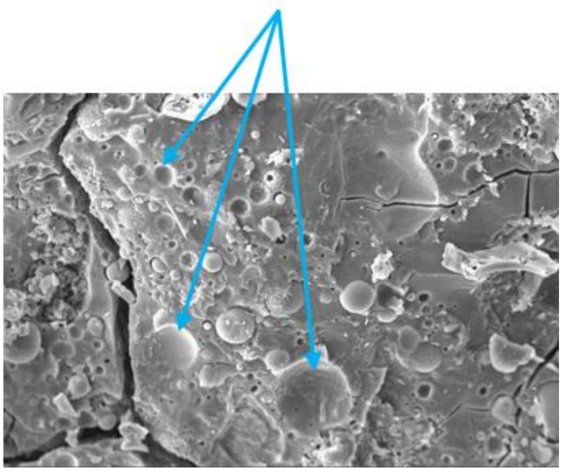

Fig. 6 SEM result for the specimen with 10% POFA addition, cured at ambient temperature for 56 days

Additionally, the comparison of Fig. 5 and Fig. 6 indicates that the specimen cured for 7 days exhibited significantly more cracking than the specimen cured for the full 56 days, underscoring the critical impact of curing duration on the structural integrity of the geopolymer concrete.

Fig. 7 shows that all specimens containing POFA and those without it exhibited increased strength when cured at elevated temperatures for over 56 days. The slope of the line from day 1 to day 7 is significantly steeper than the slope from day 7 to day 56. This indicates that the compressive strength of the samples treated at elevated temperatures experienced a substantial increase between day 1 and day 7.

A comparison of the samples treated at ambient and elevated temperatures (as shown in Tables 2 and 3) reveals that the increase in compressive strength for the ambient temperature samples ranged from 37% to 43% (Table 2), whereas the samples treated at elevated temperatures exhibited an increase ranging from 89% to 127% (Table 3). The most substantial increase in compressive strength of specimens is observed at elevated temperatures during curing periods of 1 to 7 days. This remarkable enhancement is primarily attributed to the elevated temperatures, which significantly accelerate the geopolymerization process, leading to higher initial compressive strength [25]. The 56-day curing period enables a complete reaction of the available reactive materials, resulting in a more homogeneous and well-formed geopolymer structure. Consequently, the improvements in compressive strength decrease [26].

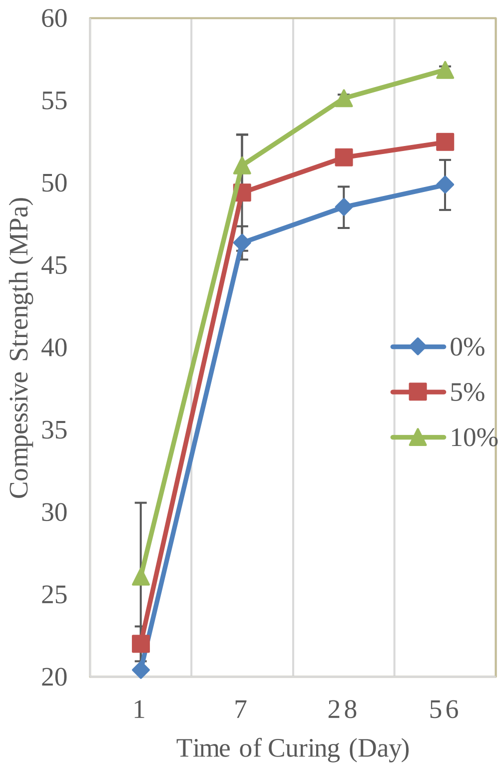

Fig. 7 Relationship between compressive strength and curing time at elevated temperature

Table 3. The effect of adding POFA on the compressive strength of specimens with 12 molarity, elevated to 60°C for 24 hours.

Time of curing (day)	Amount of POFA addition					
	0%		5%		10%	
	Avg	SD	Avg	SD	Avg	SD
1	20.4	1.44	22	1.06	27.07	4.50
7	46.35	1.01	49.4	3.53	51.06	1.85
28	48.51	1.25	51.52	0.27	55.13	0.23
56	49.87	1.52	52.46	0.18	56.83	0.21

A comparison of images (Fig. 4 and Fig. 8) from two geopolymer specimens, both without the addition of POFA, and cured at different temperatures—ambient and elevated (60 °C)—shows that curing at the elevated temperature allows for greater agglomeration of the powder materials. This increased agglomeration is due to enhanced polymerization at higher temperatures within the same time frame.

The increase in agglomeration caused by high temperatures is reflected in the compressive strength of the specimens. For example, after 1 day of curing, the compressive strength for specimens cured at ambient temperature is 11.47 MPa, whereas specimens cured at elevated temperature achieve a compressive strength of 20.4 MPa. Similarly, after 7 days of curing, the compressive strength at ambient is 15.66 MPa, compared to 46.35 MPa for those elevated curing. After 56 days of treatment, the compressive strength at ambient measured 43.72 MPa, while the specimens treated at elevated temperatures reached 49.87 MPa.

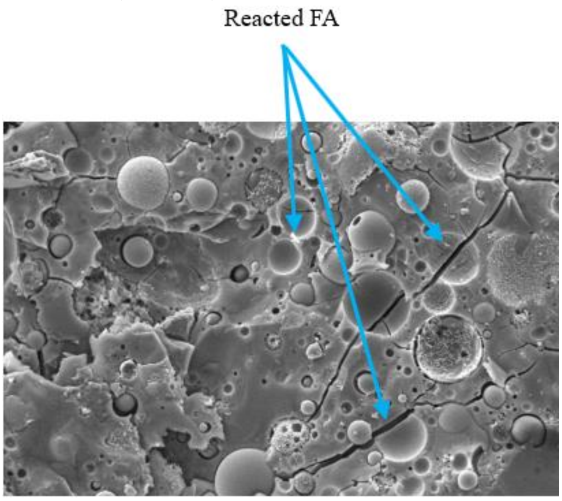

Fig. 8 SEM result for the specimen without POFA addition, cured at elevated temperature for 7 days.

A closer examination of Tables 2 and 3 reveals that the differences in compressive strength between ambient and elevated treatments are 78%, 195%, 25%, and 14% for curing 1, 7, 28 and 56 days, respectively. Thus, for a 56-day treatment period, the difference in curing temperature is less significant. This is an important consideration for practical applications. If high initial compressive strength is required, geopolymer concrete should be heated. However, high initial compressive strength is not a priority. In that case, it may be beneficial to cure the geopolymer concrete at ambient temperature to reduce emissions while achieving the desired compressive strength.

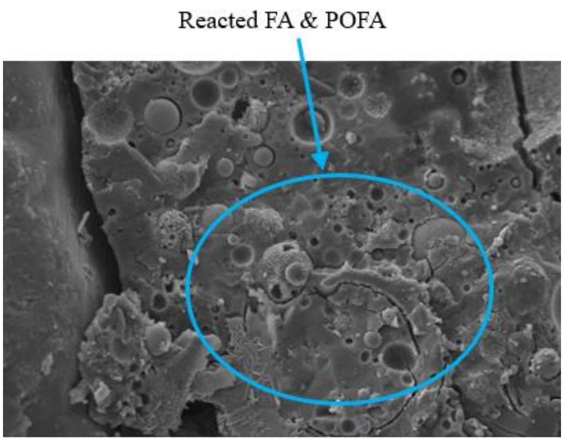

Fig. 9 shows the SEM result for the specimen with a 10% POFA addition, which was cured at an elevated temperature for 7 days.

A comparison of images (Fig. 9 and Fig. 10) from two geopolymer specimens with 10% POFA addition indicates that the specimen cured for 7 days displayed significantly more cracking than the full 56 days. This highlights the crucial impact of curing duration on the structural integrity of the geopolymer concrete.

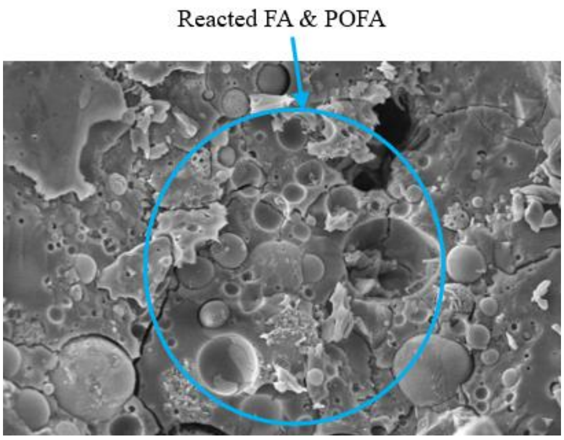

Fig. 10 SEM results for specimens with 10% POFA addition, cured at elevated temperature for 56 days.

5. CONCLUSION

The elevated temperature curing method significantly accelerates the chemical reaction rate in geopolymer concrete, leading to a striking increase in initial compressive strength. After just one day, specimens cured at elevated temperatures exhibit a strength increase of 74-79% compared to those cured at ambient temperatures, soaring to an extraordinary 139-196% after seven days. By 28 days, these specimens are 13-28% stronger, though the difference narrows to 6-14% by 56 days. For projects requiring high initial strength, geopolymer concrete heating is beneficial, while curing at ambient temperature offers a chance to reduce emissions without sacrificing desired compressive strength.

POFA also proves beneficial, with 10% POFA increasing compressive strength, especially when the specimens were cured at ambient temperature. At elevated temperatures, there is also an increase in strength for adding 10% POFA, but not as large as when the samples are treated at ambient temperature. Several other studies also support this by stating that an additional 10% is the optimal addition.

Further research is recommended to examine how different particle sizes of POFA affect the compressive strength of concrete. Additionally, exploring the flexural strength performance of this non-cement green concrete is essential. Furthermore, the influence of POFA on the self-healing properties of green concrete warrants future investigation.

6. ACKNOWLEDGMENTS

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