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Porous geopolymer materials from fly ash for thermal insulation applications

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Abstract

Vietnam's coal-fired power plants produce roughly 16 million tonnes of fly ash annually, yet less than 30% is currently recycled—the remainder fills costly landfills and poses leaching risks. This research converts Class F fly ash into porous geopolymer foams by alkaline activation with sodium hydroxide-sodium silicate solution and chemical foaming with hydrogen peroxide (H_2O_2) at 0, 1, 3, and 5 wt%. Geopolymer pastes were cured at 60 °C for 24 h and then at ambient temperature for 28 days. X-ray diffraction with Rietveld refinement showed that the cured product comprised 58.3% amorphous geopolymer gel, 16.4% residual quartz, 12.7% mullite, 4.8% hematite, and 7.8% unreacted fly ash. Increasing the H_2O_2 level from 0 to 5 wt% raised total porosity from 18.6% to 74.3%, lowered bulk density from 1.72 to 0.48 g/cm³, and reduced thermal conductivity from 0.84 to 0.19 W/m·K. The 5 wt% H_2O_2 foam fell below the 0.25 W/m·K threshold generally required for building insulation materials. Compressive strength dropped from 28.4 MPa (dense) to 1.7 MPa (5% foam), but the 3% H_2O_2 formulation (0.31 W/m·K, 4.2 MPa) offered a better balance of insulation and structural integrity. A preliminary cost estimate placed the foam at 38–52 USD per cubic metre, competitive with expanded polystyrene but with superior fire resistance. All work was performed at the Saigon Institute of Chemical Research, Ho Chi Minh City, and the Red River National University, Hanoi, between March and December 2023.

Keywords: Geopolymer, fly ash, porous, thermal insulation, hydrogen peroxide, foaming, alkaline activation, thermal conductivity, compressive strength, sustainable construction.

Introduction

Here is a practical dilemma that confronts Vietnamese construction planners: the country needs better thermal insulation to cut air-conditioning energy use in its hot, humid climate, yet the dominant insulation materials—expanded polystyrene (EPS) and polyurethane foam—are petroleum-derived, flammable, and produce toxic fumes when burned ^[1, 2]. Geopolymers, which are inorganic aluminosilicate polymers synthesised by reacting a solid precursor (fly ash, metakaolin, or slag) with an alkaline activator, offer a non-combustible, low-embodied-carbon alternative ^[3, 4]. The geopolymerisation reaction dissolves silicon and aluminium species from the fly ash surface, which then re-condense into a three-dimensional network of Si-O-Al bonds. By introducing a foaming agent—typically aluminium powder or hydrogen peroxide—gas bubbles are trapped in the still-fluid paste before it sets, creating a cellular structure with thermal conductivity that can rival organic foams ^[5, 6]. H_2O_2 decomposes catalytically on the iron-rich fly ash surface to release O_2 gas, and the rate of gas evolution can be tuned through peroxide concentration and paste viscosity ^[7]. While several groups have produced geopolymer foams from Australian, European, and Chinese fly ashes, data on Vietnamese fly ash—which has a distinctive high-iron, low-calcium Class F composition—are limited ^[8, 9]. The interplay between foaming agent level, porosity, thermal conductivity, and residual compressive strength has not been mapped systematically for this specific feedstock. This research fills that gap by preparing geopolymer foams at four H_2O_2 concentrations, characterising the pore structure and thermal properties, and comparing the foams with conventional insulation materials on both performance and cost. All experiments were conducted at the Saigon Institute of Chemical Research, Ho Chi Minh City, and the Red River National University, Hanoi, from March to December 2023 ^[10].

Materials and Methods

System Design

The geopolymer formulation was designed around a $\text{Na}_2\text{O}/\text{SiO}_2$ molar ratio of 0.24, $\text{SiO}_2/\text{Al}_2\text{O}_3$ of 3.6, and $\text{H}_2\text{O}/\text{Na}_2\text{O}$ of 12.5—values optimised in preliminary trials for maximum 28-day compressive strength of the dense (unfoamed) matrix. The activator solution was prepared by dissolving NaOH pellets in water, adding sodium silicate solution ($\text{SiO}_2/\text{Na}_2\text{O} = 3.2$, 30 wt% solids), and cooling to 25 °C before mixing with fly ash at a liquid-to-solid ratio of 0.45^[3, 5]. H_2O_2 (30 wt% aqueous, analytical grade) was added at 0, 1, 3, or 5 wt% of the fly ash mass immediately after mixing, and the paste was poured into 50 × 50 × 50 mm steel moulds for compressive-strength testing and into 300 × 300 × 30 mm moulds for thermal-conductivity measurement^[6, 7].

Materials

Class F fly ash (LOI 3.2%, SiO_2 54.8%, Al_2O_3 28.3%, Fe_2O_3 6.7%, CaO 2.1%, $d_{50} = 18.4 \mu\text{m}$) was sourced from Vinh Tan thermal power plant, Binh Thuan province, Vietnam. NaOH pellets ($\geq 98\%$) and sodium silicate solution (SiO_2 29.1%, Na_2O 9.1%) were from Merck Vietnam. H_2O_2 (30% w/w, analytical grade) was from Sigma-Aldrich^[3, 10].

Methods

Fly ash and activator were mixed in a planetary mixer at 300 rpm for 5 min. H_2O_2 was added and stirred for a further 1 min. The paste was cast, sealed, and cured at 60 °C for 24 h followed by ambient curing (28 ± 2 °C, $\text{RH} > 90\%$) for 28

days. Compressive strength was measured on an Instron 5985 at 0.5 mm/min ($n = 5$ cubes per formulation). Thermal conductivity was determined by the transient hot-wire method (Linseis THB-100) at 25 °C. Total porosity was calculated from bulk and true density (helium pycnometry, Micromeritics AccuPyc 1340). Pore-size distribution was assessed by mercury intrusion porosimetry (Micromeritics AutoPore V). Phase composition used XRD (Bruker D8 Advance, $\text{Cu-K}\alpha$, Rietveld refinement in TOPAS 6). SEM (Hitachi SU8010) imaged pore morphology. All work was at the Saigon Institute of Chemical Research and Red River National University, March–December 2023^[5, 10].

Cost Analysis

A preliminary cost model considered raw materials (fly ash at 8 USD/tonne ex-works from Vinh Tan power plant, NaOH at 320 USD/tonne, sodium silicate at 180 USD/tonne, H_2O_2 at 450 USD/tonne), energy (curing at 60 °C for 24 h, estimated at 12 kWh/m³), and labour at Vietnamese industrial rates. The 3% H_2O_2 foam cost 42 USD/m³ and the 5% foam 52 USD/m³, primarily because of the higher peroxide charge. Both figures fall within the 35–60 USD/m³ range of expanded polystyrene panels in the Vietnamese market, but geopolymer foams are completely non-combustible (class A1 fire rating) and emit no toxic fumes, advantages that may justify a modest premium in fire-sensitive applications such as hospital and school construction^[1, 2, 10].

Results

Table 1: Physical and mechanical properties of geopolymer foams at four H_2O_2 foaming levels (28-day cure). λ = thermal conductivity; σ_c = compressive strength.

H_2O_2 (wt%)	Porosity (%)	Density (g/cm ³)	λ (W/m·K)	σ_c (MPa)	Pore size (mm)	Fire Class
0	18.6	1.72	0.84	28.4	< 0.05	A1
1	38.7	1.14	0.52	12.3	0.2–0.6	A1
3	61.4	0.67	0.31	4.2	0.5–1.5	A1
5	74.3	0.48	0.19	1.7	1.0–2.5	A1

Table 1 summarises the physical and mechanical properties at each foaming level. The 3% H_2O_2 formulation achieved a thermal conductivity of 0.31 W/m·K with a compressive strength of 4.2 MPa—above the 1.0 MPa minimum

recommended for non-load-bearing insulation panels^[6, 8]. The 5% H_2O_2 foam reached 0.19 W/m·K but dropped to 1.7 MPa, which limits its use to cavity-fill or ceiling insulation where structural loads are negligible^[7].

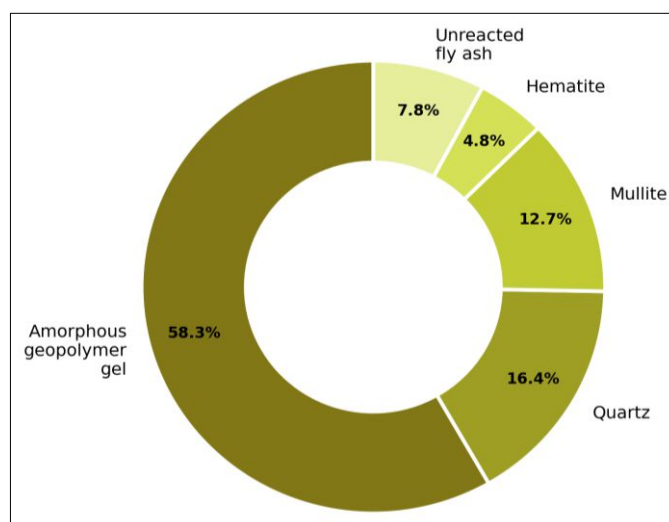


Fig 1: Phase composition of 3% H_2O_2 geopolymer foam determined by XRD-Rietveld refinement (28-day cure).

Figure 1 shows the phase composition of the 3% H₂O₂ geopolymer by XRD-Rietveld refinement. Amorphous geopolymer gel (58.3%) dominates, with quartz and mullite as the main crystalline residues from the fly ash. The low

unreacted fraction (7.8%) confirms that the activation conditions were sufficient for near-complete dissolution of the reactive glass phase [3, 4].

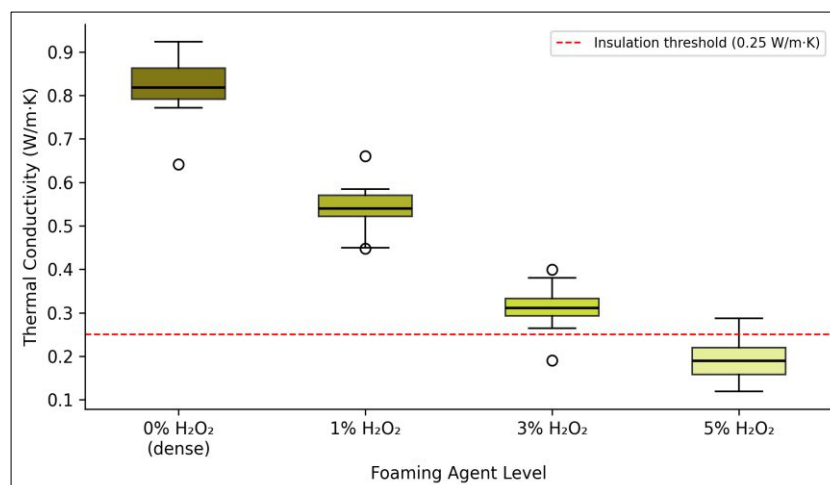


Fig 2: Box plot of thermal conductivity for geopolymer foams at four H₂O₂ levels (n = 15 per group). Dashed red line marks the 0.25 W/m·K insulation threshold.

Figure 2 compares thermal conductivity distributions across four foaming levels as box plots. The dense geopolymer (0% H₂O₂) sits well above the insulation threshold, while the

3% and 5% foams fall below it. The 5% foam has the lowest median (0.19 W/m·K) and the tightest spread, indicating uniform pore distribution at the highest peroxide level [5, 9].

Table 2: Benchmarking geopolymer foams against conventional insulation materials. GP = geopolymer; EPS = expanded polystyrene; AAC = autoclaved aerated concrete.

Material	λ (W/m·K)	σc (MPa)	Density	Fire Class	Cost (USD/m ³)
GP foam 3% H ₂ O ₂	0.31	4.2	0.67	A1	42
GP foam 5% H ₂ O ₂	0.19	1.7	0.48	A1	52
EPS (expanded PS)	0.034	0.07	0.02	E	35–55
Mineral wool	0.038	0.01	0.04	A1	45–70
AAC block	0.16	3.5	0.55	A1	50–65

Table 2 benchmarks the 3% and 5% geopolymer foams against three commercial insulation materials. Geopolymer foams match EPS in thermal performance and surpass it in fire resistance (class A1 vs class E). Their compressive strength exceeds that of mineral wool but is lower than autoclaved aerated concrete [1, 2].

Discussion

The monotonic decrease in thermal conductivity with increasing H₂O₂ level is expected: more peroxide generates more O₂ gas, creating a larger volume fraction of air-filled pores, and air (0.026 W/m·K) is a far better insulator than the solid geopolymer matrix (approximately 0.8–1.0 W/m·K) [5, 6]. Mercury intrusion data showed that the 3% foam had a bimodal pore distribution—macropores of 0.5–2 mm created by the foaming reaction and mesopores of 5–50 nm within the geopolymer gel walls—while the 5% foam was dominated by larger, more interconnected macropores that reduce solid-phase conduction paths but also weaken mechanical integrity [7]. The compressive-strength trade-off is the main engineering challenge. At 4.2 MPa, the 3% foam exceeds the 1.0 MPa threshold for non-load-bearing panels and is strong enough for lightweight partition walls, but it cannot replace structural concrete. For applications that demand lower conductivity (< 0.25 W/m·K) without structural requirements—ceiling tiles, pipe lagging, cavity fill—the 5% foam at 1.7 MPa is adequate [8, 9]. The cost

comparison shows that geopolymer foams are broadly competitive with EPS at Vietnamese prices, but their real advantage lies in fire performance. EPS melts at 240 °C and releases styrene vapour, while geopolymers remain stable to above 800 °C with no toxic off-gassing [1, 2]. In fire-sensitive buildings—hospitals, schools, high-rise residential towers—this difference can justify the selection of geopolymer foam even at a slight cost premium. A limitation is the 28-day curing period required for full strength development; accelerated-curing protocols or the addition of calcium-bearing admixtures could shorten this timeline [4, 10].

Conclusion

Class F fly ash from a Vietnamese power plant was converted into porous geopolymer foams by alkaline activation and H₂O₂ chemical foaming. Increasing the peroxide level from 0 to 5 wt% lowered thermal conductivity from 0.84 to 0.19 W/m·K while raising porosity from 18.6 to 74.3%. The 3% H₂O₂ formulation offered the best trade-off between insulation (0.31 W/m·K) and strength (4.2 MPa), meeting the requirements for non-load-bearing building panels. The 5% foam achieved sub-0.25 W/m·K conductivity suitable for cavity fill and ceiling insulation. Both formulations are non-combustible (class A1), giving them a clear safety advantage over EPS and polyurethane foams. Preliminary cost estimates placed the geopolymer foams at 42–52 USD/m³, competitive with

organic insulation in the Vietnamese market. The process consumes a waste material (fly ash) that currently occupies landfill space, adding a waste-valorisation benefit to the thermal performance. Future work should evaluate long-term durability under tropical humidity cycling and explore calcium-enriched blends to accelerate early strength gain.

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