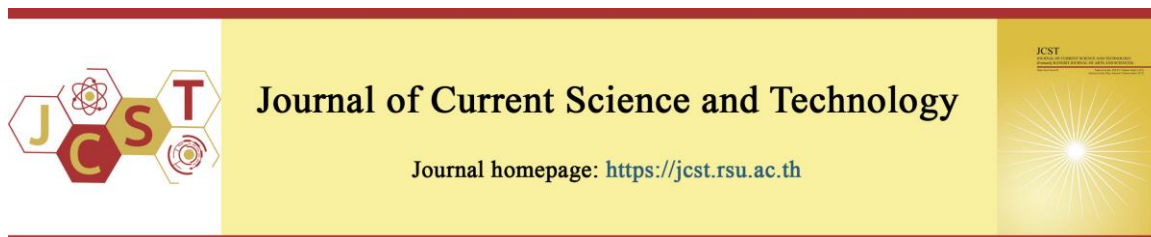


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Utilization of Waste Silicone Sealant and Aluminium Scraps as Additives in Fly Ash-Based Geopolymer for Lightweight Construction Blocks

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Abstract

This study presents a pathway for using waste silicone sealant (Si-s) and aluminium scraps (Al-s) to produce lightweight geopolymer materials. Fly ash, sodium hydroxide, and sodium silicate were used as the starting materials for geopolymerization. Ground Si-s and Al-s were added to the mixtures, which were then cured for 28 days under ambient conditions (25°C). The structural composition and morphology were analyzed using Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy (SEM-EDS). The results showed that Si-s acted as a dispersed additive in the geopolymer matrix and affected the reaction, possibly because its acidity neutralized the alkaline solution. It also increased the crystallite size to 51.68 nm, compared with 20.25 nm for the control geopolymer. The addition of Al-s produced a porous structure and reduced the crystallite size to 14.94 nm because it reacted with the alkaline solution, generating an exothermic reaction and hydrogen gas. The physical and mechanical properties, including density, apparent porosity, water absorption, compressive strength, and ultrasonic pulse velocity, were evaluated. The proportions of Al-s and Si-s were expressed as parts per hundred mixtures (phm), with the mixture comprising fly ash, NaOH, and Na₂SiO₃ used in the geopolymerization process. The addition of 0.4–0.6 phm Al-s and 40 phm Si-s resulted in geopolymers with densities of 1,292–1,438 kg/m³, apparent porosities of 18.18%–25.87%, and water absorption values of 6.97%–10.15%. The compressive strength ranged from 13.25 to 41.91 ksc, depending on the Si-s content. These geopolymers exhibited physical properties and compressive strengths that complied with the requirements for Type C12 lightweight concrete blocks specified in Thai Industrial Standard TIS 2601-2556. Therefore, waste Si-s and Al-s can be effectively recycled to produce lightweight geopolymer materials with properties suitable for construction applications.

Keywords: geopolymer, fly ash, lightweight materials, aluminium scraps, silicone sealant, post-consumer recycling

1. Introduction

A geopolymer is a synthetic material formed through the reaction of an alkaline activator with aluminosilicate and silica sources, resulting in a Si–O–Al–O network structure (Komnitsas & Zaharaki, 2007; Plaichum et al., 2020). Geopolymer precursors

can be obtained from various sources, including metakaolin (Tippayasam et al., 2018), agricultural waste (Makul et al., 2021), and slags from the metallurgical and construction industries (Barbarey et al., 2024; Parthiban & Mohan, 2017). Fly ash, a by-product of coal combustion (Delihowski & Izak,

2026; Hou et al., 2026), is widely used in geopolymer production (Bazarkhankyzy et al., 2026; Behera et al., 2026). Because fly ash is rich in silica (SiO_2) and aluminium oxide (Al_2O_3), it can serve as a precursor for geopolymerization (Rattanasak & Chindaprasirt, 2009). Previous research has shown that fly ash-based geopolymers cured for 28 days can exhibit cement-like properties and can be used to produce concrete that complies with Israeli standards (Freidin, 2007). Chindaprasirt and Rattanasak (2017) reported that heat curing can promote geopolymer network formation and produce high-strength materials comparable to those cured at room temperature. Recent studies have focused on improving the strength and durability of geopolymers (Amran et al., 2020; Rattanasak et al., 2011), particularly by investigating the effects of precursor materials and alkaline activator solutions on their engineering properties (Abdollahnejad et al., 2015; Aliabdo et al., 2016). The recycling of waste materials to produce lightweight geopolymers with properties suitable for specific applications has also attracted considerable research interest (Posi et al., 2013; Masoule et al., 2022).

Aluminium scrap (Al-s) is an industrial and construction waste generated from sources such as aluminium slag and aluminium sealant cartridges or packaging (Gou et al., 2026; Promsaro et al., 2023). Post-consumer Al-s often contains impurities that hinder its direct reuse, resulting in substantial quantities being discarded. Nevertheless, because aluminium is a valuable metal with desirable properties, the industrial sector has investigated methods for recovering and reusing aluminium waste to maximize its value (Mihailova et al., 2021; Puksisuwan et al., 2017). Bajare et al. (2011), for example, used aluminium slag and waste glass to produce lightweight bricks for construction. Previous studies have demonstrated that aluminium-based waste can serve as a foaming agent, thereby reducing density, increasing porosity, and decreasing thermal conductivity (Bajare et al., 2011; Chokkha et al., 2024). However, most of these studies used aluminium waste processed as a controlled industrial by-product (Mandal et al., 2017; Yoshimura et al., 2008). Therefore, the potential use of post-consumer aluminium scrap containing impurities remains insufficiently investigated.

Silicone sealant is an elastic polymer composed primarily of silicon, oxygen, hydrogen, and carbon (Engelmann et al., 2026; Kaki et al., 2026) and is widely used as a sealing material in the construction industry (Allen et al., 1994; de Buyl, 2001). However, residual silicone sealant waste (Si-s) adheres strongly

to aluminium packaging, making the separation and recycling of both materials difficult. Consequently, large quantities of this non-biodegradable waste are disposed of in landfills. This study therefore applies to the concept of post-consumer recycling (PCR) (Promsaro et al., 2023; Thonglor & Charoeythornkhajhorncha, 2022) to recover and reuse waste silicone sealant in an environmentally beneficial manner. Although various waste materials have been incorporated into geopolymer systems, the use of waste silicone sealant remains largely unexplored. Silicone sealant is an organic-inorganic hybrid polymer that is relatively inert under alkaline conditions and is therefore unlikely to participate directly in the formation of the aluminosilicate geopolymer network. Instead, it may function as a lightweight filler or aggregate phase. Silicone particles may influence geopolymer properties through their dispersion, interfacial bonding, and effects on pore structure. Because silicone sealant is polymeric and elastic, it may also enhance energy dissipation and sound absorption in lightweight geopolymer materials. However, these potential effects have not been systematically investigated.

Despite extensive research on aluminium-containing geopolymer systems, most studies have focused on the incorporation of a single waste material and have not considered interactions between multiple waste streams. In particular, the combined effects of aluminium-induced gas formation and polymeric-waste dispersion on the pore structure and mechanical performance of geopolymers have not been systematically investigated.

Accordingly, this study aims to develop a lightweight fly ash-based geopolymer incorporating waste aluminium scrap and silicone sealant. It investigates the effects of aluminium and silicone contents on the physical properties, microstructure, and compressive strength of the geopolymer. The study also seeks to determine suitable proportions of the starting materials for producing lightweight geopolymers with properties appropriate for construction and related applications. By incorporating post-consumer silicone sealant and aluminium scrap containing impurities into a fly ash-based geopolymer system, this study provides insight into how combined waste materials influence pore formation, microstructure, and mechanical performance.

2. Objectives

This study proposes the development of a lightweight fly ash-based geopolymer incorporating

post-consumer silicone sealant waste (Si-s) and aluminium scrap (Al-s) containing impurities. The objectives are (1) to evaluate the effects of Si-s and Al-s addition on the physical properties, compressive strength, and microstructural characteristics of fly ash-based geopolymers and (2) to determine the optimal proportions of Si-s and Al-s required to achieve an appropriate balance between low density and suitable material performance. This study provides insight into the incorporation of post-consumer Si-s and impurity-containing Al-s into fly ash-based geopolymers to produce lightweight materials with properties suitable for construction and related applications.

3. Materials and Methods

3.1 Materials and Instruments

Fly ash was obtained from a power plant in Rayong Province, Thailand. Aluminium scrap (Al-s) and silicone sealant waste (Si-s) were collected as construction-related wastes generated during aluminium-frame production. As shown in Figure 1(a), the fly ash was a fine, dry, lightweight grey powder and was therefore suitable for direct use as a precursor. In contrast, Si-s appeared as irregular agglomerated clumps [Figure 1(b)], whereas Al-s consisted of cut metallic fragments with non-uniform geometries [Figure 1(c)]. The fly ash was used after sieving through a 9.5 mm (No. 2) sieve. Si-s and Al-s were crushed and sieved through a 10 mm sieve to

obtain more uniform particle sizes before geopolymer preparation. The morphologies and elemental compositions of Si-s and Al-s were further examined using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS; HITACHI TM4000 Plus II with AZtec EDS), as shown in Figure 1(d)–(f). The chemical compositions of the raw materials were analyzed and are summarized in Table 1. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), supplied by LABSCAN, were used as alkaline activators. A hot-air oven (JSOF-Series Convection model, JSR Company) was used to dry the specimens. Specimen mass and dimensions were measured using a digital platform balance (Superior Mini Digital Platform Scale, model I-2000) and a digital Vernier caliper with a measurement range of 0–150 mm and an accuracy of ± 0.01 mm. Ultrasonic pulse velocity was measured using a Pundit Lab+ instrument to evaluate the internal structure and integrity of the specimens based on pulse transit time. Compressive strength was measured using a universal testing machine (HOUNSFIELD, model H50KS). The functional groups and crystalline phases of the geopolymers were characterized using Fourier-transform infrared spectroscopy (FTIR; Bruker Alpha-E, USA) and X-ray diffraction (XRD; PHILIPS X'Pert-MPD), respectively. The geopolymer microstructure and elemental composition were characterized using SEM-EDS.

Table 1 Elemental composition of raw materials obtained from EDS analysis

Material	Elements (wt.%)										
	C	Na	Mg	Al	Si	P	S	Ca	Ti	Fe	K
FA	-	0.65	0.24	18.52	70.81	0.21	0.11	0.34	3.65	3.97	1.51
Si-s	52.16	-	0.72	0.86	1.01	-	-	43.36	1.89	-	-
Al-s	-	-	0.39	98.15	0.64	-	-	-	-	0.82	-

Note: The results represent local elemental composition obtained from EDS rather than bulk X-ray fluorescence (XRF)

Table 2 Mix proportions of geopolymer mixtures with different silicone sealant (Si-s) contents

Mix ID	Compositions (wt.%)			Amount of Si-s (phm)
	Na_2SiO_3	8 M NaOH	Fly ash	
GC	20	20	60	0
10GSi	20	20	60	10
15GSi	20	20	60	15
20GSi	20	20	60	20
25GSi	20	20	60	25
30GSi	20	20	60	30
40GSi	20	20	60	40
50GSi	20	20	60	50
60GSi	20	20	60	60
70GSi	20	20	60	70
80GSi	20	20	60	80
90GSi	20	20	60	90

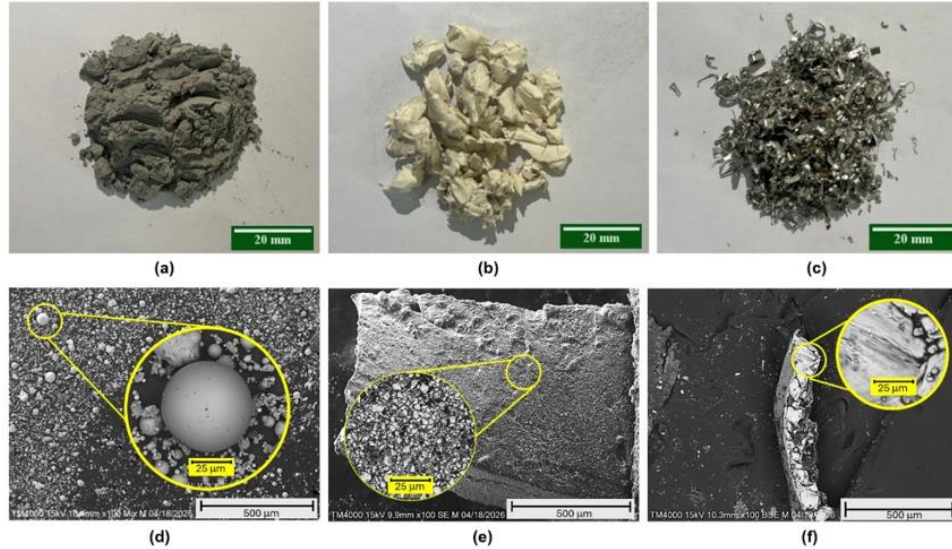


Figure 1 Representative particle size of starting materials: (a) fly ash, (b) silicone sealant (Si-s), and (c) aluminium scraps (Al-s) in as-received condition; and corresponding SEM micrographs showing particle morphology and surface characteristics of (d) fly ash, (e) Si-s, and (f) Al-s at magnifications of 100× and 1000×, operated at 15 kV

Table 3 Mix proportions of geopolymer mixtures with different aluminium scraps (Al-s) contents

Mix ID	Compositions (wt.%)			Amount of Al-s (phm)
	Na ₂ SiO ₃	8 M NaOH	Fly ash	
GC	20	20	60	0
02GA1	20	20	60	0.2
04GA1	20	20	60	0.4
06GA1	20	20	60	0.6
08GA1	20	20	60	0.8
10GA1	20	20	60	1.0

3.2 Geopolymer Preparation

An aqueous solution of NaOH (8 M) was mixed with Na₂SiO₃ (Na₂O:SiO₂ = 1:2.00) at room temperature for 1 min. The NaOH concentration and Na₂SiO₃ ratio were selected based on a previous study reporting suitable geopolymerization performance within this range, with an appropriate balance between workability and mechanical strength (Tippayasam et al., 2010). Fly ash was then added to the alkaline solution and mixed until a partially viscous paste formed. Subsequently, powdered silicone sealant waste (Si-s) and aluminium scrap (Al-s) were added to the geopolymer mixture at various proportions, as shown in Tables 2 and 3, following geopolymer preparation procedures reported in previous studies (Tippayasam et al., 2010, 2018). All proportions of Al-s and Si-s were expressed as parts per hundred mixtures (phm), where the mixture comprised the alkaline activators (Na₂SiO₃ and NaOH) and the aluminosilicate precursor (fly ash). Preliminary experiments were conducted to identify Si-s and Al-s

contents that enabled uniform distribution within the geopolymer matrix while providing suitable properties for lightweight-material applications.

The appearance of the geopolymer paste during mixing is shown in Figure 2. As illustrated in Figure 2(a), the addition of Al-s generated gas and released heat through its reaction with the alkaline solution, resulting in pore formation and increased porosity. In contrast, the Si-s-containing geopolymer paste shown in Figure 2(b) was more cohesive and less reactive, indicating that Si-s acted as a dispersed, non-reactive phase. Based on the preliminary results, the combined effects of Al-s and Si-s were investigated using a constant Al-s content of 0.4 phm and Si-s contents ranging from 40 to 80 phm, as shown in Table 4. After mixing for 20 min, the geopolymer paste was poured into cubic moulds measuring 2.5 × 2.5 × 2.5 cm³ and cured at room temperature for 72 h. The specimens were then demoulded and cured for an additional 28 days.

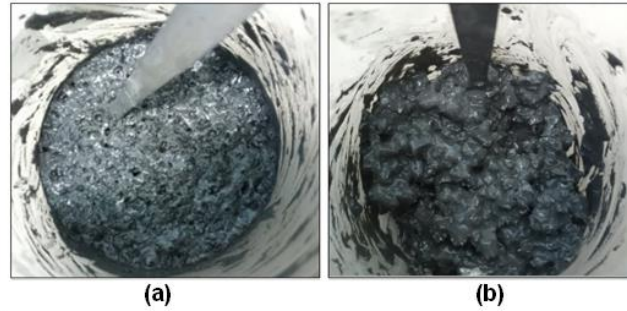


Figure 2 Geopolymer paste during mixing: (a) with Al-s and (b) with Si-s

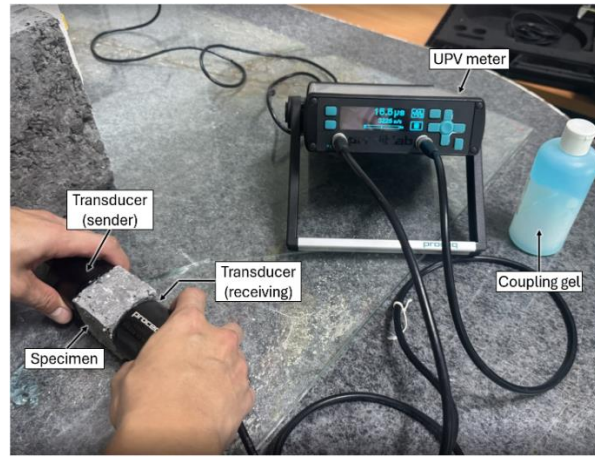


Figure 3 The ultrasonic pulse velocity measurement

Table 4 Mix proportions of geopolymer mixtures with varying Si-s contents at a constant Al-s content of 0.4 phm

Mix ID	Compositions (wt.%)			Amount of Si-s (phm)	Amount of Al-s (phm)
	Na ₂ SiO ₃	8 M NaOH	Fly ash		
G04Al	20	20	60	0	0.4
G40Si04Al	20	20	60	40	0.4
G60Si04Al	20	20	60	60	0.4
G80Si04Al	20	20	60	80	0.4

3.3 Physical Properties and Compressive Strength Investigation

According to TIS 2601-2556, the specimens were tested to determine their physical properties, including bulk density (BD), apparent porosity (AP), and water absorption (WA). All specimens were dried at $100 \pm 5^\circ\text{C}$ for 24 h and weighed in the dry state. They were then immersed in clean water for 24 h, removed, and weighed within 3 min. BD, AP, and WA were calculated from the measured dry and wet weights using Equations (1), (2), and (3), respectively.

$$\text{BD} = \frac{M_D}{M_W - M_S} \quad (1)$$

$$\text{AP} = \frac{M_W - M_D}{M_W - M_S} \times 100 \quad (2)$$

$$W_A = \frac{M_W - M_D}{M_D} \times 100 \quad (3)$$

Where BD is the bulk density (kg/m^3), AP is the apparent porosity (%), WA is the water absorption (%), MD is the weight of the dry specimen (kg), MW is the weight of the wet specimen (kg), and MS is the weight of the specimen in water (kg).

TIS 2601-2556 specifies that compressive strength testing should be performed using cubic specimens (Thai Industrial Standards Institute, 2013). The actual loaded area of each specimen was measured before testing. A compressive load was then applied at a constant loading rate until the specimen fractured. The compressive strength was calculated using Equation (4).

$$C_s = \frac{P_U}{A} \quad (4)$$

Where C_s is the compressive strength (ksc), P_U is the maximum compression load (kg), and A is the area that received the compression of the test specimen (cm^2). All experiments were conducted with at least three replicates, and the reported values represent the average results.

3.4 Ultrasonic Pulse Velocity Test

The internal quality and integrity of the optimal lightweight geopolymer concrete formulation were compared with those of commercial lightweight concrete using ultrasonic pulse velocity (UPV) testing in accordance with ASTM C597. The measurements were performed using a Pundit Lab+ instrument (PROCEQ, Switzerland), as shown in Figure 3. Before testing, the specimen surfaces were cleaned and coated with coupling gel to ensure effective transmission of ultrasonic waves between the transducers and the specimens. The transducers were positioned on opposite faces of each specimen in a direct-transmission configuration. Pulse velocity (V) was calculated using Equation (5). Higher UPV values indicate a denser and more homogeneous internal structure, whereas lower values are associated with greater porosity, lower density, or internal defects (Bogas et al., 2013). The results were used to correlate the microstructural characteristics of the geopolymers with their physical and mechanical properties.

$$V = L / T \quad (5)$$

Where L is the distance between the transducers (m), and T is the measured transit time (μs). The velocity (V) is expressed in m/s.

3.5 Functional Group, Phase Composition, and Microstructure Characterization

After compressive strength testing, the fractured specimens were ground into powder and sieved to obtain particles smaller than $45 \mu\text{m}$ (325 mesh). To investigate the effects of Si-s and Al-s additions on the geopolymer structure, representative specimens were selected for FTIR, XRD, and SEM-EDS analyses based on the preliminary experimental results. These specimens included the control geopolymer (GC), the geopolymer containing Si-s (GC+Si-s), and the geopolymer containing Al-s (GC+Al-s).

The functional groups of the geopolymers were characterized using FTIR in attenuated total

reflectance (ATR) mode with 32 scans at a resolution of 4 cm^{-1} over a wavenumber range of $4,000\text{--}500 \text{ cm}^{-1}$. The phase compositions of the cured geopolymer specimens were analyzed using XRD with Cu $K\alpha$ radiation. The diffraction patterns were recorded at 0.02° intervals with a counting time of 2 s per step over a 2θ range of $30^\circ\text{--}80^\circ$. This range was used primarily to analyze the crystalline phases and crystallite sizes of the geopolymers. The crystalline phases were identified using reference patterns from the Joint Committee on Powder Diffraction Standards, including JCPDS No. 01-089-8934 for silica (SiO_2) and JCPDS No. 00-001-1059 for mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$). The nepheline phase ($\text{NaAlSi}_3\text{O}_8$) was identified based on previously reported data (Kaewvilai et al., 2025; Kittisayarm et al., 2026). The crystallite size (D) of the phase was calculated by the Scherrer equation as Equations (6), where the λ is the X-rays wavelength at $1.54 \text{ \AA}$, the θ is the scattering angle of the main peak (Chaichawalit et al., 2026), and the β is the full width at half-maximum intensity (FWHM) of the diffraction peak analyzed using peak fitting function of the FityK software (Tippayasam & Kaewvilai, 2020).

$$D = 0.89 \times \lambda / \beta \cos\theta \quad (6)$$

The microstructure of the cured specimens was observed by SEM-EDS using backscattering mode with an accelerating voltage of $10\text{--}15 \text{ kV}$ to consider the effects of Al-s and Si-s addition.

4. Results and Discussion

4.1 Physical Properties and Compressive Strength Investigation

The physical properties and compressive strength of the geopolymer were influenced by the particle morphologies [Figures 1(d)–1(f)] and chemical compositions (Table 1) of the raw materials. As shown in Figure 1(d), the fly ash particles were spherical, with smooth surfaces and a broad particle-size distribution. These characteristics influenced the flowability, reactivity, and density of the geopolymer. In contrast, Si-s exhibited an irregular morphology with rough and porous surfaces [Figure 1(e)], which may have contributed to pore connectivity within the geopolymer. Al-s also had an irregular morphology [Figure 1(f)], and its surface readily reacted with the alkaline solution to generate hydrogen gas, producing a highly porous structure. As shown in Table 1, fly ash (FA) was composed primarily of Si (70.81 wt.%) and Al (18.52 wt.%), indicating a typical aluminosilicate composition. In contrast, Si-s consisted mainly of C

(52.16 wt.%) and Ca (43.36 wt.%), with only trace amounts of Si and Al, consistent with its polymeric nature. Si-s did not appear to participate directly in geopolymerization but instead played a physical role in modifying the pore structure and matrix continuity. Al-s contained 98.15 wt.% Al, confirming its metallic nature and its potential to generate hydrogen gas under alkaline conditions. The Si/Al and Na/Al molar ratios were calculated for the fly ash-based geopolymer without Si-s or Al-s. The resulting Si/Al and Na/Al ratios of 3.53 and 0.48, respectively, indicated a silica-rich system suitable for construction applications (Rattanasak et al., 2011).

The preliminary results are presented in Figures 4 and 5. Figure 4(a) shows the physical properties of the geopolymer specimens containing different amounts of Si-s. The control geopolymer (GC), which contained neither Si-s nor Al-s, exhibited a bulk density of 1,791 kg/m³, an apparent porosity of 17.94%, and water absorption of 9.15%. The bulk density, apparent porosity, and water absorption of the geopolymer specimens were influenced by the addition of Si-s. As the Si-s content increased from 10 to 90 phm, the bulk density generally decreased from 1,740 to 1,592 kg/m³. Apparent porosity and water absorption also decreased with increasing Si-s content, reaching minimum values of 9.15% and 3.78%, respectively, at 80 phm. These reductions indicated that Si-s acted as a dispersed additive phase within the geopolymer matrix (Coleman, 2011; Koushki et al., 2020), improving the pore structure and reducing water permeability. However, at a higher Si-s content of 90 phm, apparent porosity and water absorption increased to 21.43% and 9.87%, respectively. This increase may have resulted from the aggregation of silicone particles (Kujawa et al., 2022) and the formation of defects that increased pore connectivity.

Figure 4(b) shows that increasing the Al-s content generally reduced bulk density, apparent porosity, and water absorption. An exception was observed for the specimen containing 0.2 phm Al-s (0.2GAl), whose bulk density increased from 1,791 kg/m³ for the GC specimen to 1,906 kg/m³. This specimen also exhibited higher apparent porosity and water absorption values of 20.61% and 10.14%, respectively. The increase in bulk density may have resulted from insufficient hydrogen-gas generation within the geopolymer matrix. The small and unstable pores formed under these conditions may have collapsed during setting, producing a denser microstructure. In addition, because Al-s was a post-consumer recycled

material, impurities may have reduced gas generation or promoted denser particle packing within the geopolymer matrix. At Al-s contents of 0.4–0.8 phm, the bulk density gradually decreased to 1,305 kg/m³, while apparent porosity and water absorption decreased to 16.79% and 7.83%, respectively. These changes resulted from the reaction between aluminium and the sodium hydroxide solution, which generated hydrogen-gas bubbles and formed pores within the geopolymer matrix (Keawpapasson et al., 2014). The reduction in water absorption suggested that the resulting pores were more stable and less interconnected, indicating a more uniform pore distribution. At an Al-s content of 1.0 phm, the bulk density of the 1.0GAl specimen increased slightly to 1,354 kg/m³, while apparent porosity and water absorption remained relatively unchanged. Excessive aluminium addition may have caused uneven gas generation, partial pore collapse, or structural rearrangement within the geopolymer matrix. Therefore, an appropriate Al-s content can reduce density and produce characteristics suitable for lightweight applications.

The GC specimen exhibited a high compressive strength of 453.67 ± 11.20 ksc, which substantially exceeded the requirements of Thai Industrial Standard TIS 2601-2556 for lightweight concrete blocks: 25 ksc for Types C9–C12 and 51 ksc for Types C14–C16 (Thai Industrial Standards Institute, 2013). Figure 5(a) shows the compressive strengths of the geopolymer specimens containing 10–90 phm Si-s. Among the Si-s-containing specimens, 20GSi exhibited the highest compressive strength at 41.91 ksc. Although this value was lower than that of the GC specimen, it exceeded the minimum requirement for Types C9–C12 under TIS 2601-2556. Most specimens containing 10–60 phm Si-s also met this minimum requirement (Thai Industrial Standards Institute, 2013).

At Si-s contents of 10 and 15 phm, the compressive strengths were 30.18 and 25.90 ksc, respectively. These values were lower than the maximum strength observed at 20 phm, suggesting that the lower Si-s contents may not have provided sufficient particle distribution to improve the mechanical properties. Specimens containing 20–40 phm Si-s exhibited compressive strengths exceeding 30 ksc. This performance was attributed to reduced pore connectivity and improved local particle packing without substantial disruption of the geopolymer matrix.

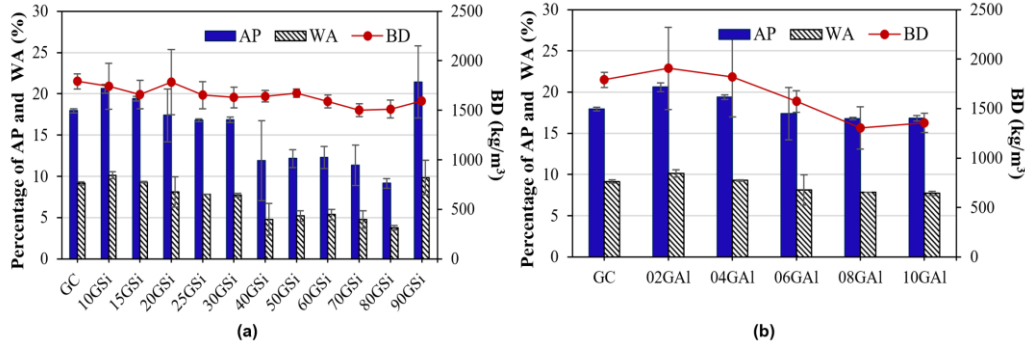


Figure 4 Physical properties (AP, WA, and BD) of geopolymer specimens with varying (a) Si-s and (b) Al-s contents

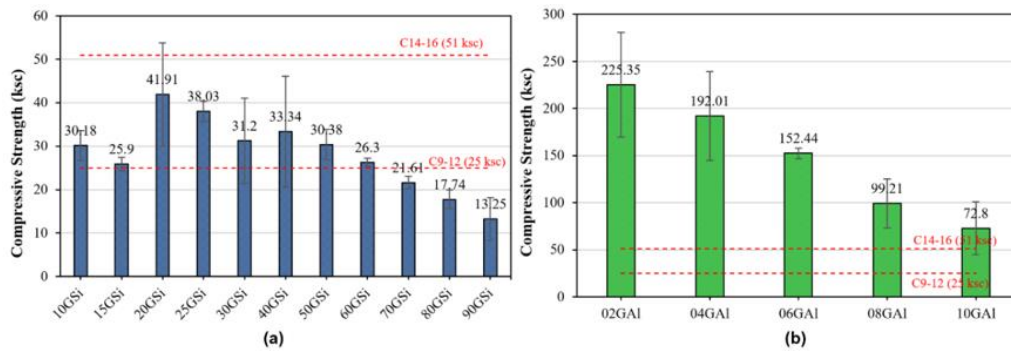


Figure 5 Compressive strengths of geopolymer specimens with varying contents of (a) Si-s and (b) Al-s.

Remarks: The dashed lines indicate the minimum compressive strength requirements for lightweight concrete blocks in Classes C9–C12 and C14–C16 according to TIS 2601-2556 (Thai Industrial Standards Institute, 2013)

However, the compressive strength decreased substantially as the Si-s content increased from 50 to 90 phm. This reduction may have resulted from the agglomeration of silicone particles when the proportion of the geopolymer matrix fell below 50%, thereby disrupting matrix continuity and reducing compressive strength. The optimal Si-s content was therefore identified as 20–40 phm, at which the compressive strength exceeded 30 ksc. Within this range, Si-s may have improved matrix continuity, interfacial bonding, energy absorption, crack resistance, and overall mechanical performance. This behavior was consistent with previously reported interaction mechanisms between polymer additives and cementitious matrices (Bekturganova & Kolesnikova, 2025; Kujawa et al., 2022).

Although the optimal Si-s content for mechanical performance was 20–40 phm, the apparent porosity, water absorption, and bulk density results in Figure 4(a) showed that specimens containing 40–80 phm Si-s had lower bulk densities and greater porosities, which were more favorable for lightweight applications. Considering both physical and mechanical performance, the geopolymer containing 40 phm Si-s provided the

most appropriate balance between weight reduction and acceptable mechanical properties.

Figure 5(b) shows the compressive strengths of geopolymer specimens containing 0.2–1.0 phm Al-s. The compressive strength decreased consistently from 225.35 ksc at 0.2 phm Al-s to 72.8 ksc at 1.0 phm. This reduction was attributed to hydrogen-gas generation during the reaction between the aluminium scrap and the alkaline activator, which produced pores within the geopolymer matrix. Although pore formation contributed to the lightweight characteristics of the geopolymer, excessive gas generation increased porosity and reduced strength (Abdollahnejad et al., 2015; Keawpapasson et al., 2014). Nevertheless, all Al-s-containing specimens exceeded the minimum compressive strength requirements specified in TIS 2601-2556 (Thai Industrial Standards Institute, 2013).

The physical properties and compressive strength of geopolymer with varying Si-s and Al-s were analyzed using single-factor ANOVA at a significance level of 0.05 (Palomas et al., 2026). The testing result of Si-s and Al-s was summarized in Table 5 and 6, respectively. The results showed that the Si-s and Al-s contents had a statistically significant

effect on the physical properties (AP, WA, and BD) of the geopolymers ($p < 0.01$, $F > F_{crit}$). This result confirmed that as Si and Al increase, the BD decreased, and the AP and WA increased, which resulted from the formation of a more porous structure.

For compressive strength, the ANOVA results showed that the effect of Si-s contents (10-90 phm) was not significant at the 95% confidence level ($p = 0.07$), indicating variability in the results might be due to insufficient distribution of Si-s at 10-15 phm. However, the compressive test showed that Si-s at 20 phm exhibited the highest compressive strength, suggesting an optimal distribution ratio between Si-s and the geopolymer matrix. Subsequently, the trend of compressive strength decreased significantly with increasing Si-s content, consistent with ANOVA testing (excluding the results of Si-s at 10 and 15 phm, which deviated from the trend), resulting in a statistically significant difference ($p = 0.01$, $F > F_{crit}$). Similarly, the addition of Al-s resulted in a noticeable decrease in the compressive strength of the geopolymer ($p = 0.005$, $F > F_{crit}$). From the statistical results, it could be explained that the decrease in compressive strength at high Si-s and Al-s was due to

the geopolymer not being densely bonded, resulting in increased voids and pores.

The preliminary results indicated that moderate Si-s contents of 40, 60, and 80 phm improved particle packing and reduced pore connectivity, thereby contributing to relatively stable compressive strength. Considering both physical and mechanical properties, an Al-s content of 0.4 phm promoted pore formation while maintaining relatively high compressive strength. Figure 6 presents the physical properties and compressive strengths of geopolymer specimens containing different Si-s contents at a constant Al-s content of 0.4 phm. As shown in Figure 6(a), Si-s addition significantly affected the bulk density, apparent porosity, and water absorption of the specimens. The specimen containing only 0.4 phm Al-s (G04Al) exhibited the highest bulk density at 1,819 kg/m³. As the Si-s content increased, the bulk density decreased to approximately 1,305–1,354 kg/m³, possibly because of the porous nature of the silicone particles. Correspondingly, apparent porosity increased from approximately 19.41% to 25.90%, while water absorption increased slightly.

Table 5 ANOVA testing results of Si-s geopolymer

Bulk Density (BD)						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p-value</i>	<i>F crit</i>
Between Groups	15486925	1	15486925	3264.188	2.04E-25	4.30095
Within Groups	104378.9	22	4744.495			
Total	15591304	23				
Water Absorption (WA)						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p-value</i>	<i>F crit</i>
Between Groups	6799.629	1	6799.629	15.91775	0.000618	4.30095
Within Groups	9397.798	22	427.1726			
Total	16197.43	23				
Apparent Porosity (AP)						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p-value</i>	<i>F crit</i>
Between Groups	3819.759	1	3819.759	8.824237	0.00706	4.30095
Within Groups	9523.168	22	432.8713			
Total	13342.93	23				
Compressive Strength (20-90 phm)						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p-value</i>	<i>F crit</i>
Between Groups	2479.019	1	2479.019	6.952895	0.017944	4.493998
Within Groups	5704.717	16	356.5448			
Total	8183.736	17				

Table 6 ANOVA testing results of Al-s geopolymer

Bulk Density (BD)						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p-value</i>	<i>F crit</i>
Between Groups	7915340	1	7915340	245.3003	2.31E-08	4.964603
Within Groups	322679.6	10	32267.96			
Total	8238019	11				
Water Absorption (WA)						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p-value</i>	<i>F crit</i>
Between Groups	202.1507	1	202.1507	377.3566	2.85E-09	4.964603
Within Groups	5.357022	10	0.535702			
Total	207.5078	11				
Apparent Porosity (AP)						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p-value</i>	<i>F crit</i>
Between Groups	935.8034	1	935.8034	745.8787	1E-10	4.964603
Within Groups	12.54632	10	1.254632			
Total	948.3497	11				
Compressive Strength						
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p-value</i>	<i>F crit</i>
Between Groups	118500.7	1	118500.7	12.65322	0.005206	4.964603
Within Groups	93652.64	10	9365.264			
Total	212153.4	11				

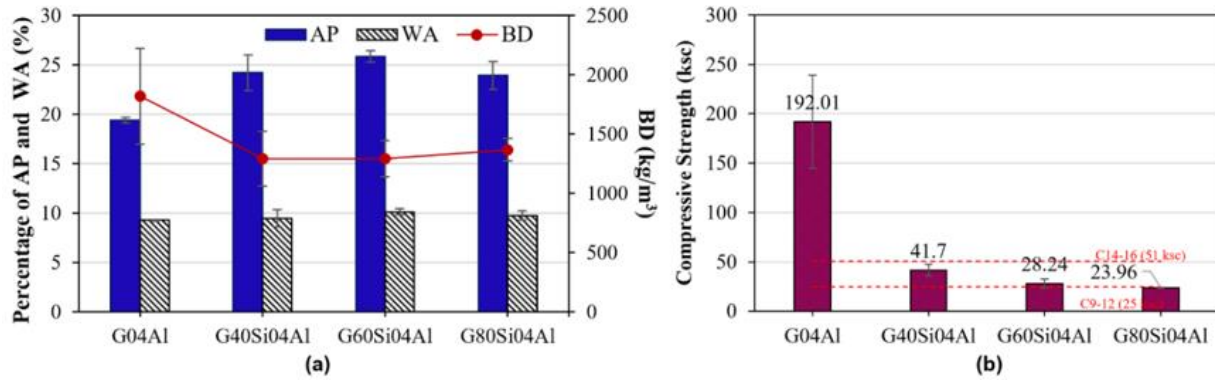


Figure 6 Geopolymer specimens with varying Si-s mixed with 0.4 phm Al-s:
(a) physical properties and (b) compressive strength

Figure 6(b) shows the compressive strengths of geopolymer specimens containing combined Si-s and Al-s additions. The G04Al specimen exhibited the highest compressive strength at 192.01 ksc. However, the compressive strength decreased to 41.70, 28.24, and 23.96 ksc as the Si-s content increased. This reduction was attributed to increased pore formation, which lowered both the bulk density and mechanical strength of the geopolymer specimens. Nevertheless, specimens containing moderate amounts of Si-s still met the minimum strength requirements for Classes C9–C12 under TIS 2601-2556 (Thai Industrial Standards Institute, 2013), indicating their potential suitability for lightweight applications.

Figure 7 presents the ultrasonic pulse velocity (UPV) results for the selected geopolymer specimen,

G40Si04Al, in comparison with lightweight concrete and autoclaved aerated concrete (AAC). Lightweight concrete exhibited the highest UPV range, approximately 3,200–3,800 m/s, indicating a relatively dense internal structure with low pore connectivity. In contrast, AAC exhibited a substantially lower UPV range of approximately 1,765–1,829 m/s because its highly porous structure strongly attenuated ultrasonic-wave propagation. The G40Si04Al specimen exhibited an intermediate UPV range of approximately 2,564–3,226 m/s, suggesting a balance between density and porosity. These results indicated that the incorporation of 40 phm Si-s and 0.4 phm Al-s produced a geopolymer matrix with controlled pore formation and relatively good structural continuity.

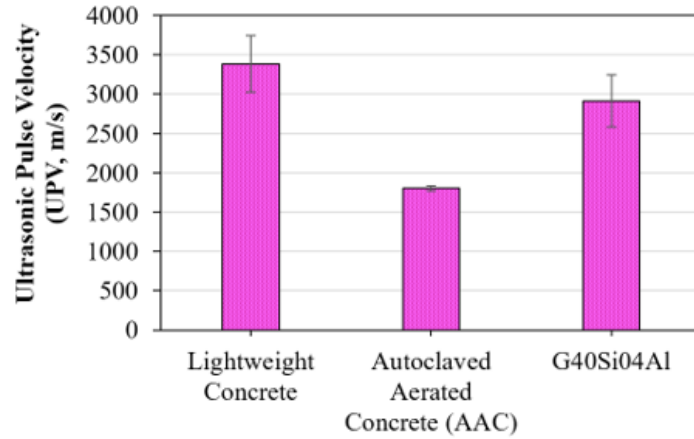
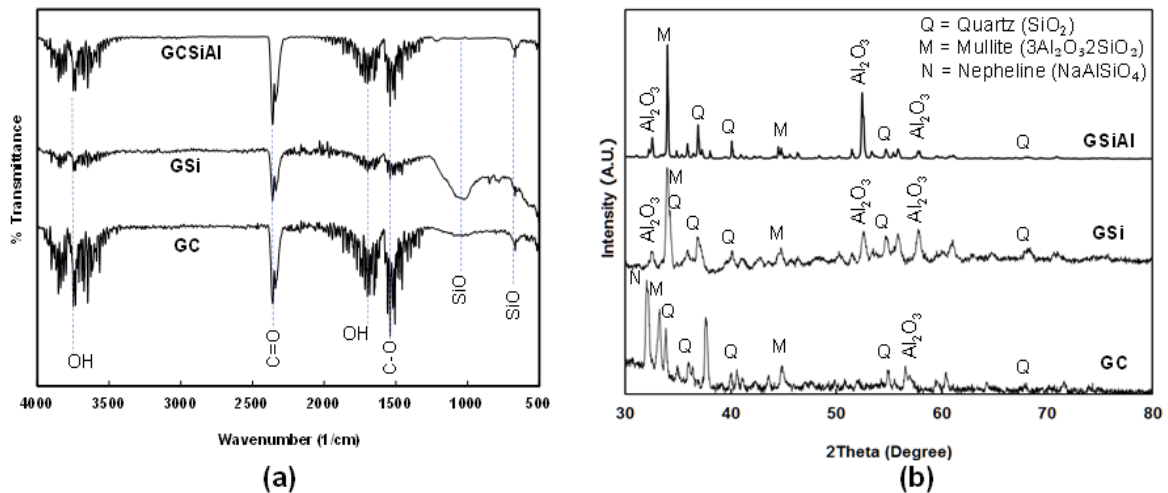


Figure 7 UPV test results of lightweight concrete, autoclaved aerated concrete and geopolymer (G40Si04Al)



4.2 Functional Groups and Phase Composition

The representative specimens (GC, 40GSi, G40Si04Al) were selected to analyze the functional groups and phase structures. From Figure 8(a), the wavenumber range of 4000–500 cm^{-1} of the three specimens showed similar spectral features, indicating the presence of identical functional groups. The main absorption band observed at approximately 950–1000 cm^{-1} was attributed to the asymmetric stretching vibration of Si–O–T (T = Si or Al), which represented the geopolymer aluminosilicate network. The position of this Si–O–T band remains nearly unchanged across all specimens, suggesting that the incorporation of Si-s and Al-s does not significantly alter the fundamental geopolymer framework.

Broad absorption bands were observed over the range of 3,600–3,200 cm^{-1} , together with a band at approximately 1,600 cm^{-1} . These bands were

attributed to the stretching and bending vibrations of hydroxyl groups (OH^-) (Thaweechai & Kaewvilai, 2019), indicating the presence of adsorbed water and structural hydroxyl groups within the geopolymer network (Sangngern et al., 2011). Bands at approximately 2,300 and 1,510 cm^{-1} were assigned to carbonyl-related functional groups ($\text{C}=\text{O}$), which may have originated from residual organic components in the silicone sealant waste or carbonate formation during geopolymerization. In addition, bands at approximately 1,000 and 769 cm^{-1} corresponded to the stretching vibrations of Si–O–Si and Si–O–Al bonds, respectively (Kaewvilai et al., 2025; Kittisayarm et al., 2024), which are characteristic of aluminosilicate geopolymer structures. Differences in percentage transmittance among the specimens may reflect variations in microstructure, porosity, or the relative concentrations of the functional groups.

The FTIR results supported the interpretation that Si-s acted primarily as a non-reactive dispersed phase, whereas Al-s contributed mainly to pore formation through gas evolution without substantially modifying the Si–O–Al network structure. Although the fundamental geopolymer network remained largely unchanged, Si-s may have influenced geopolymerization through physical interference. As a non-reactive polymeric phase, Si-s did not participate in aluminosilicate-gel formation. Instead, it may have disrupted the continuity and connectivity of the gel phase, thereby creating weak interfacial regions and increasing pore connectivity, particularly at higher Si-s contents.

The XRD patterns shown in Figure 8(b) exhibited similar diffraction characteristics, confirming that the principal crystalline phases remained unchanged after the incorporation of the waste materials. Quartz (SiO_2), mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), and nepheline ($\text{NaAlSi}_3\text{O}_8$) were identified in all specimens and are commonly reported in fly ash-based geopolymer systems (Kaewvilai et al., 2025). The diffraction features observed over the 2θ range of 30° – 35° may have been associated with aluminosilicate phases. This interpretation was consistent with the FTIR evidence of Si–O–Al bonding and the formation of aluminosilicate gel during geopolymerization. The presence of these phases suggested that geopolymerization proceeded effectively in both waste-containing systems. No additional crystalline phases attributable to Si-s or Al-s were detected, indicating that these materials were either dispersed in an amorphous form within the matrix or did not form distinct crystalline compounds. This structural stability supports the use of Si-s and Al-s as secondary raw materials for producing lightweight geopolymers without substantially altering their chemical and phase compositions.

According to the Scherrer-equation calculations presented in Table 7, the control geopolymer (GC)

had a crystallite size of 20.25 nm. The addition of Si-s increased the crystallite size to 51.68 nm, possibly because residual acidic components partially neutralized the alkaline solution and slowed the reaction rate. In contrast, the incorporation of Al-s reduced the crystallite size to 14.94 nm. This reduction may have resulted from the reaction of aluminium with the alkaline solution, which generated heat and promoted the rapid formation of smaller crystallites. These findings indicated that Si-s and Al-s affected the geopolymer crystallization mechanism and rate in different ways.

4.3 Microstructure of Geopolymer Matrix

Figure 9 shows the microstructures of the geopolymer specimens together with their corresponding EDS spectra. The SEM images in Figures 9(a)–9(c) reveal geopolymer gel and partially reacted fly ash particles, indicating incomplete dissolution of the precursor. As shown in Figure 9(a), the GC specimen exhibited a dense geopolymer matrix with a relatively homogeneous gel and partially unreacted fly ash particles embedded within the structure. The matrix appeared continuously and contained few pores, suggesting effective geopolymerization. In contrast, the 40GSi specimen [Figure 9(b)] exhibited a more heterogeneous microstructure, with visible microcracks and less uniform gel continuity. These features indicated that the geopolymer gel network was partially disrupted by the silicone particles. The lower compressive strength shown in Figure 6(b) was consistent with the presence of these microcracks and microvoids. The G40Si04Al specimen [Figure 9(c)] contained dispersed silicone residues and spherical pores within the geopolymer matrix. Despite the presence of pores, the geopolymer gel remained well distributed, and the silicone residues were relatively uniformly dispersed. This balanced microstructure helped maintain acceptable compressive strength while reducing density.

Table 7 The calculated crystallite size of geopolymer specimens

Specimens	K	λ (Å)	2θ (°)	Cos θ	FWHM	Crystallite size (nm)
GC	0.89	1.54	32.0838	0.961	0.403772	20.25
GSi	0.89	1.54	34.0278	0.956	0.158985	51.68
GSiAl	0.89	1.54	34.6082	0.955	0.550786	14.94

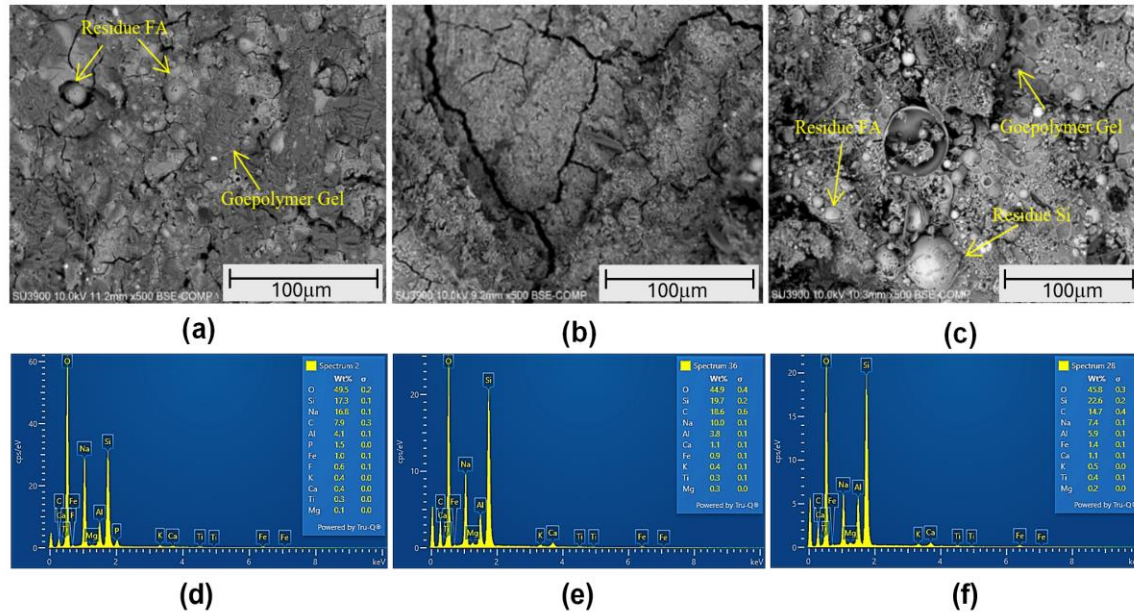


Figure 9 Microstructures examined by SEM of geopolymer specimens (a) GC, (b) 40GSi and (c) G40Si04Al; and corresponding EDS spectra of selected areas (d) GC, (e) 40GSi, and (f) G40Si04Al

The EDS spectra in Figures 9(d)–9(f) confirmed that the geopolymer matrix was composed mainly of O, Si, Na, and Al, which are characteristic elements of aluminosilicate-based geopolymer systems. The control specimen (GC) was dominated by O (49.5 wt.%), Si (17.3 wt.%), Na (16.8 wt.%), and Al (7.9 wt.%). In the Si-s-containing specimen (40GSi), the Si content increased slightly to approximately 19.7 wt.%, whereas the Na and Al contents decreased to approximately 10.0 and 3.8 wt.%, respectively. In the combined system (G40Si04Al), the Si content increased further to approximately 22.6 wt.%, while the Na and Al contents were approximately 7.4 and 5.9 wt.%, respectively.

These variations in elemental proportions were attributed to localized differences in the analyzed regions and the heterogeneous microstructures of the specimens. Importantly, no new elements were detected, and Si, Al, O, and Na remained the dominant elements in all specimens. These findings indicated that the fundamental chemical composition of the geopolymer matrix was not substantially altered by the incorporation of Si-s and Al-s.

4.4 Application Potential of Waste-Derived Lightweight Geopolymers for Construction Materials

From designed formulations and experimental production of lightweight geopolymers incorporating aluminium scraps and waste silicone sealant, the optimal formulation was selected based on physical properties and compressive strength. The selected mix (G40Si04Al) consisted of fly ash (60 wt.%), sodium silicate (20 wt.%), and 8 M sodium hydroxide (20 wt.%) as primary constituents, with aluminium scrap and ground silicone sealant added at 0.4 phm and 40 phm, respectively. The G40Si04Al was then scaled up to produce a full-size unit (20 × 60 × 7.5 cm), as shown in Figure 10. It exhibited a porous internal structure, which was consistent with the hydrogen gas-forming reaction between aluminium scraps and alkaline activators, promoting pore generation and density reduction. In practical handling and surface-finishing trials, the geopolymer block could be plastered, painted, and bonded using commercially available mortar and paint, indicating its feasibility as a construction material component.

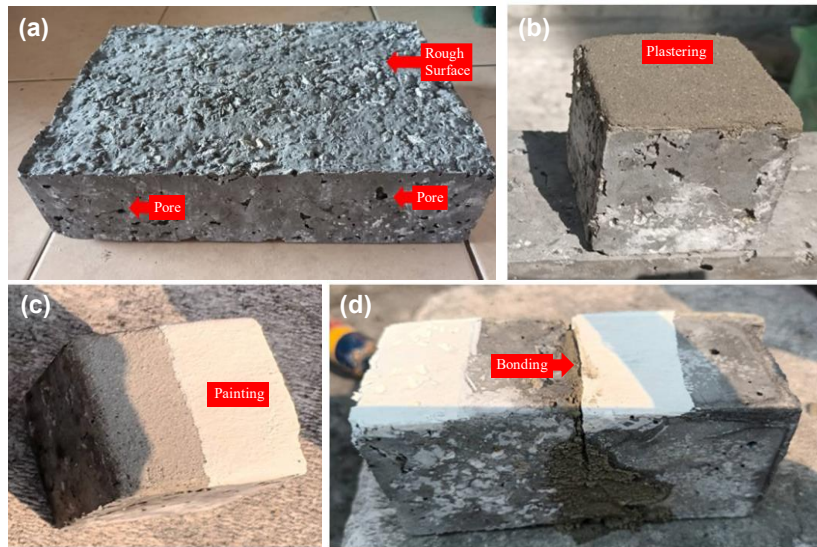


Figure 10 (a) Full-scale lightweight geopolymer block produced from G40Si04Al, (b) plastering, (c) painting, and (d) bonding using commercial materials

Table 8 Overall production cost and reuse calculation of geopolymer block production

Category	Parameter	Value
Production	Production capacity	5,200 blocks/month
	Working days	26 days/month
Direct Material (per block)	Fly ash	4,840 g/block
	Sodium silicate (Na_2SiO_3)	968 g/block
	Sodium hydroxide (NaOH , 8M)	968 g/block
	Aluminium scraps (Al-s)	19 g/block
	Silicone sealant (Si-s)	1,936 g/block
Direct Material Cost	Total material cost	79,976 THB/month
	Cost per block	15.38 THB/block
Labor Cost	Labor cost/month	9,100 THB
	Cost per block	1.75 THB/block
Production Cost (Energy + Water)	Total production cost	2,340 THB/month
	Cost per block	0.45 THB/block
Total Production Cost	Total/month	91,416 THB
	Cost per block	17.58 THB/block
Material Utilization	Al-s content	0.4 phm (~19 g/block)
	Si-s content	40 phm (~1,936 g/block)
Reuse Potential for Each Waste Material	Annual Al-s availability	21.60 tons (21,600,000 g)
	Estimated blocks from Al-s	1,136,842 blocks
	Annual Si-s availability	2.15 tons (2,150,000 g)
	Estimated blocks from Si-s	1,110.54 blocks
Overall Reuse Potential	Limiting waste material	Si-s
	Estimated blocks/year	1,110 blocks/year

The overall production cost and material utilization are summarized in Table 8. In addition to aluminium scraps (Al-s), a significant amount of silicone sealant (Si-s) was incorporated into the geopolymer system at 40 phm, corresponding to approximately 1,936 g per block. While Al-s acted as

a pore-forming agent, Si-s primarily functioned as a non-reactive dispersed phase that influenced the microstructure and density of the geopolymer. The relatively high Si-s content contributed to weight reduction and modified matrix continuity without altering the fundamental geopolymer chemistry.

Based on the mixed proportion, each block contained approximately 19 g of Al-s and 1,936 g of Si-s. Although the annual availability of Al-s was 21.60 tons, the availability of Si-s was significantly lower at 2.15 tons per year. Therefore, Si-s was identified as the limiting waste material for production. Based on the available Si-s, the estimated production capacity was approximately 1,110 blocks per year. At this production level, the consumption of Al-s would be approximately 0.021 tons per year. The cost analysis in Table 8 is based on an assumed operating scale of 5,200 blocks/month, representing a standard commercial production benchmark used for cost modeling. This scale substantially exceeds the ~1,110 blocks/year currently achievable given available Si-s supply; the reported cost of 17.58 THB/block should therefore be interpreted as the target cost achievable once feedstock collection is scaled accordingly, rather than the cost achievable at present Si-s availability.

For one full-size unit ($20 \times 60 \times 7.5$ cm), the required quantities were 4,840 g fly ash, 968 g sodium silicate, 968 g sodium hydroxide, 19 g aluminium scrap, and 1,936 g ground silicone sealant. A production cost analysis was conducted to evaluate the economic feasibility of lightweight geopolymer blocks in comparison with commercially available lightweight concrete blocks. The total production cost was divided into direct material costs, direct labor costs, and manufacturing overheads. The results indicate that the proposed geopolymer blocks can be produced at a total cost of approximately 17.58 THB per block, demonstrating the potential for value-added utilization of aluminium scraps and silicone sealant wastes.

5. Conclusion

This study addressed the research gap concerning the reuse of waste silicone sealant (Si-s) and aluminium scrap (Al-s) in fly ash-based geopolymers for lightweight-material applications. The incorporation of Si-s and Al-s generally reduced bulk density and altered apparent porosity and water absorption, although these changes were accompanied by reductions in compressive strength. Si-s contents of 40–80 phm produced lightweight characteristics while maintaining moderate porosity and acceptable compressive strength. However, excessive Si-s addition, particularly at 80 phm or higher, promoted particle agglomeration and matrix discontinuity, thereby increasing porosity and reducing strength. Si-s functioned primarily as a non-reactive dispersed phase that modified the microstructure without

substantially altering the fundamental geopolymer network. In contrast, Al-s reacted with the alkaline activator to generate hydrogen gas, producing pores that reduced density and contributed to the lightweight characteristics. At low Al-s contents, gas generation was limited, and the collapse of small, unstable pores may have increased bulk density. At Al-s contents of 0.4 phm or higher, greater gas generation promoted pore formation and reduced density. The additions of Si-s and Al-s also affected the crystallite size of the geopolymers differently. SEM observations confirmed that compressive strength was strongly influenced by pore structure and the dispersion of Si-s within the matrix. The combined addition of 40 phm Si-s and 0.4 phm Al-s produced a geopolymer block with a balanced microstructure, controlled porosity, and compressive strength that met the requirements for Type C12 lightweight concrete blocks under Thai Industrial Standard TIS 2601-2556. These findings demonstrate the potential for using post-consumer Si-s and Al-s to produce lightweight geopolymer materials for construction applications.

This study had several limitations that should be addressed in future research. The characteristic amorphous phase of geopolymers within the lower XRD scanning range of $2\theta = 20^\circ\text{--}30^\circ$, together with the relationship between the crystalline and amorphous phases, was not fully investigated and warrants further analysis. In addition, the thermal properties and performance of the developed geopolymers should be evaluated, particularly for commercial applications involving heat exposure. Further research and product development are therefore required to ensure compliance with relevant industry standards.

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7. Abbreviations

Abbreviation	Full Term
AAC	Autoclaved Aerated Concrete
Al-s	Aluminium scraps

AP	Apparent porosity
BD	Bulk density
C=O	Carbonyl functional group
C _s	Compressive strength
FA	Fly ash
FTIR	Fourier transform infrared spectroscopy
GC	Geopolymer control
M	Molar
OH ⁻	Hydroxyl functional group
phm	Parts per hundred mixtures of precursors and activators
SEM-EDS	Scanning electron microscope with energy-dispersive X-ray spectroscopy
Si-s	Silicone sealant waste
Si-O-T	Silicon bond with Si or Al
Si-O-Al	Aluminosilicate bond
Si-O-Si	Siloxane bond
TIS	Thai Industrial Standard
UPV	Ultrasonic pulse velocity
WA	Water absorption
XRD	X-ray diffraction

8. CRediT Statement

Jaroon Promsaro: Methodology, Investigation, Writing – Original Draft, Funding Acquisition.

Ratsamee Sangsirimongkolying: Conceptualization, Investigation, Formal Analysis, Validation, Resources, Writing, Supervision, Project Administration.

Attaphon Kaewvilai: Conceptualization, Software, Formal Analysis, Validation, Data Curation, Writing, Visualization, Supervision.

Chayanee Tippayasam: Conceptualization, Methodology, Investigation, Validation, Resources, Data Curation, Writing, Visualization, Supervision, Project Administration.

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