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UTILIZATION OF PALM KERNEL SHELL FOR FLY ASH GEOPOLYMER MORTAR IN INDONESIA

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ABSTRACT: Indonesia, as the world's largest palm oil producer, generates millions of tons of palm kernel shell (PKS) waste annually, posing significant environmental challenges if inadequately managed. Concurrently, fly ash from coal-fired power plants offers a sustainable resource for geopolymer mortar production. This study explores the innovative use of activated carbon derived from PKS as an additive in fly ash-based geopolymer mortar to utilize both industrial by-products and enhance material performance. Activated carbon was produced from PKS via carbonization and physical activation, while geopolymer mortars were synthesized using sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as alkaline activators with varying NaOH molarities (10 M, 12 M, and 14 M). The mortars' mechanical strength, microstructural features, and chemical characteristics were comprehensively evaluated through compressive strength testing, SEM-EDX, XRD, BET, and FTIR analyses. Mortar activated with 12 M NaOH achieved the highest compressive strength (29.51 MPa) and exhibited superior microstructural integrity, characterized by a dense matrix, reduced porosity, enhanced durability, and strong chemical bonding. These results demonstrate the feasibility of incorporating abundant industrial and agricultural waste into sustainable construction materials, contributing to environmental impact mitigation, and advancing low-carbon building technologies.

Keywords: Compressive strength, Fly ash, Geopolymer mortar, Microstructural analysis, Palm kernel shell activated carbon

1. INTRODUCTION

Indonesia is the leading global producer of palm oil, generating around 4 to 6 million tons of palm kernel shell (PKS) waste each year [1]. This agricultural waste, if untreated, poses environmental risks such as soil pollution and greenhouse gas emissions [2]. Effective waste management solutions are essential to tackle this escalating issue. A possible method involves transforming PKS into activated carbon, which, due to a highly porous material with a large surface area and fine particle size, making it a valuable adsorbent for a variety of applications, can act as a microfiller and chemically active additive. These characteristics can enhance the packing density, improve the microstructure, and contribute to better mechanical performance and durability of mortar-based building materials [3,4].

Simultaneously, fly ash, generated in substantial amounts as a byproduct of coal power plants, has been extensively studied for its application in geopolymer mortars, an environmentally sustainable substitute for Portland cement with reduced carbon emissions [5]. Fly ash geopolymer mortar has demonstrated not only environmental advantages but also favorable mechanical characteristics, such as high compressive strength and enhanced durability [6,7], surpassing conventional concrete in compression quality [8]. In contrast, the binding strength between repair geopolymer mortar and the concrete substrate is inferior to that of standard Portland cement mortar for restoring damaged concrete [9].

Despite the advantageous characteristics of activated carbon and geopolymer technology, there remains a considerable research gap concerning the use of PKS-derived activated carbon as an additive in fly ash geopolymer mortar. Most current research on activated carbon additives has concentrated on conventional carbon sources, with little investigation into activated carbon obtained from agricultural waste, particularly from PKS [10]. Furthermore, although the mechanical and durability characteristics of fly ash geopolymers have been extensively researched, there is a lack of systematic investigations into the microstructure, pore connectivity, and long-term performance of PKS-activated carbon on the geopolymer mortar [11]. There is a limited understanding about how the unique physicochemical properties of PKS activated carbon interact with the geopolymer gel network, which may influence setting behaviour, strength improvement, and chemical resistance, addressing dual waste management challenges. Although activated carbon from PKS and fly ash geopolymer mortars have been studied separately, their combined use remains inadequately investigated. This study aims to fill this gap by investigating the improved mechanical and durability characteristics of fly ash geopolymer mortar with the utilisation of PKS-

activated carbon. This novel research aims to substantially reduce the excessive PKS waste in Indonesia by transforming these dual wastes into sustainable mortar, hence promoting sustainable construction practices in Indonesia [12]. The next sections cover the research significance, the materials and methodology, then the findings and discussion, and finally the conclusions.

2. RESEARCH SIGNIFICANCE

This study highlights the critical importance of developing innovative and environmentally construction materials in addressing the pressing global challenges of climate change, resource depletion, and the urgent need for sustainable development. The research on fly ash-based geopolymer mortar combined with PKS-activated carbon holds immense significance, as it offers a promising solution that intersects crucial domains-environmental sustainability, waste management, and material innovation in the construction industry. By leveraging industrial by-products and biomass-derived resources, this study demonstrates a compelling approach to waste utilization and carbon footprint reduction, positioning it as a vital contribution towards a more sustainable built environment.

3. MATERIALS

3.1 Fly Ash

This study utilized locally sourced fly ash (FA) as the main raw material for geopolymer mortar (as the main binder), obtained from a coal-fired power plant at Indonesia Power Banten 3 Lontar. Fly ash particles were sieved using 45 μm. X-ray fluorescence analysis technique, based on ASTM E 1508 - 98 standard, was used to characterize the chemical composition, as shown in Table 1. The fly ash was included in class F according to ASTM C618 due to the total content of SiO_2 (41.96%), Al_2O_3 (16.49%), and Fe_2O_3 (17.51%) was 75.96%, higher than 70%.

Table 1. The chemical composition of the fly ash

Chemical Composition	Percentage (%)
SiO_2	41.96
Al_2O_3	16.49
Fe_2O_3	17.51
CaO	8.72
Na_2O	0.64
K_2O	0.26
MgO	2.89
SO_3	0.18
Others	11.35

3.2 Palm Kernel Shell Activated Carbon

Palm kernel shell (PKS) is the hard outer shell of the palm kernel, a by-product of palm oil production, and there are around 4 to 6 million tons of PKS waste each year [1] in Indonesia. The main advantage of using PKS as a precursor for activated carbon (AC) production is the availability and abundance of agricultural waste. These PKSs were collected from palm oil mills in Sumatra, Indonesia. PKS was washed, dried, and carbonized to produce activated carbon via chemical activation. Carbonization of palm kernel shells was carried out at a temperature of around 600°C, followed by chemical activation using materials such as potassium hydroxide and zinc chloride. The physical activation process was then carried out by flowing nitrogen gas through the carbonated material at a higher temperature, around 600°C for 3 hours, and the last step, the AC was grinding and sieving to the desired particle size of sand passing a 2.46 mm sieve, in which the average particle size might fall around 0.5 mm to 1.5 mm. Table 2 presents the chemical content of AC from PKS using the EDX (Energy Dispersive X-ray) test,

Table 2. The chemical composition of the PKS-activated carbon

Chemical Composition	Percentage (%)
C	33.04
O	29.84
Na	2.22
Mg	2.61
Al	4.56
Si	12.39
K	3.78
Ca	11.56

3.3 Alkaline Activator

An alkaline activator was used to promote the geopolymerization of fly ash and palm kernel shell (PKS)-activated carbon. The activator was prepared by mixing sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) at a fixed weight ratio of 1.5 (Na_2SiO_3/NaOH). NaOH solutions were prepared at concentrations of 10 M, 12 M, and 14 M to evaluate the influence of alkalinity. The solution was allowed to rest for 24 hours before mixing to allow proper dissolution. The activator of alkaline was then mixed with a dry blend of fly ash and PKS-activated carbon. The weight ratio of AC/FA, activated carbon to fly ash, was arranged at 0.6. The objective of this mixture was to develop a geopolymer that provides both chemical stability and mechanical strength. The concentration of alkali and the proportions of materials are critical factors influencing the effectiveness of the geopolymerization process.

4. RESEARCH METHODOLOGY

This study has explored the impact of varying molarities of NaOH, specifically 10 M, 12 M, and 14 M, on the performance of geopolymer mortar, explaining the complex relationship between alkali concentration and the behavior of the material [15]. The preparation of geopolymer mortar samples was the first step in the research process. The mixture composition comprised fly ash (FA) and activated carbon (AC) from PKS as a precursor, with a ratio of FA to AC of 1:1. The molarity of the NaOH solution was 10 M, 12 M, and 14 M. The remaining variable was a ratio of Na_2SiO_3 to NaOH of 1.5 (base activator), and the ratio of activator to precursor was 0.6 [13]. The proportion mixtures are presented in Table 3.

Table 3. The details of the mixed proportion

Fly Ash, FA (gr)	Activated Carbon, AC (gr)	NaOH	Na_2SiO_3
90	90	10 M	1.5
90	90	12 M	1.5
90	90	14 M	1.5

The initial stage was the preparation of an alkaline solution, serving as the activator, corresponding to the specified molarity of the NaOH solution. To do this, weigh the NaOH, mix it with the purified water, stir it all together, and let it sit for 24 hours, or in a sealed container. The prepared NaOH was then mixed with Na_2SiO_3 in the exact volume that was planned. The mixture was stirred until it was smooth, and it was left to sit for about 24 hours. The geopolymer mortar was prepared by combining FA and AC through a stirring process lasting three minutes. Then, the activator solution was introduced in the precise quantity, and the mixture was stirred once more for five minutes. The mixture of geopolymer mortar was ready to be poured into the mold (50 mm x 50 mm x 50 mm) for the research speciments. The first 24 hours of the treatment were managed at room temperature. The samples were then cured for an additional 24 hours in an oven heated to 70 ˚C [16].

During the preparation of speciments of geopolymer mortar, the concentration of the alkaline activator, particularly sodium hydroxide (NaOH), played a vital and crucial role in influencing the workability of the fresh mix. Higher molarity of NaOH resulted in a substantially more viscous and adhesive mortar, creating challenges during the mixing, molding, and casting processes. The heightened stickiness rendered the handling of fresh mortar more labor-intensive and necessitated additional care to maintain uniformity and consistency among the specimens. This phenomenon is attributed to the accelerated dissolution of aluminosilicate materials at higher alkalinity, which improves the rate of geopolymerization but reduces simultaneously the fluidity of the mix.

Consequently, optimizing the NaOH molarity is essential to balance reactivity and workability during the sample preparation process. Following sample preparation, a variety of tests and analysis were performed to assess their physical, mechanical, microstructural, and chemical properties. The physical attribute was examined by a density test. The compressive strength [17] was measured at curing ages of 7, 14, 21, and 28 days in agreement with ASTM C109 standards. To investigate the morphology and phase development within the samples, microstructural analysis was carried out using Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDX) and X-ray Diffraction (XRD). This enables detailed observation of the morphology of aluminosilicate gel. It also allows for the identification of unreacted precursor materials. Moreover, it supports the characterization of the interfacial transition zone between the geopolymer matrix and incorporated aggregates or additives. Elements are uniformly distributed, exhibiting good mixing and reaction [18]. Additionally, the durability and adsorption capacity of the specimens were assessed by determining the Brunauer Emmett Teller (BET) surface area and distribution of pore size, allowing an evaluation of the influence of activated carbon on the microstructural properties, particularly in terms of porosity and pore network, which are linked closely to the long-term durability of the material. Fourier Transform Infrared Spectroscopy (FTIR) was conducted to recognize functional groups and examine chemical bonding within the matrix of geopolymer.

5. RESULTS AND DISCUSSIONS

5.1 Physical and Mechanical Properties

The physical test for density is a standardized method exercised to quantify the mass and compactness of geopolymer mortar samples: 10 M, 12 M, and 14 M. At the same time, a compressive test was conducted to determine mechanical properties of the samples at the age of 7, 14, 21, and 28 days. The density testing results are seen in Fig. 1, whereas the compressive strength outcomes are depicted in Fig. 2.

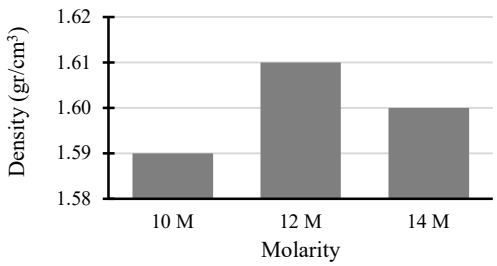


Fig. 1 Density testing results

The test results in Fig. 1 indicate that the geopolymer mortar prepared with 12 M NaOH exhibits the highest density among all samples. As shown in Fig. 2, the geopolymer mortar with 12 M NaOH concentration also achieved the highest compressive strength of 29.51 MPa, which aligns with the observed density trends. These findings are consistent with the results reported in previous research [19]. This may be attributed to improved particle packing, likely resulting from lower viscosity and reduced stickiness compared to the 14 M NaOH mixture, as the concentration of the sodium hydroxide solution, a common alkaline activator, directly influences the dissolution of the aluminosilicate precursor and the resulting formation of the geopolymer [20]. Given that higher molarity levels of NaOH during sample preparation led to increased viscosity and stickiness of the geopolymer mortar, resulting in challenges in achieving uniformity and consistency across specimens, therefore, subsequent microstructural analyses are essential to optimize the NaOH molarity and to ensure the quality.

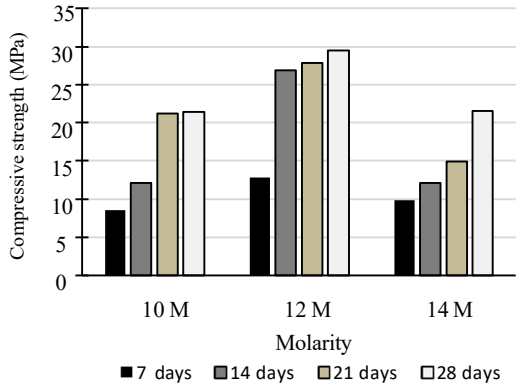


Fig. 2 Compressive strength test results

5.2 Microstructural Analysis

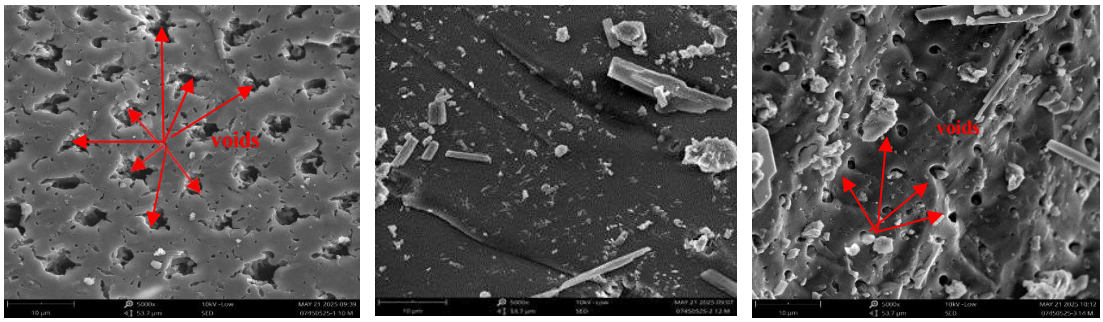
Microstructural analysis is to investigate the morphology and phase development within the samples, using Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDX) and X-ray Diffraction (XRD). Figure 3 shows a SEM image of the surface of a high-calcium fly ash geopolymer mortar with PKS activated carbon for 10 M, 12 M, and 14 M, at the age of 28 days. Pore distribution appears widespread and interconnected.

Low molarity (10 M) typically results in incomplete geopolymerization due to insufficient alkaline activation. This leads to unreacted fly ash particles and a more porous microstructure, which correlates with lower mechanical strength and durability. The rough surface suggests lower matrix densification, with many entrapped air pockets or unreacted areas. The surface is smoother with pores and elongated particles (likely remnants of PKS- activated carbon or partially reacted fly ash). Surface cracks or polishing marks are visible.

In mortar with 12 M, geopolymerization is more complete, producing more gel phases (N-A-S-H or C-A-S-H). There is a noticeable reduction in porosity compared to 10 M and 14 M, with better matrix continuity. The presence of PKS-activated carbon may contribute to micro-filler effects, enhancing densification. The surface shows dense regions but also contains microcracks, spherical voids, and many embedded particles.

While 14 M mortar provides high reactivity, excessive alkalinity may lead to rapid reaction kinetics, causing microcracking due to thermal or shrinkage stress. The increased porosity in certain regions could be due to alkaline leaching or overreaction, leading to structural instability. The structure appears heterogeneous, with some areas well-formed and others deteriorated, relevant with previous study [21]. In general, SEM testing at 12 M mortar provides the best result.

The EDX test results provide information on the elemental composition of geopolymer mortar samples, as shown on Fig. 4. A Higher Si/Al ratio (>2.0) indicates better geopolymerization and enhanced strength. At 10 Molarity, a low Si/Al ratio of 1.67 indicates incomplete geopolymerization. Elemental mapping shows uneven distribution of key elements.

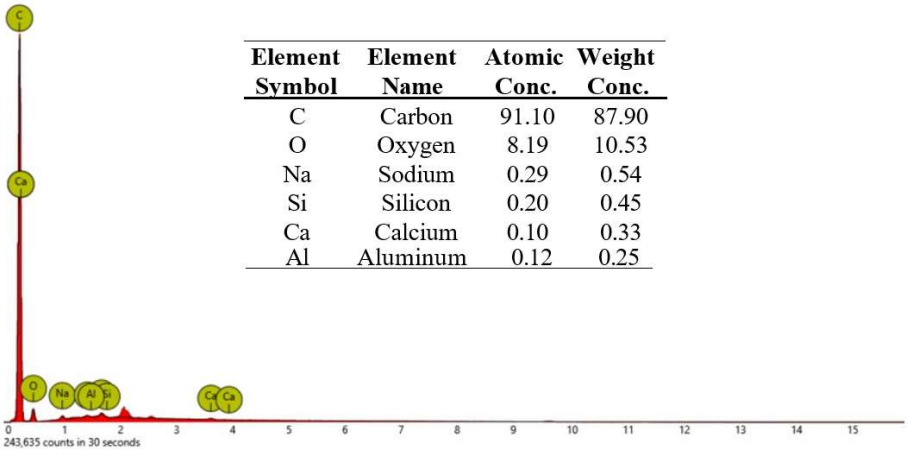


(a) 10 Molarity (b) 12 Molarity (c) 14 Molarity

Fig. 3 Surface morphology of selected samples after 28 days of curing

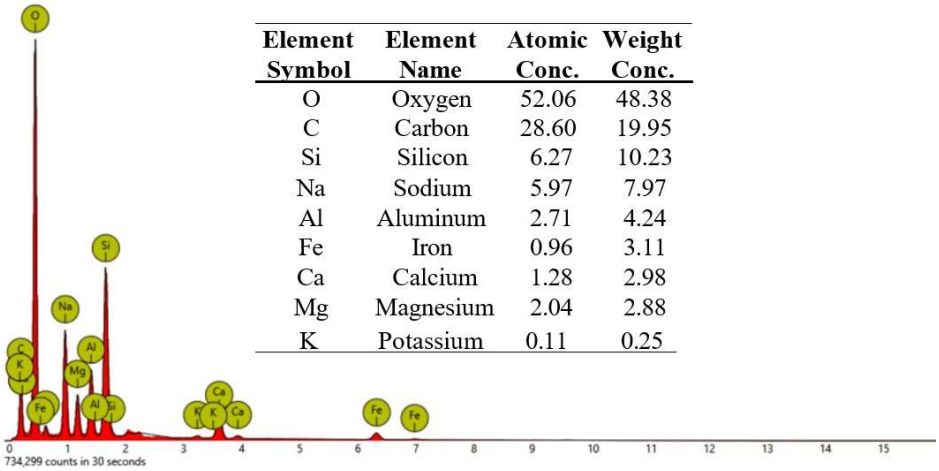
Minimal geopolymer gel formation is due to insufficient activation of fly ash, resulting in an underdeveloped binder structure. At Molarity 12, higher Si/Al ratio of 2.31 (>2.0), it presents better geopolymerization and improved strength. Elements are uniformly distributed, showing good mixing and reaction. The presence of higher K may contribute to additional alkali activation and microstructural benefits [22,23].

At mortar with 14 M, there is a prominent low Si/Al ratio of 1.32 that points to incomplete geopolymerization. One plausible explanation for this phenomenon is the increased viscosity and stickiness of the mortar mixture at elevated NaOH molarity. Higher concentrations of alkali activators tend to enhance the dissolution of aluminosilicate precursors; however, they also significantly reduce the fluidity of the geopolymer paste. This increased viscosity hampers the thorough mixing and homogenization of the constituent materials, creating difficulties during the molding and casting processes. Such physical limitations can inhibit the effective contact and reaction between dissolved elements, thereby preventing the full progression of polycondensation reactions necessary for forming a continuous and well-connected aluminosilicate network. Future efforts should focus on fine-tuning the NaOH molarity and mixing protocols to enhance fluidity without compromising the chemical reactivity. Generally, EDX testing of 12 M mortar yields the most favorable results, correlating with the XRD testing illustrated in Fig. 5.



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
C	Carbon	91.10	87.90
O	Oxygen	8.19	10.53
Na	Sodium	0.29	0.54
Si	Silicon	0.20	0.45
Ca	Calcium	0.10	0.33
Al	Aluminum	0.12	0.25

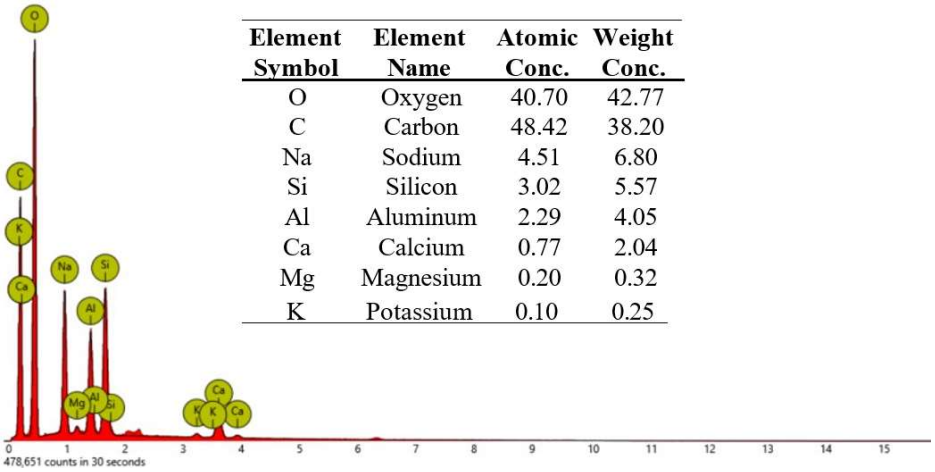
(a) 10 Molarity, Si/Al=1.67



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
O	Oxygen	52.06	48.38
C	Carbon	28.60	19.95
Si	Silicon	6.27	10.23
Na	Sodium	5.97	7.97
Al	Aluminum	2.71	4.24
Fe	Iron	0.96	3.11
Ca	Calcium	1.28	2.98
Mg	Magnesium	2.04	2.88
K	Potassium	0.11	0.25

(b) 12 Molarity, Si/Al=2.31

Fig. 4 Elemental composition the three designated samples



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
O	Oxygen	40.70	42.77
C	Carbon	48.42	38.20
Na	Sodium	4.51	6.80
Si	Silicon	3.02	5.57
Al	Aluminum	2.29	4.05
Ca	Calcium	0.77	2.04
Mg	Magnesium	0.20	0.32
K	Potassium	0.10	0.25

(c) 14 Molarity, Si/Al=1.32

Fig. 4 Elemental composition the three designated samples (continue)

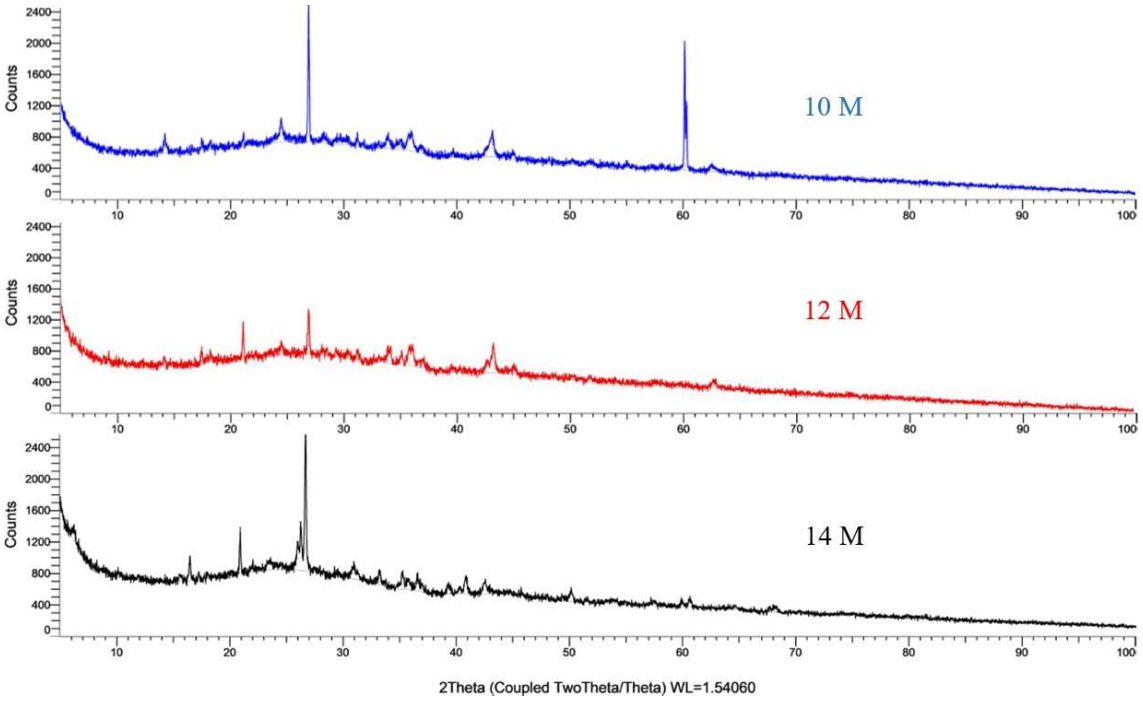


Fig. 5 XRD Pattern of 10M, 12 M, and 14 M mortars

Figure 5 illustrates the XRD analysis of the mortars, which helps to identify the presence or absence of crystalline phases such as quartz, mullite, and unreacted fly ash within the geopolymer matrix. This characterization is fundamental for assessing the degree of geopolymerization. The 10 M mortar exhibits distinct and sharp diffraction peaks corresponding to unreacted crystalline phases like quartz and mullite, indicative of incomplete activation and limited dissolution of fly ash. In contrast, the 12 M mortar shows a broad amorphous hump between 20° and 35° 2θ, reflecting the predominance of an amorphous aluminosilicate gel and a significant reduction in crystalline peak intensity, which signifies successful geopolymer formation. Although the 14 M mortar might be expected to show enhanced activation, the excessive alkalinity can induce microcracking or promote the

formation of secondary crystalline phases, which are observable in the XRD pattern. Collectively, these results demonstrate that the 12 M geopolymer mortar achieves the most effective geopolymerization.

5.3 Surface Area, Porosity, and Durability

Surface area and porosity of fly ash geopolymer mortar incorporating PKS-activated carbon can vary significantly which are effectively characterized using Brunauer Emmett Teller (BET) analysis. Low surface area corresponds with compact material and lesser porosity. In contrast, the porous microstructure generates voids within the mortar matrix. The porous structure leads to weaker mechanical interlocking and facilitates access of harmful agents (e.g., water, chlorides), which lowers both the strength and durability of the mortar. High porosity also increases susceptibility to freeze-thaw cycles and chemical attacks [24]. Table 4 presents BET test results.

Table 4. Surface area, pore volume, and durability

Mortar type	Surface area (m^2/g)	Total pore volume (cc/g)	Durability level
10 M	32.38	0.038	Low
12 M	8.03	0.026	High
14 M	21.85	0.052	Low

At a concentration of 10 M, the mortar presents the highest specific surface area of 32.38 m^2/g, indicating a correspondingly elevated porosity. This increase in surface area and porosity is likely to compromise the mortar's durability and compressive strength due to increased structural vulnerability.

Conversely, the mortar at 12 M generates the lowest surface area of 8.03 m^2/g, suggesting enhanced reactivity and more effective elemental interaction within the matrix. The 14 M mortar exhibits an increase in surface area and porosity compared to the 12 M sample, which corresponds to reduced durability. Overall, based on BET analysis, the 12 M mortar formulation demonstrates the most favorable properties, producing the highest-quality and durable material.

5.4 Chemical Bond Assessment

The chemical bonding characteristics were examined using Fourier Transform Infrared Spectroscopy (FTIR) that exhibited distinctive absorption bands associated with the fly ash-based geopolymer mortar incorporating PKS-derived activated carbon, as shown in Fig. 6.

As indicated by the compressive strength results (Fig. 2) and supported by microstructural analyses (Fig. 3), the mixture with 12 M NaOH concentration demonstrated the most favorable performance. Consequently, FTIR analysis was exclusively conducted on the geopolymer mortar with the 12 M formulation which demonstrated superior performance compared to the mortars with 10 and 14 Molarity.

Figure 6 reveals well-defined and intense absorption bands indicative of a well-formed aluminosilicate framework. The Si–O–T asymmetric stretching band at 980.68 cm^{-1} is sharp and shifted to lower wavenumbers compared to the precursor fly ash, reflecting successful polycondensation and formation of a stable geopolymer network, relevant to previous studies [25,26]. The reduction or disappearance of peaks associated with unreacted raw materials and organic groups from the palm kernel shell activated carbon confirms effective chemical bonding and uniform incorporation of the additive. Furthermore, reduced intensity of hydroxyl and water-related bands at 3439.39 cm^{-1} suggests completion of the reaction and minimal residual moisture, relevant to the previous studies [27,28]. These spectral characteristics correlate with enhanced mechanical strength, improved microstructural homogeneity, and greater durability of the mortar.

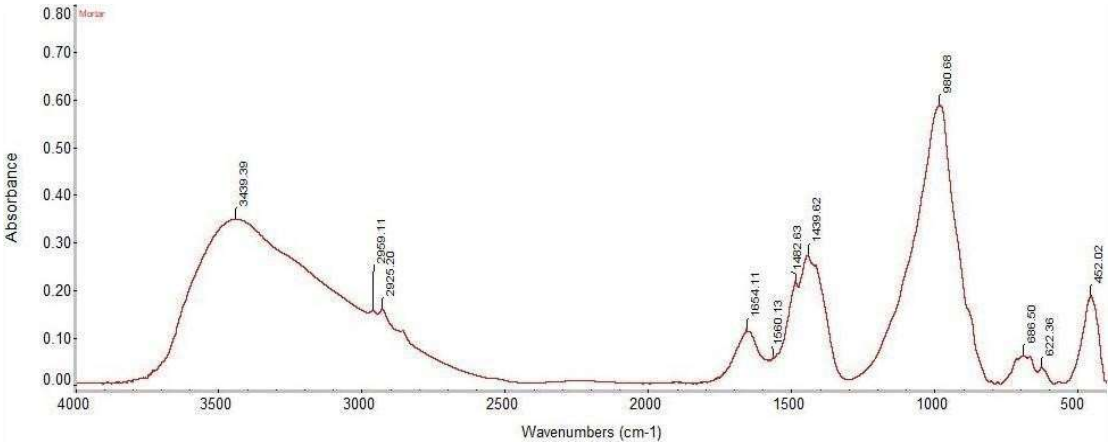


Fig. 6 FTIR test result of 12 M mortar

6. CONCLUSIONS

This study successfully reveals the effective incorporation of PKS into fly ash-based geopolymer mortar, validated through systematic experimental analyses including SEM-EDX, XRD, BET, and FTIR, using materials from Indonesia. The mortar activated with 12 M NaOH demonstrated the highest compressive strength of 29.51 MPa alongside superior microstructural integrity, characterized by a dense matrix (as provided by the highest Si/Al ratio of 2.31), reduced porosity (as provided by the lowest surface area of 8.03 m^2/g), higher durability (as provided by the lowest pore volume of 0.026 cc/g), and robust chemical bonding (as provided by well-formed aluminosilicate framework). The results indicate that fly ash and palm kernel shell (PKS), two prevalent forms of industrial and agricultural waste, can be combined to produce high-performance, sustainable geopolymer mortar, serving as a viable alternative to Portland cement. Overall, this study presents that geopolymer technology has a lot of potential as a significant part of producing low-carbon, eco-friendly building materials in Indonesia. Future research could examined its compatibility with other industrial by-products, perform life cycle assessments (LCA), and conduct cost-benefit analyses to exhibit its environmental and economic benefits in practical construction scenarios, particularly in the Indonesian context.

7. ACKNOWLEDGMENTS

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