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FLY-ASH BASED GEOPOLYMER MORTAR FOR PAVING BLOCKS: MECHANICAL PERFORMANCE AND MICROSTRUCTURE ANALYSIS

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ABSTRACT: This study investigates low-carbon alternatives to cement-based paving blocks by assessing ambient-cured, fly-ash-based geopolymer mortars with varying fly ash (FA) proportions (100%, 85%, 80%, and 75% of binder) and minimal cement content (0%, 15%, 20%, and 25% of binder). To mitigate the approximately 8% contribution of global CO_2 emissions from cement production, mixes were activated using an alkaline system consisting of 10 M sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) at a Na_2SiO_3/NaOH ratio of 2.5, generated at a solid-to-liquid (binder-to-activator) ratio of 2.0. Specimens were cast into 5×5×5 cm cubes and evaluated for compressive strength (ASTM C109) at 7 and 28 days; microstructure was examined using scanning electron microscopy (SEM). The ideal formulation (80% FA + 20% cement) attained 14.0 MPa at 7 days and 20.7 MPa at 28 days, conforming to Indonesia's paving block standard (SNI 03-0691-1996 Class B). SEM demonstrated a compact, densely arranged matrix with minimal apparent porosity and insignificant cracking at the optimal level, while elevated or reduced FA amounts exhibited microcracking, voids, or unreacted particles. Restricting cement to 20% of the binder significantly decreases binder-associated CO_2 emissions while fulfilling performance standards, thereby substantiating fly-ash geopolymers as viable, sustainable materials for paving blocks and elucidating the microstructural mechanisms that support the appropriate fly ash concentration.

Keywords: Paving block, Fly ash, Geopolymer, Compressive strength, SEM

1. INTRODUCTION

The building sector is recognized as a significant contributor to global carbon emissions, with the production of Ordinary Portland Cement (OPC) accounting for nearly 8% of total CO_2 emissions worldwide [1,2]. In light of growing environmental concerns, academics and practitioners are actively investigating sustainable alternatives to reduce the environmental impact of traditional cement-based materials. Geopolymer technology has garnered considerable interest as a new and environmentally sustainable binder system, presenting the possibility of substituting Ordinary Portland Cement (OPC) in various construction applications [3,4].

Originating from coal combustion in thermal power plants, fly ash has been extensively explored as a primary precursor for geopolymer production [5,6,7,8]. Rich in reactive silica and alumina, fly ash reacts with alkaline activators like NaOH and Na_2SiO_3, generating a hardened matrix that exhibits substantial early-age strength [8,9,10,11]. The incorporation of fly ash in paving block manufacture improves the mechanical qualities of the product while promoting sustainable waste management and the creation of low-carbon construction materials [12,13,14]. The presence of fly ash changes the physical features of the geopolymer matrix, particularly its microstructure and pore system. Due to their spherical morphology and fine size, fly ash particles promote better packing density, which minimizes voids and enhances overall compactness [8,9,15,16]. This densification effect is linked to enhanced durability and compressive strength in comparison to traditional cement-based paving blocks [17]. The change in fly ash composition directly affects strength and durability, which are essential elements in assessing the overall performance and longevity of paving blocks [18,19,20].

Chemically, the geopolymerization process involves a series of dissolution, transportation, and polycondensation reactions [21,22]. During the dissolving phase, hydroxide ions from the alkaline solution interact with the amorphous aluminosilicate components of fly ash, liberating silicate (SiO_4^{4-}) and aluminate (AlO_4^{5-}) species into the solution. The species then experience reorientation and polycondensation, leading to the formation of Si–O–Al and Si–O–Si linkages, which create a three-dimensional aluminosilicate network referred to as geopolymeric gel [23,24].

This gel gradually sets, linking solid particles and producing a compact matrix that contributes to higher mechanical performance and long-term durability [12,15,18,19,25]. The level of geopolymerization depends greatly on precursor chemistry, activator dosage, curing environment, and, most critically, the amount of fly ash incorporated [12,14,15,25,26,27,28].

Although geopolymer composites have been widely studied, the bulk of existing work concentrates on high-temperature curing as a means to accelerate geopolymerization, especially in the context of non-structural applications [18,29,30,31,32,33,34,35]. Recent studies [32,33,35], indicate that room-temperature (ambient-cured) geopolymer paving units can attain specification-compliant strengths while reducing clinker requirements. Nonetheless, for Class-C fly ash (FA) systems, the quantitative correlations between FA concentration, strength progression at 7 and 28 days, and microstructural densification are inadequately characterized. Due to the impracticality of heat curing in large-scale manufacturing, particularly in areas where ambient curing is the feasible method, it is essential to investigate the influence of FA content on strength development and microstructure during ambient curing.

This research investigates geopolymer paving blocks produced with different fly ash ratios, cured at ambient temperature, and evaluates the compressive strength at 7 and 28 days and density. The results are compared with the Indonesian Standard for paving blocks [36] to assess the applicability of fly ash as an alternative binder in sustainable paving materials. The microstructure of the geopolymer mortar was also evaluated using a Scanning Electron Microscope (SEM). This study addresses that gap by (i) varying FA proportion at fixed activator ratios, (ii) curing under ambient temperature, (iii) quantifying compressive strengths against Indonesian Standard [36] limits, and (iv) explaining observed strength trends via SEM-based evidence of pore/gel development and crack mitigation.

This study has practical implications for the potential CO_2 reduction by lowering OPC usage in paving block mortars. OPC manufacture is a major contributor to industrial CO_2 emissions. Room-temperature (ambient-cured) fly-ash geopolymers address this by (i) replacing most OPC with FA and (ii) eliminating thermal curing, thereby lowering both binder-related and process-energy emissions. Operationally, ambient curing is well-suited to tropical conditions and factory-ready: mixes can be produced with a conventional mixer and a steel mold, without specialized ovens or steam chambers.

2. RESEARCH SIGNIFICANCE

This work presents quantitative, ambient-cured proof that a binder composed of 80% fly ash (FA) and 20% cement attains compressive strengths of 12.0 MPa at 7 days and 17.2 MPa at 28 days, thereby meeting SNI Class-B standards for paving blocks while significantly decreasing cement consumption. SEM verifies a denser, low-porosity matrix and minimal microcracking at the optimal mixture, suggesting a synergistic interaction between N-A-S-H and calcium-bearing gels (C-(A)-S-H) rather than fineness alone as the principal factor influencing strength. The mixture employs ambient curing and accessible fly ash, facilitating scalable production with reduced binder-associated CO_2 emissions compared to mortars high in ordinary Portland cement. These findings elucidate the requisite FA–cement equilibrium for producing compliant, lower-carbon paving blocks and establish a replicable mixture proportion (kg/m³ mix table; Solid/Liquid and Sodium Silicate/Sodium Hydroxide ratios) for industrial implementation.

3. MATERIALS AND METHODS

The utilization of recycled waste, specifically fly ash, as a cement alternative for eco-friendly paving blocks via the geopolymer process has been a longstanding research priority at the Structural Strength Technology Research Center, National Research and Innovation Agency. This research involved producing numerous test samples by a combination of fly ash and differing molarities of sodium hydroxide solution via the geopolymer method. Figure 1 displays the fly ash geopolymer specimen.

Fig.1 Fly-ash based geopolymer mortar specimens

This research section examines sample preparation techniques, where fly ash serves as an alternative to cement in environmentally friendly paving block fabrication using the geopolymer method. Details of the testing procedure to determine the compressive strength of 5×5×5 cm cube samples are provided.

3.1 Materials Preparation

This study employed Class C high-calcium fly ash from a nearby coal-fired power plant as the primary binder, together with cement. The activators were prepared using NaOH pellets and a commercial Na_2SiO_3 solution. Before mixing, fly ash and cement were dried, homogenized, and evenly spread.

3.2 Mix Design and Mixing Process

A 10 M NaOH solution was prepared from pellets, allowed to cool to ambient temperature, and aged for 24 hours before utilization. This concentration was selected based on prior experiments and corroborating literature [8,9,13], indicating that 10 M at approximately 25 °C ensures adequate aluminosilicate dissolution while preserving manageable viscosity and regulated setting. Before mixing, sodium silicate (SS) and sodium hydroxide (SH) solutions were combined at a mass ratio of SS/SH = 2.5 to provide soluble silicate for initial gel formation without excessively increasing the viscosity of the paste. The mixing process was performed at 25 °C. Natural River sand was used as fine aggregate. Geopolymer paste was produced by combining fly ash, cement, alkali activator A, and fine aggregates with a fixed solid-to-liquid ratio of 2.0 (by mass). Mixes were prepared with varying fly ash contents to assess their effect on mechanical performance. The fly ash content was varied at selected intervals (0%, 100%, 85%, 80%, and 75% of the binder weight). The detailed mix design of additives utilized in this study is presented in Table 1. All dry components were homogenized, after which the alkaline solution was incrementally introduced. The newly mixed mortar was poured into steel molds measuring 50 × 50 × 50 mm for the purpose of compressive strength evaluation. Specimens were maintained at about 25 °C (ambient) for 24 hours, thereafter demolded, and stored under identical ambient laboratory settings on ventilated steel racks until testing at 7 and 28 days. No water or heat curing was utilized, and relative humidity was not actively regulated. Compressive strength was assessed according to ASTM C109 [37] using a calibrated apparatus with spherically seated platens, maintaining a stress rate of 0.9 ± 0.2 MPa/s. For each mixture and test age, n = 3 cubes were evaluated; the three values were then averaged, and the mean value was reported. Surfaces were wiped dry and inspected before testing. The mixing sequence is illustrated in Figure 2.

3.3 Mechanical Performance and Microstructure Analysis

Compressive strength tests were performed with a testing machine following ASTM C109 [37]. The highest load obtained was recorded, with the results expressed as the average of three specimens for each variation and curing period. These tests were carried out to assess the suitability of fly ash-based geopolymer as a paving block material, particularly in meeting the Indonesian National Standard (SNI 03-0691-1996) for paving blocks [36]. The unconfined compressive strength testing apparatus is shown in Figure 3. The study involved conducting chemical composition and morphology analysis using a Scanning Electron Microscope (SEM) and X-ray Fluorescence (XRF). These processes aim to evaluate the impact of geopolymers on the mechanical characteristics of fly ash and cement, as well as to analyze the elemental composition and morphology of the resultant geopolymer materials.

Table 1. Mix design of geopolymer mortar (in kg/m^3)

No	Cement (C)	Fly Ash (FA)	Sand	Water	Solid (S) S=FA+C	Liquid (L) L=SS+SH	Sodium Silicate Solution (SS)	Sodium Hydroxide Solution (SH)
1	667	0	1833	242	0	0	0	0
2	0	667		0	667	333	238	95
3	100	567						
4	133	533						
5	167	500						

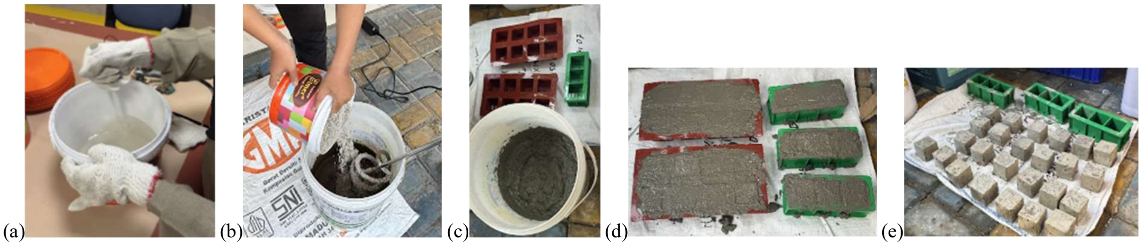
(a) (b) (c) (d) (e)

Fig.2 Procedures for the manufacturing and curing of the examined geopolymer mixtures: (a) alkali activator mixing, (b) mixing materials and alkali activator, (c) sample pasta, (d) molding sample, and (e) sample curing under ambient conditions

Fig.3 Unconfined Compression Strength (UCS) test

4. RESULT AND DISCUSSION

4.1 Properties of Raw Materials

Table 2 shows the test results for the physical characteristics of the cement and fly ash used in this exploration. According to Table 2, the fly ash and cement compaction test produced water absorption content values of 12.9 % and 1.31%. The diminished absorption of fly ash leads to decreased water loss during curing, facilitating a more regulated geopolymerization response. This corroborates the findings in [12,19], which highlighted that low-absorption pozzolans, including fly ash, can enhance the durability of geopolymer cementitious composite. The findings indicate that fly ash usage improves sustainability and alters physical performance, requiring optimized mix designs to reconcile early strength with long-term durability [38,39,40].

Table 2. Properties of materials

No	Properties	Value		Unit
		Cement	Fly ash	
1	Grain size	14.4	52.6	µm
2	Density	1,85	2.18	g/cm^3
3	Water Absorption	12.9	1.31	%

The mean particle size of fly ash (52.6 µm) is significantly larger than that of cement (14.4 µm), indicating less fineness and potentially weaker reactivity due to a smaller specific surface area. Reduced particle sizes generally enhance hydration and pozzolanic reactions by increasing interactions with water and other constituents, as demonstrated in [41,42] regarding the geopolymer process with fly ash. However, geopolymerization reactions can increase reactivity and density by filling interstitial voids between sample particles with fine fractions of fly ash and cement, which can contribute to improved strength under compression [13,43].

Besides that, the dry density values are 1.85 g/cm3 and 2.18 g/cm3. This indicates that fly ash possesses a denser microstructure, potentially influencing the packing density of the matrix during blending. Increased density can augment mechanical interlocking within the mixture, hence enhancing compressive strength over time. Previous studies [44,45] revealed analogous findings, indicating that heightened fly ash density enhanced the densification of the geopolymer matrix and augmented durability.

Table 3 shows the elements of fly ash and cement, which significantly influence their reactivity and efficacy in binder systems. Fly ash possesses a calcium oxide (CaO) percentage of 24.3%, hence categorizing it as high-calcium or Class C fly ash [46]. This fly ash's CaO percentage is lower than that of cement. The reduced CaO level indicates that fly ash has a greater role in pozzolanic processes than in hydration, as also indicated by the ASTM C618-22 classification [46]. In contrast, the elevated CaO concentration in cement signifies its pivotal function in the early development of strength via hydration processes [9,45,47].

The microstructural characteristics of fly ash and cement were analyzed through scanning electron microscopy, as demonstrated in Figure 4. The results indicate that SEM of fly ash exhibits a particle morphology predominantly characterized by spherical forms with typically smooth and glassy surfaces, characteristic of class C fly ash derived from coal burning. These particles exhibit a range of sizes, from small micrometer scales to several tens of micrometers, which enhances particle distribution and promotes material densification when utilized in geopolymers or paving block combinations. The existence of spherical particles of diverse sizes facilitates the occupation of voids between aggregates, thereby enhancing density and diminishing the porosity of paving blocks, which ultimately elevates compressive strength [48,49].

Table 3. Elemental structure of fly ash and cement

Material	Elemental (%)					
	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	SO_3
Fly ash (FA)	24.3	13.6	29.4	6.67	19.5	2.23
Cement (S)	62.7	6.67	17.8	1.88	5.92	2.59

Moreover, the cement SEM results, as shown in Figure 4, indicate that the cement exhibits heterogeneous particle morphology, a rough surface, and porosity. Rough and porous cement particles enhance the contact area among particles in the mixture, thus expediting the hydration reaction and the development of robust chemical bonds inside the geopolymer concrete matrix or paving blocks. The presence of pores enables efficient ingress of water and chemical agents, thereby accelerating the hydration process and resulting in the development of a dense and uniform material structure that enhances the material's compressive strength [50,51]. Moreover, diverse particle sizes facilitate effective compaction and the filling of interstitial gaps, hence diminishing porosity and augmenting the density of paving blocks [52,53].

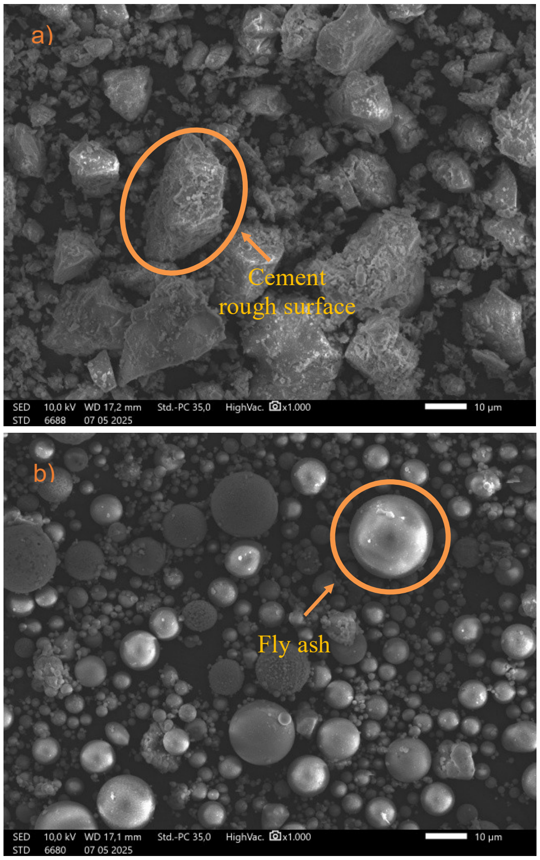

Fig.4 SEM of: (a) cement and (b) fly ash

4.2 Mechanical Performance of Mortar Samples

The influence of adding fly ash and cement-based geopolymer on raising compressive strength value was shown in Table 4 and Figure 5. Increasing curing time contributed to a further increase in compressive strength. The utilization of 100% FA resulted in a significant enhancement in compressive strength for both curing durations, measuring 7.6 MPa and 11 MPa. The enhancement was augmented by the use of cement in the mixture. The FA 85% + Cement 15% mixture achieved 11.9 MPa and 16.9 MPa at 7 and 28 days. Calcium's presence in cement likely expedited the geopolymerization reaction and facilitated further gel formation, such as C–S–H, which aids in matrix densification. This is supported in the literature [54], which demonstrated that the concurrent development of C–S–H and N–A–S–H gels, supported by an appropriate amount of calcium hydroxide, works synergistically to densify the geopolymer matrix, decrease porosity, and markedly enhance strength under compression. The highest value is shown based on the comparison of the mean value. The statistical measure of the spread (dispersion) from a set of data values around their mean is shown as standard deviation (SD) in Table 4. The SD value is less than 3.5, showing the consistency and uniformity, according to ACI 314R [55].

Table 4. Compressive strength of mortar sample (FA: fly ash, S: cement, SD: Standard deviation)

Curing	Sample	Compressive Strength (MPa)				
		1	2	3	Mean	SD
7 days	Control	8	8.8	8.8	8.5	0.46
	FA 100%	8.4	7.2	7.2	7.6	0.69
	FA 85% + S 15%	11	12	12.8	11.9	0.90
	FA 80% + S 20%	14.4	13.2	14.4	14	0.69
	FA 75% + S 15%	12	10	10	10.7	1.15
28 days	Control	10.8	11.2	11.2	11.07	0.23
	FA 100%	13	9.6	10.4	11	1.78
	FA 85% + S 15%	16.8	16.8	17	16.9	0.12
	FA 80% + S 20%	22	18	22	20.7	2.31
	FA 75% + S 15%	14	16	14	14.7	1.15

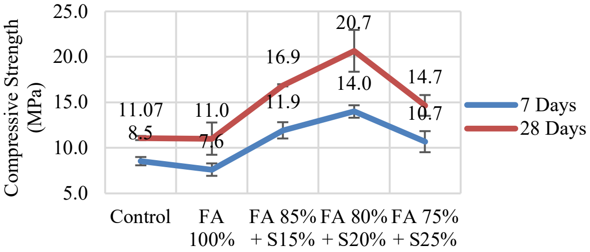

Fig.5 The effect of compressive strength value on mixture variation (FA: fly ash and S: cement)

The highest compressive strength was attained with a blend of 80% fly ash and 20% cement, producing 14 MPa and 20.7 MPa after 7 and 28 days. These results comply with the class B paving block criteria outlined in Indonesian Standard SNI 03-0691-1996 [36]. This signifies that at this composition, the equilibrium between geopolymeric gel (derived from FA) and cementitious hydration products attained an ideal state. Furthermore, fine particles in fly ash and cement filled the space between particles, leading to high compressive values. Nonetheless, augmenting the cement component to 25% (FA 75% + Cement 25%) led to a reduction in strength. This decrease in strength could be due to poorer workability, faster setting, or tiny cracks inside caused by too much cement, which affects the even development of the structure. The morphology and calcium content of fly ash (FA) critically dictate the balance between N–A–S–H and C–S–H formation, which explains the observed compressive strength trend—peaking at 80% FA and declining when FA drops to 75% as cement increases. At 80% FA, the predominantly spherical, amorphous cenospheres dissolve moderately in the alkaline activator, releasing Si and Al species that form a continuous N–A–S–H network. A moderate Ca supply from limited cement addition promotes the formation of intergrown C–(N)–A–S–H gels, which bridge the geopolymeric matrix, refine pore structures, and enhance mechanical integrity. The hybridization of both gel types densifies the matrix without prematurely halting FA dissolution, leading to an optimum, highly cross-linked microstructure that maximizes compressive strength [56,57]. However, when FA content is reduced to 75%, and cement proportion increases, excess Ca drives rapid C–S–H precipitation and portlandite formation, which consume available silicate, coat unreacted FA particles, and inhibit further geopolymerization. This is supported by findings in previous studies [9,58], which observed that excessive binder quantity in geopolymer mixtures leads to reduced flowability, accelerated setting times, and the formation of internal microcracks due to uneven heat distribution and shrinkage during curing.

Figure 6 illustrates the effect of density values on different mixture variations. The density of the geopolymers mixtures showed a substantial increase compared to the control sample (which did not include fly ash), with the highest value observed at 2.184 g/cm^3 for the mix containing 100% fly ash. This enhancement is attributed to the fine particles of fly ash, which likely led to improved particle packing efficiency and reduced porosity in the matrix. This trend supports earlier findings [59,60], which showed that a higher proportion of fly ash in geopolymer systems leads to improved material density due to a more cohesive and refined microstructure. Consequently, replacing cement with fly ash enhances sustainability while also increasing density, which is typically linked to improved compressive performance and durability in geopolymer-based mortar and paving block applications [12,16,60,61].

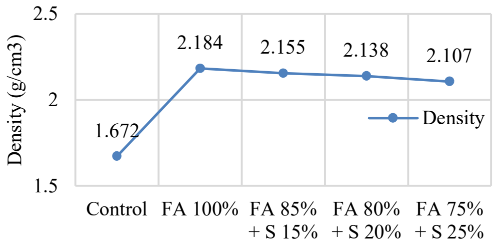

Fig.6 The effect of the density value on mixture variation (FA: fly ash and S: cement)

The density is lower in the sample with the decrease of fly ash content, because the density of cement is lower than that of fly ash. Thus, the density trend is not linear with the compressive strength.

4.3 Microstructural Analysis of Mortar Samples

SEM investigation demonstrated significant disparities in crack propagation, pore distribution, and void content among geopolymer paving blocks with differing fly ash compositions, as illustrated in Figure 7. The control sample (0% fly ash) demonstrated a very porous microstructure, characterized by numerous huge voids and broad, irregular fissures. The lack of pozzolanic reaction products, including N-A-S-H gels, signifies inadequate reactivity and feeble interparticle interaction. This result matches the conclusions drawn in [16,61], which indicated that cement paste lacking extra pozzolanic ingredients tended to develop unstable microstructures due to inadequate hydration. Conversely, the 100% and 85% fly ash samples exhibited denser matrices characterized by -

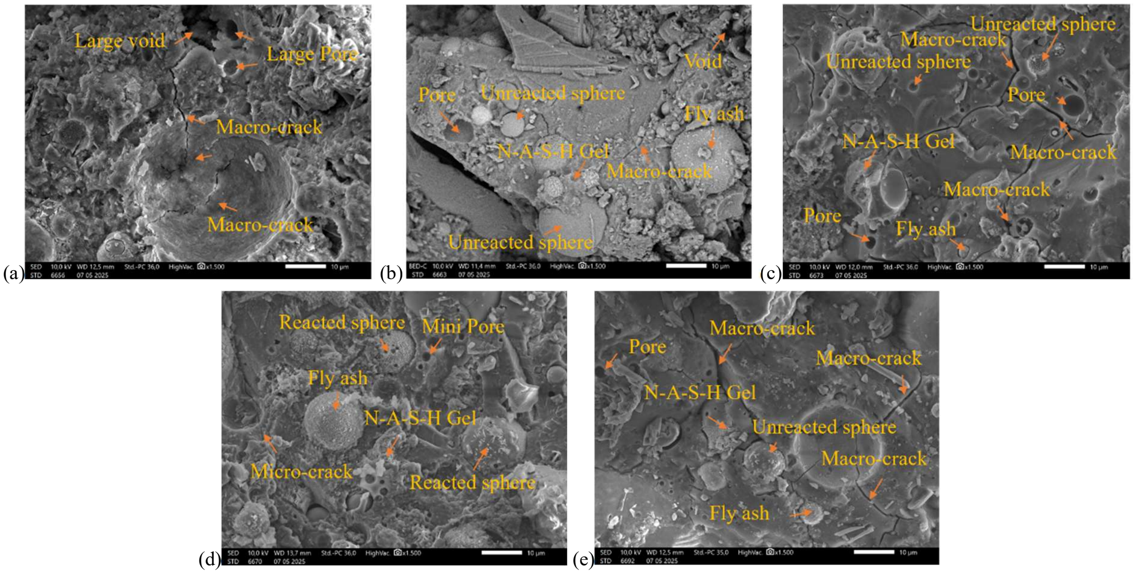

Fig.7 SEM of mortar: a) control, b) 100% fly ash, c) 85% fly ash, d) 80% fly ash, and e) 75% fly ash

finer fissures and reduced pore sizes. Although certain spherical fly ash particles remained unreacted, the initiation of geopolymer gel formation was clearly observed. The geopolymerization process seems to have been constrained by inadequate alkali activator, as evidenced in literatures [44,62].

The 80% fly ash sample had the most favorable microstructure, characterized by high density, low porosity, and an absence of visible fissures. The lack of significant fissures indicates diminished internal tensions during the curing process. This formulation attained the highest compressive strength, validating that the fly ash-to-activator ratio at this level facilitates optimal geopolymerization. Findings in previous studies [17,63] also showed that high-calcium fly ash, when adequately activated under ambient circumstances, can yield a dense matrix with elevated compressive strength.

Nonetheless, when the fly ash proportion was reduced to 75%, the quality of the microstructure markedly declined. SEM scans indicated the resurgence of substantial fissures, heightened open porosity, and inadequately adhered fly ash particles. The data suggest that inadequate precursor availability at reduced fly ash levels restricts N-A-S-H gel formation, compromising structural integrity. A previous study [64] also noted that diminished aluminosilicate concentrations impede gel formation, leading to more significant cracks and voids. Thus, all compositions showed a substantial drop in strength under compression, indicating that fly ash levels under 80% fail to enable the establishment of a stable geopolymer framework crucial for long-term structural applications.

5. CONCLUSION

The role of different fly ash proportions on the strength under compression evolution of eco-friendly geopolymer mortar for paving block applications was examined. The conclusions are as follows:

a. The optimal mix design of fly ash ratios was 80% fly ash and 20% cement for geopolymer mortar samples. The sample produced using this mix design exhibited the highest strength under compression, with recorded values of 12.0 MPa ± 0.69 MPa at 7 and 17.2 MPa ± 2.31 MPa at 28 days, satisfying the requirements for class B paving blocks in the Indonesian standard.
b. The microstructure analysis by SEM indicated that the 80% fly ash sample had the most advantageous microstructure, marked by high density, low porosity, and a lack of visible cracks.

These results provide a pathway to alternative paving blocks by using fly ash as a substitute for cement, which complies with the Indonesian standard, hence reducing the CO2 emission in construction, as promoted by the United Nations Sustainable Development Goals, is such that by the year 2050 [65]. Further study will be conducted for a more comprehensive study on material characterization, quantitative results of micro-structure, setting behavior, durability/permeability test, and utilization of other alternative green materials to replace cement.

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