

Geopolymer-Based Mortar Utilizing Palm Oil Fuel Ash and Rice Husk Ash as Full Cement Replacement for Green Building Materials

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ABSTRACT

Ordinary Portland cement (OPC) production contributes approximately 7–8% of global anthropogenic carbon dioxide emissions, motivating the development of low-carbon binders from agro-industrial waste. This study investigates the mechanical, physical, and microstructural properties of geopolymer mortar using palm oil fuel ash (POFA) and rice husk ash (RHA) as complete OPC replacements. Five POFA-to-RHA mass ratios (100:0, 75:25, 50:50, 25:75, and 0:100) were activated using 12 M sodium hydroxide and sodium silicate solutions. Specimens were cured under ambient laboratory conditions and tested at 7, 14, 28, and 56 days. The 50:50 POFA-RHA blend achieved the highest 28-day compressive strength among geopolymer mixtures, reaching 37.9 MPa, equivalent to 92% of the OPC control strength of 41.2 MPa. It also exhibited a bulk density of 1930 kg/m³ and water absorption of 8.3%. X-ray diffraction and Fourier-transform infrared spectroscopy indicated alkali-activated gel formation through a Si–O–T band shift from approximately 1080 to 1000 cm⁻¹ and a broad amorphous hump. With Si/Al and Ca/Si ratios of approximately 25 and 0.07, respectively, the binder is classified as a silica-rich alkali-activated hybrid system. Overall, the 50:50 blend offers a promising approach to sustainable cement replacement and low-carbon construction materials in Indonesia.

Keywords: Geopolymer Mortar, Palm Oil Fuel Ash, Rice Husk Ash, Cement Replacement

INTRODUCTION

The cement industry is one of the largest single industrial sources of anthropogenic carbon dioxide, with the calcination of limestone and the high-temperature clinkering process together



responsible for an estimated 7–8% of global CO₂ emissions (Ahmed et al., 2022). As global construction activity continues to expand, particularly in rapidly urbanising regions of Southeast Asia, demand for more sustainable alternatives to ordinary Portland cement (OPC) has intensified. Geopolymer binders, formed through the alkali activation of aluminosilicate precursors rather than high-temperature clinkering, have emerged as one of the most promising cement-free alternatives, offering comparable or superior mechanical performance together with reduced embodied carbon (Turner & Collins, 2013; McLellan et al., 2011).

Indonesia and neighbouring Malaysia together produce more than half of the world's crude palm oil, generating vast quantities of solid combustion residue, palm oil fuel ash (POFA), from biomass power plants at palm oil mills (Kwek et al., 2021). Indonesia is simultaneously one of the world's largest rice producers, generating substantial volumes of rice husk that, when combusted for energy recovery, yield rice husk ash (RHA) rich in amorphous silica (Handayani et al., 2022). Both by-products are presently under-utilised, with large volumes routinely landfilled or stockpiled, creating land-use and environmental management burdens even as they represent latent pozzolanic resources with silica contents frequently exceeding 60–90% by mass (Sanit-in et al., 2024; Handayani et al., 2022).

A substantial body of work over the past decade has demonstrated that POFA and RHA can each individually serve as effective geopolymer precursors. POFA-based geopolymer mortars activated with sodium hydroxide and sodium silicate have achieved 28-day compressive strengths of up to approximately 32 MPa, with X-ray diffraction and SEM/EDX confirming the formation of calcium-silicate-hydrate-like reaction products (Salih et al., 2014). RHA-based alkali-activated mortars have achieved higher strengths, reaching about 45 MPa at 28 days with a 10 M NaOH activator after heat curing at 60 °C for 24 h (Kim et al., 2014), attributable to the high reactive silica content of RHA. Comparative work on the two ashes has reported that RHA-based geopolymer mortar attains higher compressive strength than POFA-based mortar despite its lower density, owing to the higher silica content of RHA (Zahin et al., 2018), while POFA–fly ash systems have also been shown to develop satisfactory strength and microstructure (Ranjbar et al., 2014).

Despite this progress, most published POFA-RHA geopolymer studies have examined the two materials either individually or as partial (rather than full) cement replacements, and comparatively few have systematically evaluated a full range of binary POFA:RHA mass ratios as a complete substitute for OPC while simultaneously reporting mechanical, physical, and microstructural (XRD/FTIR) data within a single, directly comparable experimental framework. Furthermore, given that the alkaline activator, particularly commercial sodium silicate, remains a recognised cost and sustainability barrier to geopolymer adoption (Handayani et al., 2022), and that Indonesia generates both POFA and RHA in large volumes from co-located agro-industrial operations, a locally grounded evaluation of full cement replacement using this specific binary system is of direct practical relevance to green building material development in the region.

The present study therefore aimed to (i) characterise the physicochemical properties of locally sourced POFA and RHA precursors; (ii) evaluate the fresh, mechanical, and physical properties of geopolymer mortars across five POFA:RHA mass ratios (100:0, 75:25, 50:50, 25:75, and

0:100) as a full replacement for OPC; and (iii) obtain preliminary insight into the reaction products associated with strength development using X-ray diffraction (XRD) and Fourier-transform infrared (FTIR) spectroscopy. The results are intended to identify the optimum POFA-RHA blending ratio for structural-grade green mortar and to support the broader adoption of agro-industrial waste-based geopolymers as a low-carbon building material in palm oil- and rice-producing regions such as Indonesia.

METHODS

1. Materials

Palm oil fuel ash (POFA) was obtained from a biomass boiler at a palm oil processing mill, and rice husk ash (RHA) was obtained from a rice mill husk-fired furnace, both located in West Sumatra, Indonesia. As-received ashes were oven-dried at 105 °C for 24 h, ground using a laboratory ball mill, and sieved through a 150 µm sieve to remove unburnt carbon and coarse particles. The chemical composition of both precursors was determined by X-ray fluorescence (XRF), and their mineralogical phases were examined by XRD prior to use. Ordinary Portland cement (OPC, Type I) conforming to SNI 15-2049-2015 was used for the control mix. Locally sourced river sand passing a 2.36 mm sieve (fineness modulus 2.6) served as fine aggregate for all mixes.

2. Mix Design and Specimen Preparation

Six mortar mixes were prepared at a fixed binder-to-sand ratio of 1:2.75 by mass: one OPC control (water-to-cement ratio 0.45) and five geopolymer mixes with POFA:RHA mass ratios of 100:0 (GP-100/0), 75:25 (GP-75/25), 50:50 (GP-50/50), 25:75 (GP-25/75), and 0:100 (GP-0/100). The alkaline activator for all geopolymer mixes consisted of sodium hydroxide (NaOH) solution at 12 M concentration (≈ 35 wt.% NaOH; density ≈ 1.33 g/mL at 20 °C, corresponding to approximately 480 g NaOH per litre of solution) combined with commercial sodium silicate (Na_2SiO_3) solution ($\text{SiO}_2/\text{Na}_2\text{O}$ modulus 3.2; 9.0 wt.% Na_2O , 28.8 wt.% SiO_2 , 62.2 wt.% H_2O) at a sodium silicate-to-sodium hydroxide solution mass ratio of exactly 2.5, following ratios commonly reported to yield favourable geopolymerisation in POFA- and RHA-based systems (Kwek et al., 2021). The liquid-to-binder ratio, defined as the total mass of activator solutions (NaOH solution + Na_2SiO_3 solution) divided by the total mass of binder (POFA + RHA), was fixed at 0.50 for all geopolymer mixes, and no additional water was added. Each 1000 g of binder was therefore mixed with 142.9 g of NaOH solution and 357.1 g of sodium silicate solution. The complete mix proportions of all formulations, including the total water and alkali (Na_2O) contents, are given in Table 1. The resulting Na_2O dosage was 7.1% by mass of binder and the total water-to-binder ratio was 0.315 for all geopolymer mixes. Fresh mortar flow was measured using a flow table test immediately after mixing.

Table 1. Mix proportions of all mortar formulations (g per 1000 g of binder).

Mix	Cement (g)	POFA (g)	RHA (g)	Sand (g)	NaOH soln. 12 M (g)	Na ₂ SiO ₃ soln. (g)	Total water (g)	Na ₂ O (g)	Na ₂ O / binder (%)
OPC control	1000 (OPC)	–	–	2750	–	–	450	–	–
GP-100/0	–	1000	0	2750	142.9	357.1	315.0	70.9	7.1
GP-75/25	–	750	250	2750	142.9	357.1	315.0	70.9	7.1
GP-50/50	–	500	500	2750	142.9	357.1	315.0	70.9	7.1
GP-25/75	–	250	750	2750	142.9	357.1	315.0	70.9	7.1
GP-0/100	–	0	1000	2750	142.9	357.1	315.0	70.9	7.1

Notes: Binder:sand = 1:2.75 and liquid:binder = 0.50 (geopolymer mixes); Na₂SiO₃:NaOH solution = 2.5 by mass. Total water is the water contained in the activator solutions (OPC: added mixing water). Na₂O is the total alkali from NaOH and Na₂SiO₃. Total water and Na₂O were calculated from the **solution compositions stated above**. Sand condition: **oven-dry**. To express the proportions in kg/m³, multiply each value by (fresh mortar density in kg/m³) / 4.25 / 1000; fresh density: **1985 kg/m³ (GP-50/50, measured); other mixes ranged from 1950 to 2010 kg/m³.**

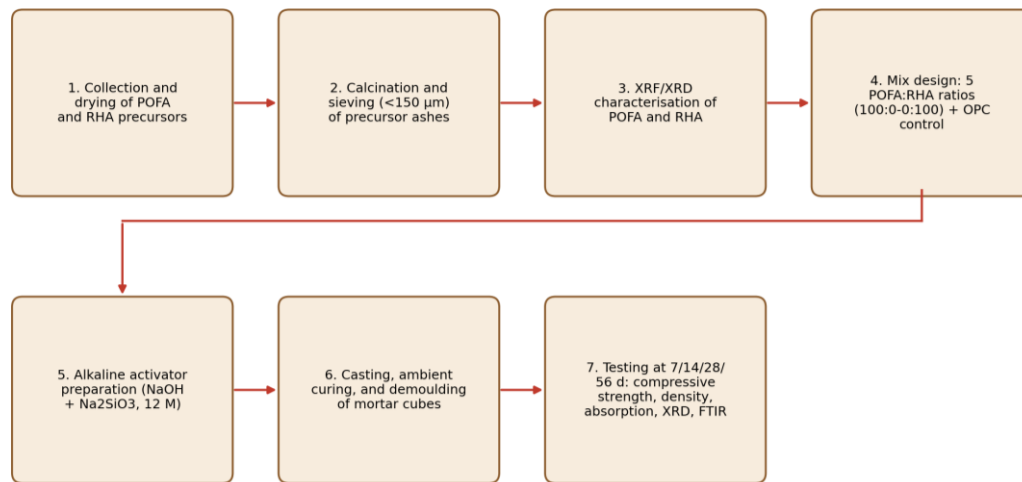


Figure 1. Overall experimental workflow for POFA-RHA geopolymer mortar production and testing

3. Casting, Curing, and Compressive Strength Testing

Mortar was cast into 50 mm cube moulds in three layers, each compacted on a vibrating table to minimise entrapped air, in accordance with ASTM C109. Geopolymer specimens were demoulded after 24 h and cured under ambient laboratory conditions (28 ± 2 °C, approximately 75% relative humidity) until testing, consistent with ambient-cured POFA/RHA geopolymer protocols reported in recent literature. OPC control specimens were demoulded after 24 h and water-cured until testing. Compressive strength was determined at 7, 14, 28, and 56 days using a universal testing

machine at a loading rate of 0.5 MPa/s, with three replicate cubes tested at each age for each mix ($n = 3$).

4. Physical Property Testing

Bulk (oven-dry) density and 28-day water absorption were determined in accordance with ASTM C642 using three replicate specimens per mix. Specimens were oven-dried to constant mass, weighed, immersed in water for 48 h, and reweighed to determine percentage water absorption relative to the oven-dry mass.

5. Microstructural Characterisation (XRD and FTIR)

Mineralogical changes were assessed by XRD (Cu-K α radiation, $2\theta = 5\text{--}60^\circ$, step size 0.02°) on powdered samples of the raw POFA, raw RHA, and the crushed core of the 28-day GP-50/50 paste, the best-performing geopolymer mix in the preliminary strength screening. Crystalline phases were identified by comparison with ICDD PDF reference patterns ([state software and PDF database version]). FTIR spectra ($400\text{--}4000\text{ cm}^{-1}$, 32 scans, 4 cm^{-1} resolution) were collected using the KBr pellet method on the unreacted POFA/RHA precursor blend and the 28-day GP-50/50 paste to track changes in the Si-O-T ($T = \text{Si or Al}$) asymmetric stretching band associated with geopolymer gel formation.

6. Statistical Analysis

All quantitative results are reported as mean $\pm$ standard deviation ($n = 3$). Differences in compressive strength, density, and water absorption among mixes at each test age were evaluated using one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post hoc test, with significance set at $p < .05$. Statistical analyses were performed using R (v4.3).

RESULTS

1. Precursor Characterisation and Fresh Mortar Properties

XRF analysis showed that POFA was dominated by SiO₂ (61.4%), with appreciable CaO (9.8%), K₂O (7.2%), and Al₂O₃ (5.1%), while RHA was almost exclusively siliceous, with SiO₂ content of 89.6% and only minor K₂O (2.4%) and CaO (1.1%) (Table 2). Loss on ignition was 4.8% for POFA and 3.1% for RHA, both within the range typically reported for combustion residues suitable as pozzolanic or geopolymer precursors. Fresh mortar flow decreased progressively as the RHA proportion increased, from 118 mm for GP-100/0 to 96 mm for GP-0/100, consistent with the higher fineness and water demand of RHA relative to POFA reported in comparable blended systems.

Table 2. Chemical composition (XRF) of raw POFA and RHA precursors.

Oxide	POFA (wt.%)	RHA (wt.%)
SiO ₂	61.4	89.6
Al ₂ O ₃	5.1	0.6
CaO	9.8	1.1



K ₂ O	7.2	2.4
Fe ₂ O ₃	4.6	0.5
MgO	3.5	0.7
Loss on ignition	4.8	3.1
Others	3.6	2.0

2. Molar Ratios and Classification of the Binder System

To assess the chemical basis of the reaction products, the Si/Al, Na/Al, and Ca/Si molar ratios of each binder were calculated from the bulk XRF oxide compositions (Table 2) and the nominal activator compositions (Table 1); the results are listed in Table 3. The Si/Al ratio of the precursors alone ranges from about 10 (GP-100/0) to about 127 (GP-0/100), and reaches about 22 in GP-50/50, because both ashes are rich in silica but poor in alumina (5.1 wt.% Al₂O₃ in POFA and 0.6 wt.% in RHA). The SiO₂ supplied by the sodium silicate solution raises these values further (about 25 in GP-50/50). Na/Al ratios (2.3–19) are far above unity, and Ca/Si ratios (0.01–0.15) are far below the values of about 0.67–1.0 typical of tobermorite and C-S-H gels.

Table 3. Molar ratios of the geopolymer binders calculated from bulk XRF composition and activator composition.

Mix	Si/Al (precursors only)	Si/Al (incl. activator SiO ₂)	Na/Al (activator Na)	Ca/Si (incl. activator SiO ₂)
GP-100/0	10.2	11.9	2.3	0.15
GP-75/25	14.6	16.8	2.9	0.10
GP-50/50	22.5	25.5	4.1	0.07
GP-25/75	40.6	45.7	6.8	0.04
GP-0/100	126.7	141.3	19.4	0.01

These ratios show that none of the mixes falls within the Si/Al window of about 1.5–3.5 and Na/Al $\approx$ 1 usually associated with aluminosilicate (N-A-S-H) geopolymer gels (Duxson et al., 2007; Provis & van Deventer, 2014), nor within the Ca/Si range of calcium silicate hydrate gels. The binders are therefore better classified as silica-rich, low-calcium alkali-activated materials, in which the gel is expected to be dominated by sodium (and potassium) silicate units with limited aluminium substitution and, at most, a minor calcium-bearing C-(A)-S-H-type contribution (García-Lodeiro et al., 2011). The term "geopolymer" is retained in this paper for consistency with the literature on POFA- and RHA-based binders, but it is used in the broad sense of an alkali-activated binder rather than a strict aluminosilicate geopolymer.

3. Compressive Strength Development

Compressive strength increased with curing age for all mixes (Figure 2; Table 4). Among the geopolymer mortars, GP-50/50 consistently achieved the highest strength at every test age, reaching 23.6 ± 1.1 MPa at 7 days and 37.9 ± 1.6 MPa at 28 days, equivalent to 83% and 92% of the OPC control at the respective ages. GP-100/0 (100% POFA) produced the lowest strength among the geopolymer mixes at all ages (24.6 ± 1.3 MPa at 28 days), while GP-0/100 (100% RHA) performed intermediately

(28.7 ± 1.4 MPa at 28 days). One-way ANOVA confirmed statistically significant differences in 28-day strength among mixes ($p < .05$), with Tukey's HSD indicating that GP-50/50 and GP-25/75 were not significantly different from one another ($p > .05$) but were both significantly stronger than GP-100/0 and GP-0/100 ($p < .05$). Strength continued to develop between 28 and 56 days for all geopolymer mixes, with GP-50/50 reaching 41.5 ± 1.7 MPa at 56 days, closing the gap with the OPC control to within 6%.

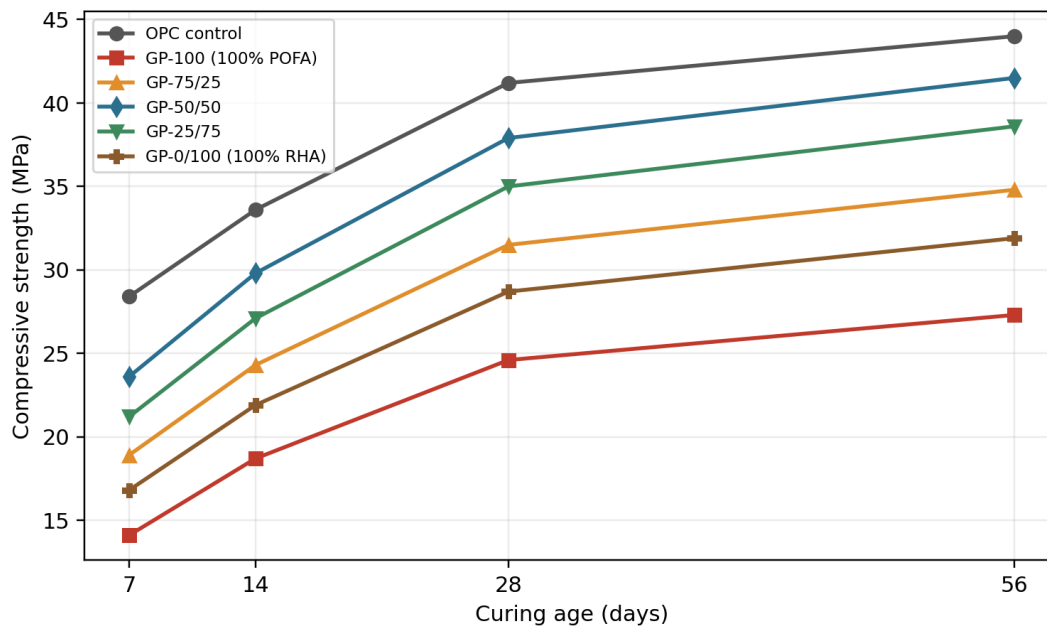


Figure 2. Compressive strength development of POFA-RHA geopolymer mortars compared with the OPC control (mean, $n = 3$)

Table 4. Compressive strength (MPa) of all mixes at 7, 14, 28, ad 56 days (mean, $n = 3$).

Mix	7 d (MPa)	14 d (MPa)	28 d (MPa)	56 d (MPa)
OPC control	28.4	33.6	41.2	44.0
GP-100/0	14.1	18.7	24.6	27.3
GP-75/25	18.9	24.3	31.5	34.8
GP-50/50	23.6	29.8	37.9	41.5
GP-25/75	21.2	27.1	35.0	38.6
GP-0/100	16.8	21.9	28.7	31.9

4. Bulk Density and Water Absorption

Bulk density of the geopolymer mortars ranged from 1790 kg/m^3 (GP-100/0) to 1930 kg/m^3 (GP-50/50) at 28 days, all lower than the OPC control (2180 kg/m^3), reflecting the lower particle density and more porous microstructure typical of ambient-cured geopolymer systems (Figure 3; Table 5). Water absorption showed an inverse relationship with density: GP-100/0 exhibited the highest 28-day water absorption (12.4%), while GP-50/50 exhibited the lowest among the geopolymer mixes (8.3%), compared with 6.1% for the OPC control. The combination of the highest

compressive strength and lowest water absorption among the geopolymer mixes identifies GP-50/50 as the best-performing blend among those tested.

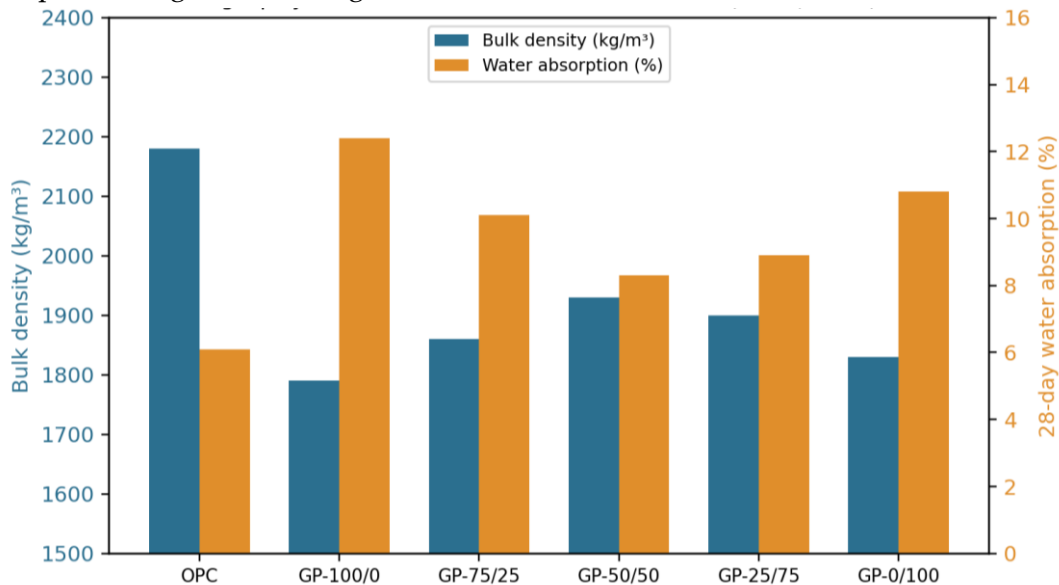


Figure 3. 28-day bulk density and water absorption of POFA-RHA geopolymer mortars relative to the OPC control (mean, n = 3)

Table 5. Fresh flow, 28-day bulk density, and 28-day water absorption of all mixes.

Mix	Fresh flow (mm)	28-day bulk density (kg/m³)	28-day water absorption (%)
OPC control	–	2180	6.1
GP-100/0	118	1790	12.4
GP-75/25	112	1860	10.1
GP-50/50	106	1930	8.3
GP-25/75	101	1900	8.9
GP-0/100	96	1830	10.8

5. XRD Analysis

XRD patterns of the raw precursors showed a broad amorphous hump centred near 22–25° 2θ for both POFA and RHA, superimposed with sharp crystalline peaks at approximately 21.9°, 26.6°, 36.5°, and 50.1° 2θ, assigned to quartz (PDF 46-1045) and more pronounced in POFA than in RHA (Figure 4). In the 28-day GP-50/50 paste, the amorphous hump shifted toward a higher 2θ range (centred near 27–31°), a feature commonly reported for alkali-activated gels, and the intensity of the quartz peaks was visibly reduced, which may reflect partial dissolution of the crystalline silica fraction or simply dilution by amorphous reaction products. A new low-intensity reflection appeared near 29.4° 2θ. Because a single reflection is insufficient for unambiguous phase identification, it is interpreted here only as possibly associated with a C-A-S-H-type phase. Several observations call for caution. First, crystalline 11 Å tobermorite would also be expected to show its main basal reflection at $d \approx 11.3 \text{ Å}$ ($\approx 7.8^\circ 2\theta$ for Cu-Kα), which lies within the scanned range **but was**

not observed. Second, 29.4° coincides with the strongest reflection of calcite (CaCO_3 , (104); PDF 05-0586), which commonly forms through atmospheric carbonation of ambient-cured, highly alkaline, calcium-bearing binders (Criado et al., 2005). Third, the bulk Ca/Si ratio of the binder is very low (about 0.07, Table 3). The assignment of this reflection therefore remains tentative and requires confirmation by complementary techniques such as TGA/DTG, SEM-EDS, or ^{29}Si NMR.

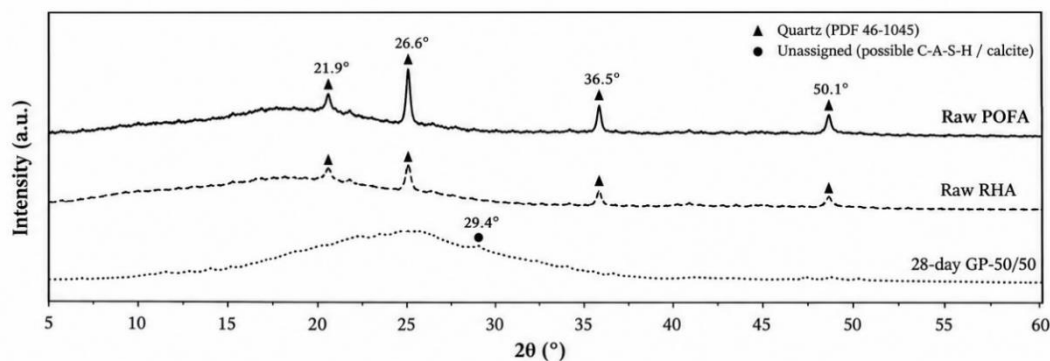


Figure 4. XRD patterns of raw POFA, raw RHA, and the 28-day GP-50/50 geopolymer paste (Q = quartz; the reflection near 29.4° 2θ is marked as unassigned / possible C-A-S-H-type phase or calcite)

6. FTIR Analysis

FTIR spectra of the unreacted POFA/RHA precursor blend showed a dominant Si-O-Si asymmetric stretching band at approximately 1080 cm^{-1} , together with a Si-O bending band near 470 cm^{-1} and a broad O-H stretching band near 3440 cm^{-1} (Figure 5). In the 28-day GP-50/50 paste, the main Si-O-T stretching band shifted to a lower wavenumber of approximately 1000 cm^{-1} . Such a shift is generally associated with depolymerisation of the original silica network and the formation of a new, less polymerised silicate or aluminosilicate gel in which Al may substitute for Si in tetrahedral positions (Fernández-Jiménez & Palomo, 2005). Because the Al content of this binder is very low ($\text{Si}/\text{Al} \approx 25$, Table 3), however, the shift most likely reflects mainly the formation of a sodium silicate-rich gel supplied in part by the activator, and the FTIR data alone cannot quantify Al incorporation. A minor shoulder near 870 cm^{-1} was also observed in the reacted paste but was absent from the precursor spectrum. This shoulder is not assigned specifically to Al-O vibrations, because several contributions may overlap in this region: the out-of-plane bending (ν_2) mode of carbonate groups (about $870\text{--}880\text{ cm}^{-1}$), which would indicate carbonation of the ambient-cured paste and should be accompanied by a ν_3 band near $1400\text{--}1450\text{ cm}^{-1}$ (Criado et al., 2005); Si-O stretching of non-bridging oxygen or Si-OH groups in low-polymerised silicate units, as reported for calcium silicate hydrate phases (Yu et al., 1999); and Al-O stretching of tetrahedral Al. A weak band at approximately 1420 cm^{-1} was also observed in the reacted paste, consistent with the ν_3 mode of carbonate groups and supporting the possible presence of calcite indicated by XRD. The shoulder is therefore regarded as an unresolved band of mixed origin, not as direct evidence of aluminosilicate network formation.

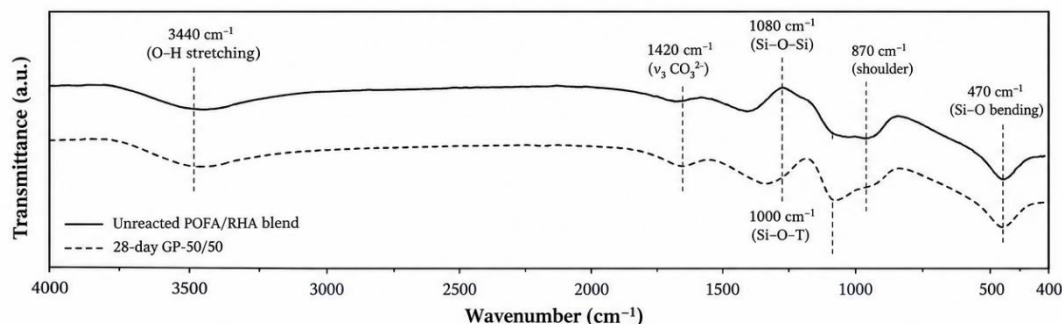


Figure 5. FTIR spectra of the unreacted POFA/RHA blend and the 28-day GP-50/50 geopolymer paste, showing the shift of the main Si-O-T band and the 870 cm⁻¹ shoulder

DISCUSSION

The central finding of this study is that a 1:1 mass blend of POFA and RHA (GP-50/50) produced the best overall balance of mechanical and physical performance among the five POFA:RHA ratios tested, achieving 92% of the OPC control's 28-day compressive strength while using no Portland cement at all. This result is consistent with the view that combining a calcium-bearing, coarser precursor (POFA) with a highly siliceous, finer precursor (RHA) may improve particle packing and the completeness of the geopolymerisation reaction relative to either precursor alone. The individual-ash comparison of Zahin et al. (2018), in which RHA-based mortar outperformed POFA-based mortar owing to its higher silica content, also points to the importance of reactive silica supply. The higher calcium content of POFA (9.8% CaO) may have supplied some calcium for calcium-bearing gel products alongside the sodium-rich gel typical of alkali-activated systems, a dual-gel mechanism reported for calcium-bearing blends (García-Lodeiro et al., 2011). However, the overall calcium content of the binder is low ($\text{Ca/Si} \approx 0.07$ in GP-50/50, Table 3), so any calcium-bearing gel is likely a minor component and this interpretation remains hypothetical.

The comparatively lower strength of the GP-100/0 (100% POFA) mix is consistent with the lower strength of POFA-based relative to RHA-based mortar reported by Zahin et al. (2018). It is also consistent with the chemical differences between the two precursors observed here: POFA contained markedly less SiO_2 than RHA (61.4% vs. 89.6%) and a higher loss on ignition (4.8% vs. 3.1%) (Table 2), indicating a lower reactive silica supply and a higher residual carbon fraction. Conversely, the GP-0/100 (100% RHA) mix, while achieving higher strength than GP-100/0, did not match GP-50/50, suggesting that RHA alone, despite its very high amorphous silica content, may generate an overly siliceous gel network with insufficient calcium to optimise gel densification. This hypothesis is consistent with the much higher Si/Al ratio of GP-0/100 (about 141) than of GP-50/50 (about 25) (Table 3), but it was not tested directly in this study and requires confirmation.

The XRD and FTIR results are consistent with, but do not by themselves prove, alkali activation of the ash precursors, namely dissolution of reactive silica (and the limited alumina and calcium) in the alkaline activator followed by precipitation of a new amorphous gel. Given the molar ratios in Table 3, this gel is expected to be a silica-rich alkali-activated gel rather than a classical N-A-S-H geopolymer gel. The downward shift of the main Si-O-T FTIR band from approximately 1080

cm^{-1} to approximately 1000 cm^{-1} is widely reported to accompany the formation of a less polymerised gel and may include Al substitution (Fernández-Jiménez & Palomo, 2005), but at the very high Si/Al ratios of these binders it cannot be taken as evidence of extensive aluminosilicate network formation. The reduced quartz peak intensity may indicate partial dissolution of crystalline silica, but it could also result from dilution by amorphous products, and semi-quantitative analysis (e.g. Rietveld refinement with an internal standard) would be needed to distinguish the two. The weak reflection near $29.4^\circ 2\theta$ is tentatively associated with a C-A-S-H-type phase but may equally arise from calcite (Criado et al., 2005), and the 870 cm^{-1} FTIR shoulder is of mixed origin, so both observations require confirmation by complementary techniques.

From a green-building-materials perspective, the density reduction of 11–18% relative to OPC observed across the geopolymers is a potentially favourable secondary property, offering reduced structural dead load, even though it is accompanied by higher water absorption that would need to be addressed, for example through the incorporation of fine fillers, optimisation of the liquid-to-binder ratio, or the use of superplasticisers, before the GP-50/50 mix could be recommended for exposure classes with stringent durability requirements. The full replacement of OPC demonstrated here, using two waste streams already generated in large volumes by Indonesia's palm oil and rice-processing industries, aligns directly with the circular-economy and low-carbon construction objectives emphasised in recent reviews of geopolymer concrete (Ahmed et al., 2022; Saeed et al., 2022).

Several limitations should be acknowledged. First, this study relied on ambient curing without elevated-temperature curing, which has been shown to enhance strength development in both RHA-based and POFA-based systems (Kim et al., 2014; Salih et al., 2015). For example, RHA-based mortar reached 31 MPa at 7 days and 45 MPa at 28 days after 24 h at 60°C (Kim et al., 2014). The ambient-cured strengths reported here may therefore understate the potential performance of this binder system under optimised curing regimes. Second, long-term durability properties, including drying shrinkage, sulfate and acid resistance, carbonation, and chloride ingress, were not evaluated in this study and represent an important direction for follow-up work, particularly given the elevated water absorption of the POFA-rich mixes. Third, XRD and FTIR analyses were performed on a single representative mix (GP-50/50) rather than across the full mix series; extending microstructural characterisation to all five ratios would strengthen mechanistic interpretation of the strength trends observed. The phase assignments proposed here, in particular for the 29.4° reflection and the 870 cm^{-1} shoulder, are tentative and should be confirmed by complementary techniques such as SEM-EDS, TGA/DTG, or ^{29}Si and ^{27}Al MAS NMR.

Overall, the results support the technical feasibility of fully replacing OPC with a locally sourced, 1:1 POFA-RHA geopolymer binder for non-critical or moderately loaded structural applications, while highlighting curing optimisation and durability testing as priorities for translating this laboratory-scale formulation into a practically deployable green building material.



CONCLUSIONS

This study demonstrated that ordinary Portland cement can be fully replaced by a binary blend of palm oil fuel ash and rice husk ash to produce a viable geopolymer mortar, with the 50:50 POFA-RHA ratio (GP-50/50) providing the best overall performance among the five ratios tested: a 28-day compressive strength of 37.9 ± 1.6 MPa (92% of the OPC control), a bulk density 11% lower than OPC, and the lowest water absorption (8.3%) among the geopolymer mixes. XRD and FTIR analyses of the GP-50/50 paste indicated the formation of an amorphous alkali-activated gel, evidenced by a shift in the main Si-O-T FTIR band from ~ 1080 to ~ 1000 cm^{-1} and a broad XRD hump shifted to higher angles; a weak reflection near 29.4° 2θ was tentatively associated with a C-A-S-H-type phase but requires confirmation. With a bulk Si/Al ratio of about 25 and Ca/Si of about 0.07, the binder is best described as a silica-rich alkali-activated (hybrid) system. These findings support the use of co-located agro-industrial waste streams POFA and RHA as a technically viable, locally available, and lower-carbon full replacement for cement in Indonesian and other palm oil- and rice-producing regions.

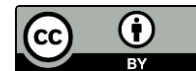
Future work should evaluate elevated-temperature and extended ambient curing regimes, long-term durability under aggressive exposure conditions, and life-cycle carbon and cost assessment relative to conventional OPC mortar, to support the translation of this binder system into practical green building applications.

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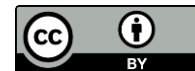


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