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Investigating the properties of local minerals as a supplementary cementitious material for foamed concrete

Keumala Citra Sarina Zein[1,2], Abdullah[3*], Sri Mulyati[4], Rijalul Fikri[3]

[1] Doctoral Program in Engineering, Graduate School, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia
[2] Department of Civil Engineering, Faculty of Engineering, Universitas Muhammadiyah Aceh, Banda Aceh, 23123, Indonesia
[3] Department of Civil Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia
[4] Department of Chemical Engineering, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh, 23111, Indonesia
* Corresponding author's e-mail: abdullahmahmud@usk.ac.id

ABSTRACT

Portland cement production is currently one of the major sources of global carbon dioxide emissions. This makes Portland cement production a significant contributor to global climate change. To mitigate these environmental impacts, Supplementary Cementitious Materials (SCMs) are expected to provide an appropriate and effective solution. This study focuses on examining the potential of quartz sand and kaolin from Aceh, Indonesia, as materials utilized as SCMs in the production of foam concrete. These two materials were selected due to their pozzolanic activity, which allows them to react with the calcium hydroxide formed during cement hydration and act as additional binding agents. The primary objective of this study is to reduce the carbon footprint of foam concrete and to sustainably enhance its mechanical properties. The percentage variations of quartz sand and kaolin used as SCMs were investigated at 0% (as a control), 5%, 10%, 15%, and 20%. The physical, chemical, and microstructural properties of the specimens were tested at curing ages of 7, 28, and 56 days. The results of the study indicate that quartz sand and kaolin can function as SCMs. This is because quartz sand and kaolin contain calcium silicate hydrate (C-S-H) as a binding agent. The use of SCMs at 10% of the cement weight has a very significant impact on mechanical properties as the curing age of the concrete increases. Based on these conditions, it can be proven that quartz sand and kaolin derived from local mineral rocks in Aceh have very effective potential for use as SCMs in foam concrete, as demonstrated by the microstructural patterns, and can serve as sustainable alternative materials.

Keywords: properties, sustainability, kaolin, quartz sand, foamed concrete, supplementary cementitious materials.

INTRODUCTION

With the advancement of material technology, lightweight concrete has been increasingly utilized as an alternative material in various construction applications, such as insulated wall panels and pavement materials for bridges (Kim et al., 2013). This trend is driven by its ability to reduce structural load while providing optimal thermal performance, thereby supporting energy efficiency in construction. One of the most widely used lightweight materials today is foamed concrete.

As part of the lightweight concrete category, foamed concrete is produced from several primary components, including cement, water, and a foam agent, which functions to create a porous internal structure. However, the use of cement as the main binder in foamed concrete construction raises important concerns that require further investigation. These concerns are associated with the high energy consumption and carbon emissions involved in cement production. Therefore, an optimization strategy is needed to partially replace cement with supplementary cementitious materials (SCMs) in foamed concrete production

(Christófolli et al., 2025; Heede and Belie, 2012; Moreno et al., 2024; Sanjayan et al., 2015). This approach aims to achieve a balance between materials performance and overall efficiency.

SCMs function as partial replacements for cement, reducing the demand for conventional cement while enhancing concrete performance through pozzolanic reactions. The use of SCMs can lower both energy consumption and production more than other construction materials (Yaseen et al., 2024). Most SCM research has focused on industrial by-products. However, their inconsistent availability has encouraged the exploration of naturally occurring, locally available materials as an alternative binder for foamed concrete (Al-amoudi et al., 2022; Nicoara et al., 2020; Shekarchi et al., 2023).

Aceh possesses a complex geological structure and is rich in mineral resources, including quartz sand and kaolin, which remain underutilized in the construction industry (Sciences et al., 2020). Both materials exhibit potential as supplementary cementitious materials due to their reactive silica and alumina content, which enables pozzolanic activity through reaction with calcium hydrate generated during cement hydration (Formosa et al., 2024a). However, systematic studies investigating the use of natural quartz sand and locally sourced kaolin from Aceh as SCMs, particularly in foamed concrete, along with their microstructural and mechanical performance, remain very limited.

Based on these conditions, quartz sand and kaolin sourced from Aceh are expected to contribute to the formation of additional C-S-H gel, resulting in a stronger and denser binding matrix. This strategy aligns with the global efforts to develop sustainable construction materials aimed at reducing carbon emissions, particularly those associated with the highly energy- intensive production of Portland cement (Amran et al., 2015). Accordingly, this study aims to evaluate the effect of partial replacement of Portland cement using SCMs based on quartz sand and kaolin at substitution levels 0% (as a control), 5%, 10%, 15% and 20% by weight of cement. This investigation includes the assessment of physical and chemical properties of materials, as well as the mechanical characteristics of foamed concrete at curing ages of 7, 28, and 56 days. The findings of this study are expected to provide a comprehensive understanding of the feasibility of locally sourced quartz sand kaolin from Aceh Province as sustainable and cost-effective SCMs, contributing to environmentally friendly construction practices.

MATERIALS AND METHODS

Materials constitute a critical component of this study. The materials prepared include the primary constituents of foamed concrete, consisting of a binder in the form of ordinary Portland cement (OPC) produced by PT. Solusi Bangun Andalas (SBA), located in Lhoknga, Aceh, Indonesia, complies with SNI 2049:2000 standards. The mixing water used in this research was supplied by PT. Tirta Daroy, a local water utility company in Aceh Province, Indonesia. SCMs used in this study were derived from local mineral resources in Aceh. These include quartz sand obtained from volcanic soil in the Ketol District, Central Aceh Regency, and kaolin sourced from volcanic rock formations in the Jaboi Mountains, Sabang Island. Both materials are naturally occurring resources originating from Aceh Province, Indonesia.

Prior to being utilized as SCMs in foamed concrete. Both quartz sand and kaolin were first processed into fine materials in accordance with ASTM C131 using the Los Angeles Abrasion testing apparatus. Subsequently, the materials were sieved following ASTM E11 standards using an 8-inch sieve with a No. 325 mesh size. The preparation process of the SCMs is illustrated in Figure 1 (Machine and Statements, 2014; Sieve, 2010).

Following the preparation of materials for foamed concrete production, the next step involved the development of the concrete mix design. Prior to this stage, several key material characteristics were required. These included the physical properties of the materials, particularly specific gravity. The specific gravity of each material was determined using a 50 mL pycnometer, and the results are presented in Table 1.

Subsequently, chemical characterization of the materials was conducted. This analysis included the determination of elemental composition using x-ray fluorescence (XRF), as well as microstructural observations of the SCMs using scanning electron microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDS). The chemical properties of the SCMs

Table 1. Specific of cement and SCMs

Physical properties	Spesific gravity (g/m^3)
Quartz sand	2.63
Kaolin	2.63
Cement	3.14

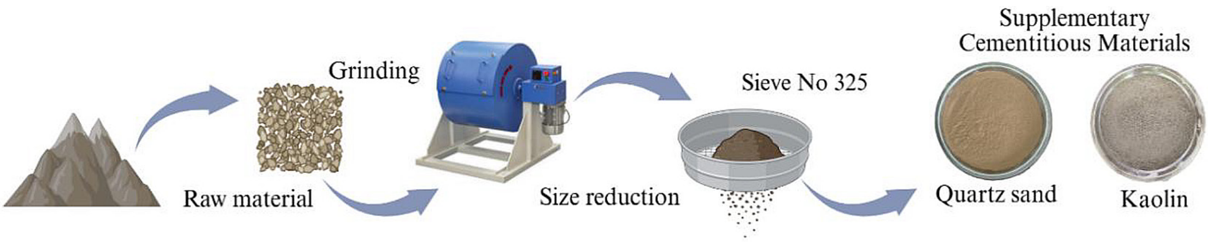

Figure 1. Preparation process of supplementary cementitious materials

Table 2. Chemical composite of cement and SCMs

Oxide constituents (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Cement OPC	18.56	5.23	3.19	64.15	1.02	2.66
Pasir Kuarsa	54.13	20.53	8.74	4.48	1.06	0.00
Kaolin	75.19	2.27	0.14	0.17	0.06	0.01

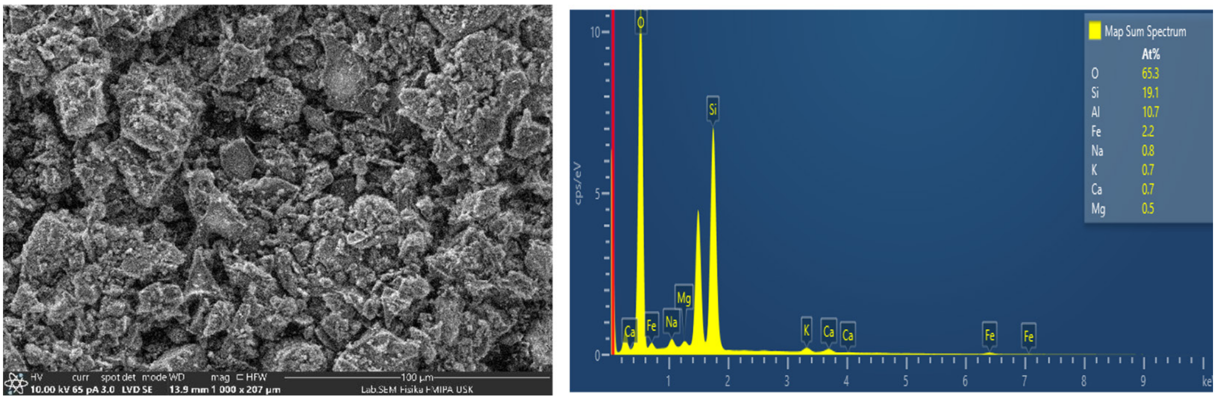

Figure 2. The SEM-EDS of Quartz sand

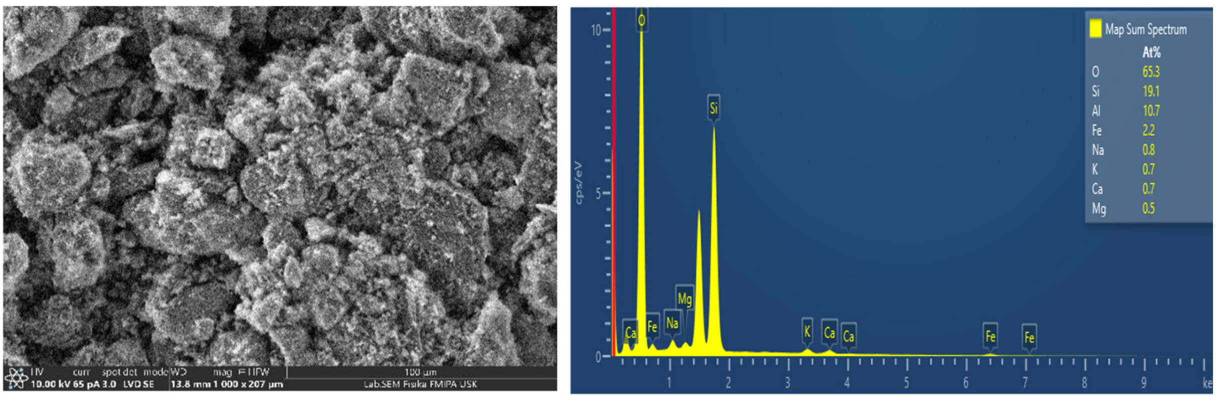

Figure 3. The SEM-EDS of kaolin

used in this study are presented in Table 2, Figure 2, and Figure 3 (da Silva et al., 2021; Dewi et al., 2018; Pacewska and Wilińska, 2020).

Foamed concrete mixture methodology

In this study, the foamed concrete mixtures were prepared using a target specific gravity of 1600 and a water-to-cement (w/c) ratio of 0.5 (Liu, et al., 2016). Variations in the proportion of SCMs, consisting of quartz sand and kaolin as partial cement replacements, were introduced at level 5%, 10%, 15%, and 20% by weight of cement, with 0% used as the control mixture. The resulting mixture were subsequently evaluated for their mechanical properties, including compressive strength, tensile strength, and flexural strength at curing ages of 7, 28, 56 days. The detailed experimental variations and mix proportions of foamed concrete incorporating SCMs are presented in Table 3.

To ensure that the foamed concrete mix composition met the required workability and the targeted specific gravity, fluidity, and density tests of the mortar were conducted.

Consistency was defined by a flow diameter exceeding 200 mm and a mortar density of 1600. The measures were implemented to verify that each 1 L of foamed concrete mortar incorporating SCMs, produced based on the cement-water-foam ratio, achieved an appropriate balance between lightweight characteristics and the desired density (Falliano et al., 2018; Liu et al., 2016).

Preparation of specimens

The production process began by introducing the constituent materials cement, water, and SCMs into a concrete mixer to form a base mortar. In parallel, high-quality foam was generated by mixing a foaming agent with water using a foam generator. The produced foam was then gradually incorporated into the base mortar and mixed gently until a homogeneous fresh foamed concrete mixture was obtained. The foamed concrete production process is illustrated in Figure 4.

Prior to casting, the fresh foamed concrete mortar was evaluated for its consistency using the ASTM D6103 method, and its density was determined by measuring the mass 1 liter of mortar, in accordance with the planned mix design (Figure 5).

Table 3. Variation and mix proportion of foamed concrete with SCMs

Specimen	Specific gravity	w/c ratio	SCMs		Cement	SCMs	Water	Foamed agent
			Type	Persentage	kg/m³	kg/m³	kg/m³	L/m³
FC 0	1600	0.5	-	0	1066.67	-	533.34	128.04
QS 5	1600	0.5	Quartz	5	1013.33	53.3	533.34	119.82
QS 10	1600	0.5	Quartz	10	960.00	106.7	533.34	111.59
QS 15	1600	0.5	Quartz	15	906.67	160.0	533.34	103.36
QS 20	1600	0.5	Quartz	20	853.33	213.3	533.34	95.14
KO 5	1600	0.5	Kaolin	5	1013.33	53.3	533.34	119.82
KO 10	1600	0.5	Kaolin	10	960.00	106.7	533.34	111.59
KO 15	1600	0.5	Kaolin	15	906.67	160.0	533.34	103.36
KO 20	1600	0.5	Kaolin	20	853.33	213.3	533.34	95.14

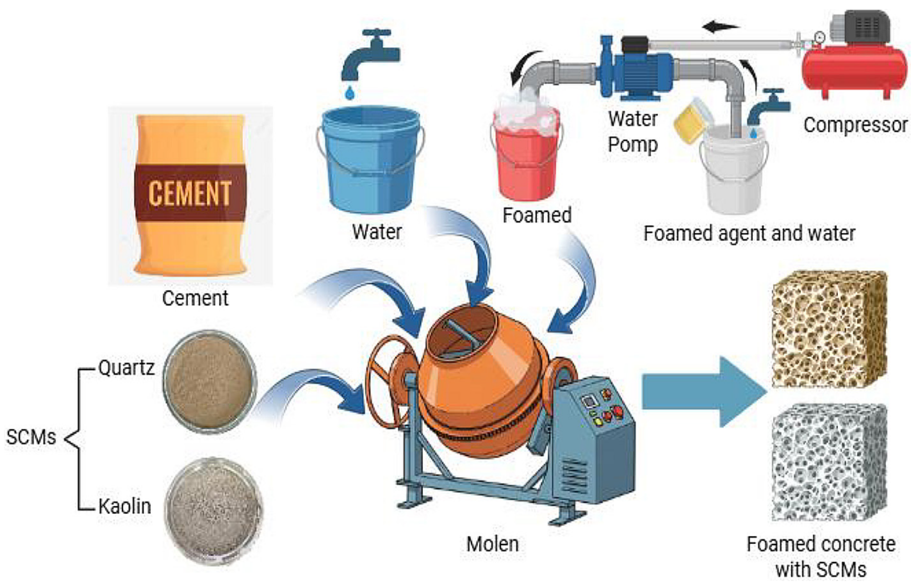

Figure 4. Mixing process of foamed concrete

Figure 5. Preparation of foamed concrete specimens

Testing methods

Hydration mechanism

The analysis conducted to determine the mineral composition of the SCMs derived from quartz sand and kaolin prior to their incorporation into the foamed concrete mixture was performed using an X-ray diffractometer, specifically the Shimadzu-7000 X-ray Diffractimeter Maxima. XRD testing was carried out on quartz sand and kaolin samples that had been sieved through a No. 325 mesh. Corresponding to a particle size of approximately 45 μm.

Fluidity and density of mortar

Fluidity and mortar density tests were conducted under fresh concrete conditions for foamed concrete incorporating SCMs in the form of quartz sand and kaolin. The fluidity test was performed in accordance with ASTM D6103, while the density test followed ASTM C462.

The fluidity of the foamed concrete mixture was evaluated by pouring the mortar into a cylindrical mold with a diameter and height of 80 mm. Once the mold was completely filled, the surface was leveled flush with the top edge of the mold. The mold was then lifted vertically within approximately 3 seconds. Allow the mixture to flow and spread freely over a smooth acrylic palette. After 1 minute, the maximum horizontal spread diameter was measured and used as an indicator of the mixture's fluidity.

Following the fluidity test, the mortar density was determined by measuring the mass of 1 liter of mortar to verify its conformity with the target density specified in the mix design.

Compressive strength

Compressive strength testing was conducted in accordance with ASTM C39-10. The tests were performed on cylindrical specimens with a diameter of 100 mm and a height of 200 mm at curing ages of 7, 28, and 56 days.

The testing procedure was carried out using a universal testing machine, specifically the Ton Industri 2547/14/1970 manufactured in Germany, with a maximum capacity of 1500 kN.

The reported result represents the average values obtained from three specimens for each variation in SCM percentage curing age.

Splitting tensile strength

The splitting tensile strength test was conducted in accordance with ASTM C496 (ASTM C496/C496M − 17, 2011). The specimens used were cylindrical, with a diameter of 250 mm and a height of 300 mm. The test was performed using the same equipment as the compressive strength test, namely the Ton Industri 2547/14/1970, with a maximum capacity of 1500 kN. All specimens were tested at a curing age of 28 days.

Flexural strength

Flexural tensile strength was evaluated in accordance with ASTM C293 (ASTM C923/C293M., 2002). The specimens used for this test were beam elements measuring 150 × 150 × 400 mm. All mechanical test specimens were evaluated at a curing age of 28 days.

Microstructure of foamed concrete

For the visualization of the microstructure of foamed concrete incorporating SCMs in the form of quartz sand and kaolin, representative samples were selected based on the highest compressive strength result at replacement levels of 0%, 5%, 10%, 15% and 20%. Microstructural specimens were prepared by cutting the hardened concrete into small sections measuring 10 × 10 × 5 mm. These specimens were subsequently analyzed using SEM by placing them into a Thermo Scientific Prisma E SEM. This analysis was conducted to obtain a detailed microstructural image of the foamed concrete incorporating SCMs and to identify the pore structure characteristics after the addition of quartz sand and kaolin.

RESULTS AND DISCUSSION

Mineralogical analysis of supplementary cementitious materials

The mineralogical composition of quartz sand and kaolin was characterized using X-ray diffractometry (XRD), as presented in Figure 6. The diffraction pattern of kaolin exhibits a characteristic reflection at 2θ ≈ 12°, 20–25°, and 35–38°, which are consistent with the crystalline structure of kaolinite ($Al_2Si_2O_5(OH)_4$). A prominent basal reflection observed at approximately 12° correspond to the (001) plane of kaolinite, indicating the presence of a layered aluminosilicate structure. This confirms the existence of a layered aluminosilicate framework, which is widely recognized as a suitable precursor for SCM applications (Yahaya et al., 2017).

Additionally, a minor diffraction peak detected at approximately 26.6° suggests the presence of quartz impurities, which are commonly associated with natural kaolin deposits (Andrini et al., 2016).

The XRD pattern of kaolin exhibits a relatively broad diffraction peak with moderate intensity, indicating a medium degree of crystallinity and the presence of structural disorder. This characteristic reflects the partially amorphous nature of clay minerals, which is crucial for pozzolanic reactivity, particularly after thermal activation into metakaolin (Formosa et al., 2024b).

The contrast, the XRD pattern of quartz sand is dominated by sharp and intense diffraction peaks. With the primary reflection located at 2θ ≈ 26.6°, corresponding to the (101) plane of crystallinity and structural stability of quartz (Calvo-de et al., 2023). The absence of secondary mineral phases indicates a high level of mineralogical purity, which is desirable for its function as an inert material in cementitious composites (Calvo-de et al., 2023).

Fresh properties of foamed concrete

Slump flow test

The slump flow testing process is illustrated in Figure 7, with corresponding results presented

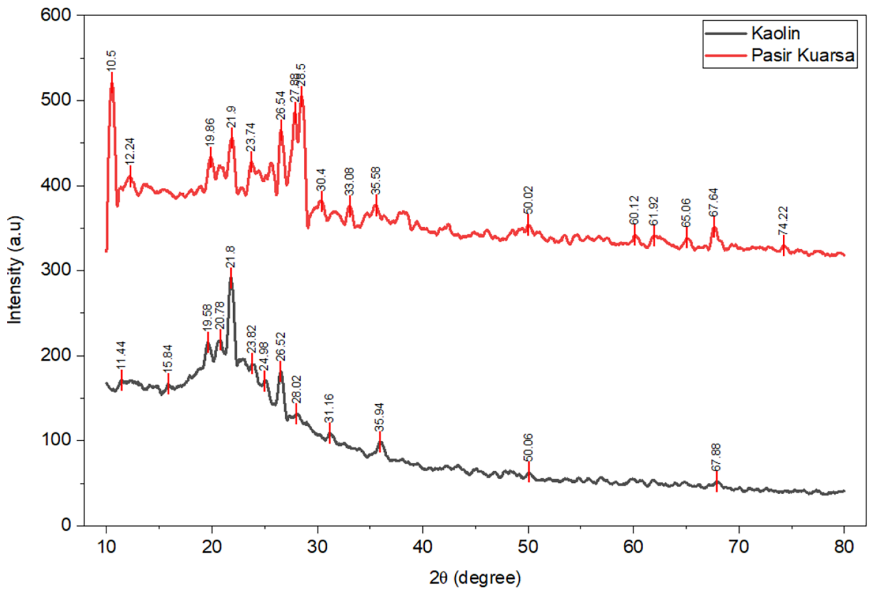

Figure 6. XRD patterns of quartz sand and kaolin

Figure 7. Slump flow testing procedure

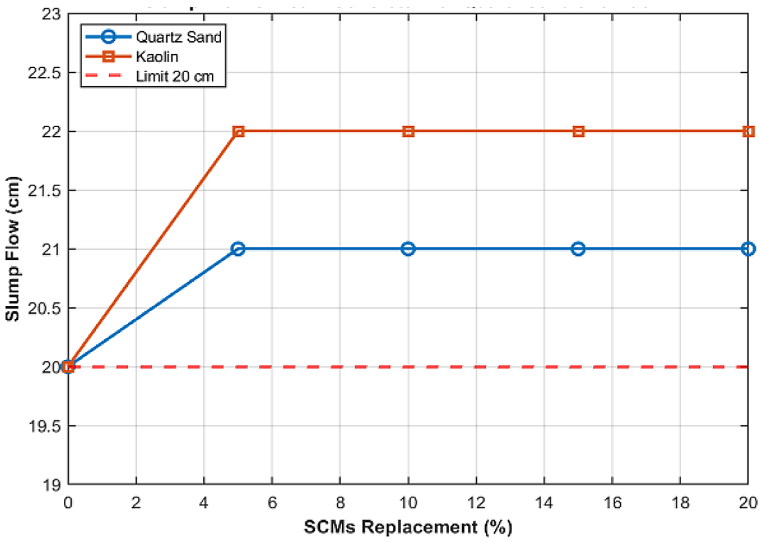

Figure 8. Results of the slump flow test

in Figure 8, indicates that the partial substitution of Portland cement with SCMs derived from local Aceh mineral resources, namely quartz sand and kaolin, produces significant effects on the workability of the mixture.

The fluidity result obtained from the slump flow test indicates that kaolin processes a much finer particle size compared to quartz sand. This condition suggests that finer particles enhance the flowability and promote a more uniform distribution of water within the foamed concrete mortar. Moreover, increasing the percentage of SCMs does not produce a significant effect when compared to the normal foamed concrete (Rodrigues et al., 2020). However, mixtures incorporating SCMs from quartz sand and kaolin exhibit improved fluidity, exceeding the target flow diameter of 200 mm. Based on the fresh properties, the use of these SCMs plays a significant role in the performance of foamed concrete. The finer the SCMs particles, the higher the fluidity of the mortar, without needing to increase the proportion of SCMs (Raj et al., 2019; Yang et al., 2022).

Mortar density testing

The result of the mortar density test with incorporation of SCMs in the form of quartz sand and kaolin indicates that the resulting densities range from 1610 to 1624 kg/m^3. This condition remains close to the target density of foamed concrete, which is 1600 kg/m^3, as shown in Figure 9.

As shown in Figure 9, the mortar density increases with SCMs replacement levels from 0% to 10% forth both quartz sand and kaolin. This increase can be attributed to the filler effect and improved particle packing provided by the fine SCM particles, which effectively fill the void between cement grains, resulting in a denser and more compact matrix. This condition arises because both reactive and inert SCMs contribute to pore refinement, producing a more homogeneous microstructure and reducing overall porosity. Consequently, SCMs based on quartz sand and kaolin can enhance the compressive strength and durability of foamed concrete (Feng et al., 2021).

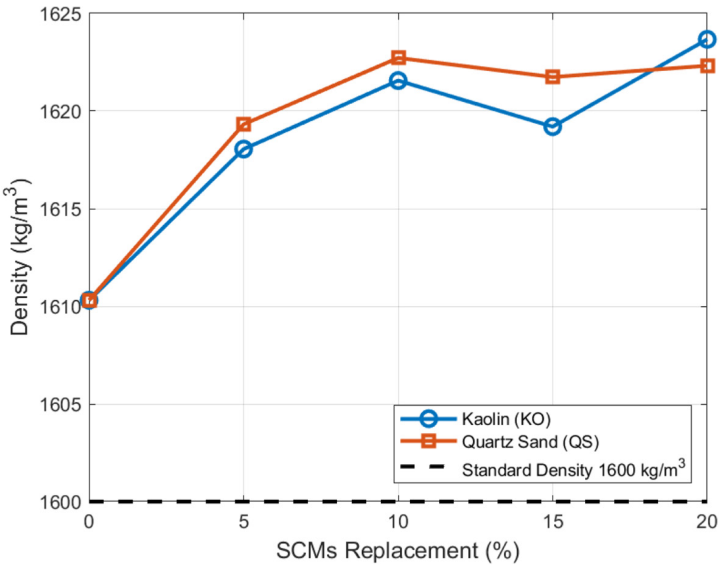

Figure 9. Results of the mortar density test

Compressive strength

The compressive strength result of foamed concrete incorporating quartz sand and kaolin as SCMs at curing ages of 7, 28, and 56 days was analyzed using response surface methodology (RSM), as illustrated in Figure 10.

As illustrated in Figure 10, the partial replacement of cement with SCMs in the form of quartz sand (QS) and kaolin (KO) at proportions of 5%, 10%, 15%, and 20% generally results in a significant increase in compressive strength compared to the control specimen (CTRL) or normal foamed concrete (FC0). Both SCMs demonstrate that QS provides higher compressive strength than KO. This trend is evident at an early curing age of 7 days, where the maximum compressive strength for QS at a 10% replacement level reaches 22.51 MPa, whereas KO achieves only 15.29 MPa. This difference can be attributed to the more effective filler effect and matrix densification provided by QS during the early stages of curing, compared to KO.

At 28 days, the compressive strength increases compared to that at 7 days. However, the trend in the percentage variation of both SCMs remains consistent with that observed at 7 days. The compressive strength of mixtures containing QS reaches 25.27 MPa at a 10% replacement level. This improvement can be attributed to the continued hydration process and the formation

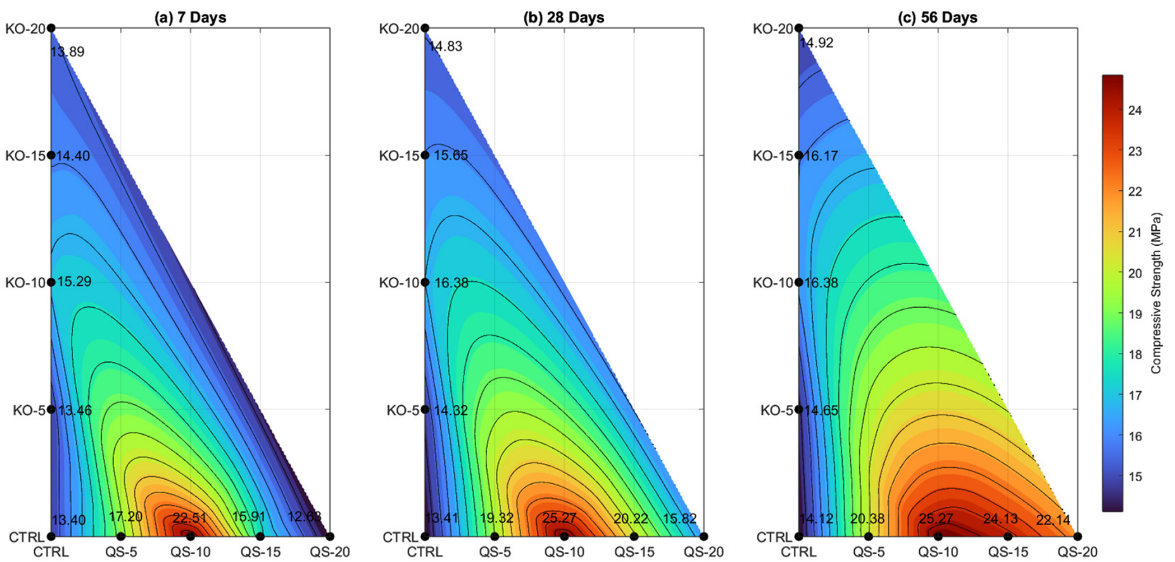

Figure 10. Compressive strength of foamed concrete

of secondary calcium silicate hydrate (C-S-H) associated with QS incorporation. The increase in compressive strength is strongly related to the pozzolanic interaction between the amorphous silica phase and calcium hydroxide ($Ca(OH)_2$) released during cement hydration, leading to the formation of additional C-S-H gel. The newly formed hydration products progressively fill internal pores and refine the pore structure, resulting in a denser cementitious matrix and stronger interfacial transition zone (ITZ). In contrast, mixture with KO exhibits a more gradual increase, with a compressive strength of 16.38 MPa. This behavior is likely due to the relatively limited pozzolanic contribution of KO compared to QS as an SCM. Although kaolin contributes aluminosilicate compounds capable of participating in pozzolanic reactions, its reactivity without thermal activation remains relatively limited compared to highly reactive SCMs. Consequently, the formation of secondary hydration products occurs at a slower rate, resulting in lower strength development.

At 56 days, the compressive strength region becomes both higher and more extensive, particularly for mixtures incorporating QS as SCMs at replacement levels of 10–15%. The optimum SCM content is observed at a QS replacement level of 10%. The continued increase in compressive strength at later curing ages indicates that long-term pozzolanic reactions continue to occur within the matrix. These reactions gradually consume calcium hydroxide and generate additional C-S-H gel, which contributes to pore refinement and improved microstructural compactness. The densification effect reduces internal microcracks and enhances load transfer efficiency throughout the foamed concrete structure. The behavior can be attributed to continued hydration and ongoing pozzolanic reaction, whose contribution of KO remains relatively moderate.

Overall, the compressive strength results indicate that the use of quartz sand (QS) as an SCM at a 10% replacement level yields optimal performance across curing ages of 7, 28, and 56 days. This behavior can be attributed to the transition from predominantly physical effects to chemical mechanisms, which enhance the density and structural stability of the foamed concrete (Mydin et al., 2024). Compared with commonly used SCMs such as fly ash, silica fume, and ground granulated blast furnace slag (GGBFS), the performance of QS in this study demonstrates competitive characteristics, particularly in terms of matrix densification and long-term strength development. Silica fume generally provides superior early-age strength due to its ultrafine particle size and very high silica content, while fly ash and GGBFS contribute more significantly to later-age strength through slower pozzolanic and latent hydraulic reactions. The compressive strength achieved by QS at a 10% replacement level indicates that locally available quartz sand possesses promising potential as an alternative SCM for lightweight foamed concrete applications, especially considering its local availability and lower processing requirements (Qu et al., 2022).

Splitting tensile strength and flexural strength

The results of the splitting tensile strength (Figure 11) and flexural strength (Figure 12), as analyzed using response surface methodology (RSM), indicate that foamed concrete incorporating QS and KO at replacement levels of 5%, 10%, 15% and 20% exhibits similar contour patterns. Both tests demonstrate that QS provides a more dominant contribution compared to KO in terms of splitting tensile and flexural strength. At a 10% QS replacement level, the splitting tensile strength reaches a maximum value of 1.65 MPa. This behavior can be attributed to the optimal range of 5–10% QS, where the foamed concrete benefits from a filler effect and enhanced matrix densification. This improvement contributes to a stronger interfacial transition zone (ITZ) and a reduction in stress concentration. In contrast, the influence of KO shows a more gradual improvement, primarily due to its relatively limited pozzolanic contribution (Hilal et al., 2014, 2015). This enhancement can be attributed to increased microstructural densification and improved homogeneity, rather than solely chemical reactions. The optimal composition is achieved due to a balance between matrix densification and the availability of active paste to sustain the hydration process.

The improvement in tensile and flexural performance is closely associated with microstructural refinement caused by the incorporation of SCM particles. The finer particles of QS and KO contribute to reducing pore connectivity and improving the bond between hydration products and aggregate surfaces. As the pore structure becomes more homogeneous, crack initiation and crack propagation within the cement matrix are reduced, leading to improved resistance against tensile and bending stresses (Rodrigues et al., 2020).

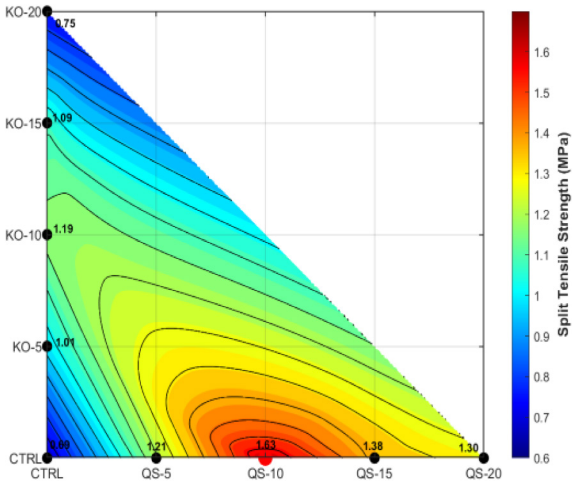

Figure 11. Splitting tensile strength

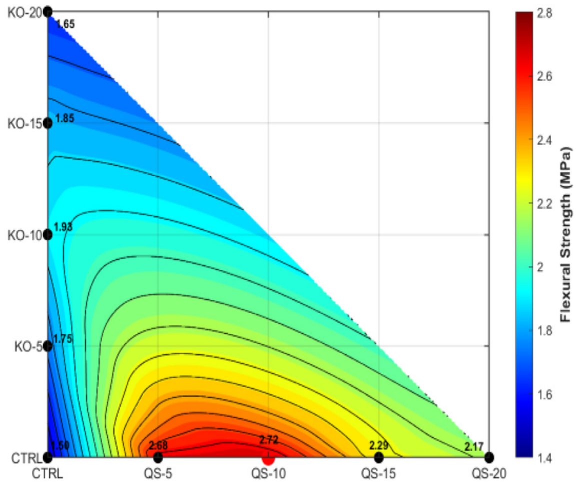

Figure 12. Flexural strength

In comparison with conventional SCMs, silica fume is generally recognized for providing superior tensile and flexural enhancement because of its ultrafine particle packing and high pozzolanic activity, whereas fly ash and GGBFS commonly improve long-term ductility and crack resistance. Nevertheless, the present results demonstrate that quartz sand-based SCMs can still produce meaningful improvements in mechanical performance, particularly through physical densification mechanisms that enhance matrix integrity and reduce microstructural defects (Ahmed, 2024; Raghav et al., 2021).

Microstructure analysis

Figure 13 presents the microstructural characteristics of foamed concrete without SCMs and with the incorporation of locally sourced SCMs from Aceh, based on Scanning Electron Microscopy (SEM) images. The analysis focuses on specimens exhibiting maximum mechanical performance at a 10% replacement level across three mix variations: foamed concrete without SCMs (FC non – SCM), foamed concrete with quartz sand (FC SCM-QS), and foamed concrete with kaolin (FC SCM-KO).

The microstructural evaluation emphasizes the distribution of air voids and coalesced pores, as well as the development of hydration products, particularly calcium silicate hydrate (C-S-H).

Figure 13 presents a comparative microstructural evaluation of foamed concrete at two magnification levels (50x and 500x) for three mix variations: without SCMs, with kaolin (KO), and with quartz sand (QS). The interpretation of each condition is described as follows – for foamed concrete without SCM incorporation (a and b), the distribution of air voids appears relatively large and non-uniform. Numerous interconnected pores (coalesced air voids) are observed, indicating bubble merging during the foaming process. The matrix structure is relatively loose, and at magnification (b), hydration products such as calcium silicate hydrate (C-S-H) are present but unevenly distributed and localized in limited regions. This condition reflects a highly porous microstructure with suboptimal bonding characteristics.

For the mixture containing kaolin (c and d), significant modifications in pore morphology are clearly observed. Although large air voids are still present, the degree of pore interconnectivity is reduced compared to the specimen without SCMs. At a magnification of 500x (d), the formation of calcium silicate hydrate (C-S-H) becomes more evident and partially fills the void spaces, indicating that kaolin acts as a pozzolanic material that enhances secondary hydration reaction. As a result, the matrix becomes denser and more homogeneous than that of the control mixture. The reduction in pore connectivity suggests that the pozzolanic reaction contributes to the refinement of the pore system by generating additional hydration products that occupy capillary voids. This phenomenon improves matrix continuity and enhances the mechanical interlocking between cementitious phases.

For foamed concrete incorporating quartz sand (e and f), the distribution of air voids appears finer and more uniformly dispersed, although some larger pores remain visible. The occurrence of coalesced air voids is still present but more controlled. At higher magnification (f),

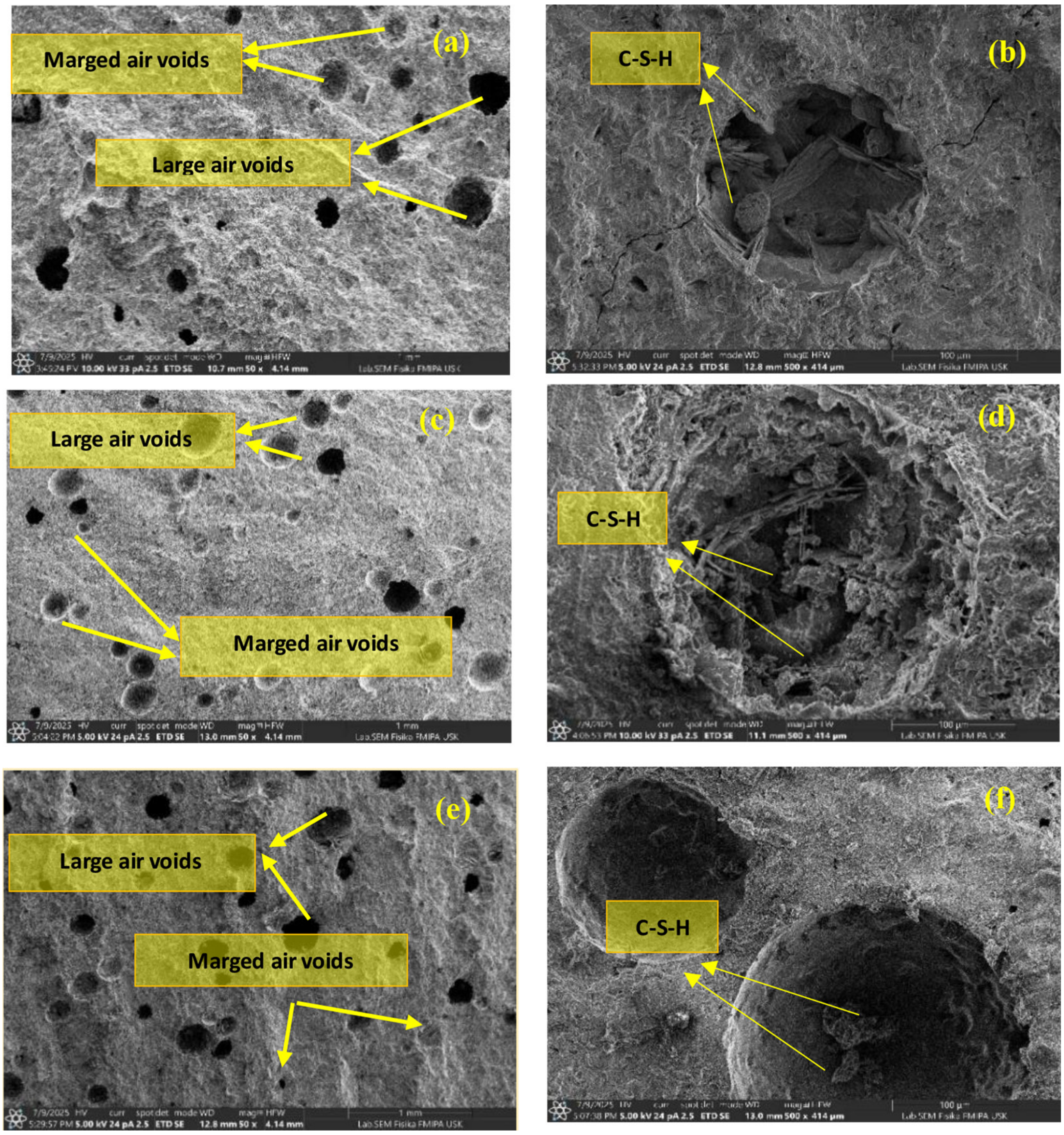

Figure 13. Microstructural image of foamed concrete: (a) FC non SCMs (50 x mag), (b) FC non SC(500 x mag), (c) FC SCMs-QS (50 x mag), (d) FC SCMs-QS (500 x mag), (e) FC SCMs-QS (50 x mag), (f) FC SCMs-QS (500 x mag)

the C-S-H structure appears more compact, contributing to improved matrix cohesion. Although relatively inert compared to kaolin, quartz sand functions effectively as a filler, promoting microstructural densification by reducing internal void spaces. The finer quartz particles improve particle packing density and reduce the formation of weak zones within the matrix. This densified microstructure is directly associated with the higher compressive, tensile, and flexural strengths observed in the QS mixtures (Mikhailenko and Sigaev, 2020).

Overall, the incorporation of SCMs, both kaolin and quartz sand, enhances the microstructural characteristics and the formation of additional calcium silicate hydrate (C-S-H), while quartz sand improves particle packing. The combined effects result in a denser structure, a more refined pore system, and a more homogeneous matrix compared to foamed concrete. These findings are consistent with the microstructural behavior commonly reported for other SCMs such as fly ash, silica fume, and GGBFS, where improvements in mechanical performance are primarily governed by pore refinement, matrix densification, and secondary hydration reactions (Ahmed, 2024). However, the present study demonstrates that locally sourced quartz sand and kaolin from Aceh can provide comparable microstructural benefits, indicating their potential as sustainable alternative SCMs in foamed concrete production.

CONCLUSIONS

Based on the results of this study on foamed concrete incorporating locally sourced mineral materials from Aceh, namely quartz sand and kaolin, it can be concluded that:

1. Local mineral materials from Aceh, namely quartz sand and kaolin, demonstrate strong potential as supplementary cementitious materials and can be utilized as an alternative binder component in foamed concrete.
2. Both materials contain constituents that support the formation of hydration products, particularly calcium silicate hydrate (C-S-H), thereby contributing to improved performance as SCMs in cementitious systems.
3. The use of quartz sand as an SCM at 10% replacement level has been shown to significantly enhance the properties of foamed concrete compared to both the control mixture incorporating kaolin, particularly increasing curing age (7, 28, and 56 days).
4. In particular, quartz sand demonstrates a more pronounced improvement in mechanical properties compared to foamed concrete without SCMs, and that incorporating kaolin, indicating its greater effectiveness in enhancing overall material performance.
5. Microstructural analysis using SEM indicates that the incorporation of quartz sand and kaolin improves the pore structure by reducing both pore size and quantity, resulting in a dense matrix.

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