*- Technical Paper -*

# COMPRESSIVE STRENGTH OF ALKALI-ACTIVATED MATERIAL USING SEWAGE SLUDGE ASH WITH SUPPLEMENTARY BINDERS

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## ABSTRACT

This study develops a mix design for alkali-activated material (AAM) using sewage sludge ash, GGBS, silica fume, and fly ash with (12M to 16 M) NaOH molarities. The 28-day compressive strength of 42.80 MPa was achieved with SSA-GGBS at 12M, while 36.68 MPa and 39.58 MPa were recorded with 14% SF at 12M and 10% FA at 14M, respectively. However, higher molarity and SSA replacement ratios negatively affected compressive strength. Furthermore, the hardening mechanism of AAMs in this study was assumed based on microstructure analysis.

Keywords: sodium hydroxide molarity, sewage sludge ash, GGBS, silica fume, fly ash

## 1. INTRODUCTION

Sewage sludge, a byproduct of wastewater treatment, is increasing due to urbanization, industrialization, and population growth. Its disposal through conventional methods such as landfilling and ocean dumping poses significant environmental challenges. Sewage sludge ash (SSA) can be used as a replacement for cement and aggregates in concrete, promoting recycling and reducing environmental impact. Conventional cement production is energy-intensive and a major source of $CO_2$ emissions. Geopolymers, utilizing aluminosilicate precursors like SSA, fly ash, and ground granulated blast furnace slag (GGBS), offer superior mechanical properties, enhanced durability, and a lower carbon footprint, providing a sustainable alternative for construction [1]. SSA contains high $SiO_2$, $Al_2O_3$, CaO and $P_2O_5$, which are essential for geopolymerization, forming durable binders via alkaline activation. Geopolymer use reduces $CO_2$ emissions, minimizes landfill waste, and supports circular economy practices, offering a technically viable and eco-friendly solution for construction [2], [3].

Several studies have investigated sewage sludge ash (SSA) as a sustainable option in geopolymer manufacture, specifically as a partial substitute for fly ash in geopolymer mortars. Sitarz et al. [4] investigated SSA-based mortars using a sodium silicate $SiO_2/Na_2O$ ratio of 1, with GGBS and fly ash as supplementary materials. They achieved compressive strengths at a mix of 50% SSA and 50% GGBS, effectively immobilizing heavy metals within safe limits.

Istuque et al.[5] investigated the effect of SSA on metakaolin-based geopolymers and showed that substituting 10％ by weight of metakaolin with SSA produced compressive strengths that were on part with the MK-only samples, reaching maximum strength. In addition, Zhao et al.[6] studied the influence of silica fume on one part GGBS-SSA-based geopolymers by using sodium metasilicate anhydrous. He observed that adding 10% silica fume reduced efflorescence, minimized Na+ discharge, and increased compressive strength. These findings show that SSA can be a valuable resource for sustainable geopolymers, enhancing waste management and contributing to environmentally friendly construction materials.

Either way, developing a mix design for alkali-activated material and geopolymer mortar is challenging due to the complex interplay of factors like binder type, chemical composition, activator ratios, molarities, curing conditions, and molar ratios ($SiO_2/Al_2O_3$, $Na_2O/SiO_2$, $H_2O/Na_2O$, $CaO/SiO_2$) in general. Optimizing these parameters to achieve target compressive strength while balancing fresh, hardened, and durability properties remains a significant difficulty. For a suitable mix design, selecting appropriate parameters is crucial as synthesizing activators like sodium hydroxide and sodium silicate involves high energy consumption and $CO_2$ emissions. While higher NaOH molarity enhances compressive strength by improving aluminosilicate dissolution and matrix density, excessive molarity negatively impacts workability, setting time, and strength due to excess $Na^+$ ions, reduced silica dissolution, and microstructural defects like porosity or crystalline phases. Optimizing NaOH molarity is key to achieving balance and maximizing performance [7]–[9].

This study investigates the behavior of SSA with supplementary binders (GGBS, SF, FA) under three NaOH molarities (12M, 14M, and 16M) and partial replacements SF, FA (10%, 14%, and 20%). The objective is to develop a rational mix design for SSA-

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GGBS-based geopolymers, evaluating the impact of these variables on compressive strength and their potential as sustainable construction materials.

## 2. TEST PROGRAM

### 2.1 Materials and Properties

This study synthesised the geopolymer binder using SF, FA, SSA, and GGBS. Table 1 shows the

Table 1 Chemical composition of different precursors

| Oxides (%) | $SiO_2$ | $Al_2O_3$ | CaO | $Fe_2O_3$ | $P_2O_5$ | $TiO_2$ | MnO | $K_2O$ | $SO_3$ |
|---|---|---|---|---|---|---|---|---|---|
| SSA | 37.32 | 12.74 | 10.01 | 16.74 | 15.72 | 1.14 | 0.28 | 1.89 | 0 |
| GGBS | 24.37 | 8.29 | 56.28 | 0.62 | 0 | 0.86 | 0.23 | 0 | 6.32 |
| SF | 95.38 | 0 | 1.84 | 0.61 | 0 | 0 | 0.26 | 0.16 | 0 |
| FA | 57.24 | 31.07 | 1.86 | 3.27 | 0.78 | 0.97 | 2.04 | 1.32 | 0.27 |

Table 2 Mix design of alkali-activated Geopolymer mortar

| Mix ID | Mix design | Binder | | | | Fine aggregate | AA | | Extra water |
|---|---|---|---|---|---|---|---|---|---|
| | | SF (kg/m$^3$) | FA (kg/m$^3$) | GGBS (kg/m$^3$) | SSA (kg/m$^3$) | NS (kg/m$^3$) | SH (kg/m$^3$) | SS (kg/m$^3$) | (kg/m$^3$) |
| C1 | 50%SSA50%GGBS-12M | 0 | 0 | 283 | 283 | 1132 | 97.03 | 242.57 | 136 |
| C2 | 50%SSA50%GGBS-14M | 0 | 0 | 283 | 283 | 1132 | 97.03 | 242.57 | 136 |
| C3 | 50%SSA50%GGBS-16M | 0 | 0 | 283 | 283 | 1132 | 97.03 | 242.57 | 136 |
| S1 | 45%SSA45%GGBS-10%SF-12M | 57 | 0 | 254 | 254 | 1132 | 97.03 | 242.57 | 136 |
| S2 | 45%SSA45%GGBS-10%SF-14M | 57 | 0 | 254 | 254 | 1132 | 97.03 | 242.57 | 136 |
| S3 | 45%SSA45%GGBS-10%SF-16M | 57 | 0 | 254 | 254 | 1132 | 97.03 | 242.57 | 136 |
| S4 | 43%SSA43%GGBS-14%SF-12M | 80 | 0 | 243 | 243 | 1132 | 97.03 | 242.57 | 136 |
| S5 | 43%SSA43%GGBS-14%SF-14M | 80 | 0 | 243 | 243 | 1132 | 97.03 | 242.57 | 136 |
| S6 | 43%SSA43%GGBS-14%SF-16M | 80 | 0 | 243 | 243 | 1132 | 97.03 | 242.57 | 136 |
| S7 | 40%SSA40%GGBS-20%SF-12M | 112 | 0 | 227 | 227 | 1132 | 97.03 | 242.57 | 136 |
| S8 | 40%SSA40%GGBS-20%SF-14M | 112 | 0 | 227 | 227 | 1132 | 97.03 | 242.57 | 136 |
| S9 | 40%SSA40%GGBS-20%SF-16M | 112 | 0 | 227 | 227 | 1132 | 97.03 | 242.57 | 136 |
| F1 | 45%SSA45%GGBS-10%FA-12M | 0 | 57 | 254 | 254 | 1132 | 97.03 | 242.57 | 136 |
| F2 | 45%SSA45%GGBS-10%FA-14M | 0 | 57 | 254 | 254 | 1132 | 97.03 | 242.57 | 136 |
| F3 | 45%SSA45%GGBS-10%FA-16M | 0 | 57 | 254 | 254 | 1132 | 97.03 | 242.57 | 136 |
| F4 | 43%SSA43%GGBS-14%FA-12M | 0 | 80 | 243 | 243 | 1132 | 97.03 | 242.57 | 136 |
| F5 | 43%SSA43%GGBS-14%FA-14M | 0 | 80 | 243 | 243 | 1132 | 97.03 | 242.57 | 136 |
| F6 | 43%SSA43%GGBS-14%FA-16M | 0 | 80 | 243 | 243 | 1132 | 97.03 | 242.57 | 136 |
| F7 | 40%SSA40%GGBS-20%FA-12M | 0 | 112 | 227 | 227 | 1132 | 97.03 | 242.57 | 136 |
| F8 | 40%SSA40%GGBS-20%FA-14M | 0 | 112 | 227 | 227 | 1132 | 97.03 | 242.57 | 136 |
| F9 | 40%SSA40%GGBS-20%FA-16M | 0 | 112 | 227 | 227 | 1132 | 97.03 | 242.57 | 136 |

chemical compositions of the precursors (SF, SSA, fly ash, and GGBS) as determined by X-ray fluorescence (XRF) testing. The alkaline activator is a combination of NaOH and $Na_2SiO_3$ solution. The activator solution is made from sodium hydroxide pellets (more than 93% purity), and the chemical composition of $Na_2SiO_3$ solution ($SiO_2$ 28.52%, Na2O 11.74%, and $H_2O$ 59.74%). The natural sand used as a fine aggregate for the mortar was well-graded, with a maximum particle size of 4.75 mm and a density of 2.59 g/cm³. The densities of SSA, GGBS, SF, FA, were 2.39 g/cm³, 2.88 g/cm³, 2.40 g/cm³, 2.37 g/cm³ respectively. But the density of alkaline solution of 12M,14M,16M and $Na_2SiO_3$ solution 1.36g/cm³,1.40g/cm³, 1.44g/cm³, and1.465 g/cm³ respectively.

## 2.2 Mix design and Binder preparation

The precursor materials were mixed with different weight ratios of FA and SF. Table 2 lists the ingredients and mixing ratios for the alkali-activated mortars and binders. The mixtures containing 0%, 5%, 10%, and 20% SF and FA by the weight of other SSA-GGBS precursors are denoted as (50% SSA, 50% GGBS) series C (C1-C3), while those with (10%, 14%, and 20%) SF and FA are labeled as (%SSA, %GGBS, %SF) series S (S1-S9) and (%SSA, %GGBS, %FA) series F (F1-F9), under (12M, 14M, and 16M) alkaline concentrations of NaOH respectively.

To achieve adequate workability and strength for all mixes, other parameters are the same in all mixes; sodium silicate (SS) to sodium hydroxide (SH) ratio 2.0.

## 2.3 Mixing, casting, molding, and curing

Geopolymer mortar preparation involves careful mixing, casting, molding, and curing to achieve optimal properties. Dry precursors (SSA, GGBS, SF, FA, and fine aggregate) are mixed for 3 minutes to ensure uniformity, followed by gradually adding an alkaline activator and further mixing for 2 minutes. The mixture is then placed into clean, dry plastic molds and compacted to remove air bubbles. Specimens are cured at room temperature for 48 hours and then stored in a controlled environment with a temperature 20°C andhumidity 60% for continued hardening. Curing times range from 7 to 28 days for strength development. Six cylindrical specimens (100 mm diameter, 200 mm height) are prepared for compressive strength testing.

## 3. RESULTS AND DISCUSSION

### 3.1 Compressive strength

Fig.1 and 2 illustrates the 7 days and 28 days compressive strength test results, respectively, showing the influence of NaOH molarity on the compressive strength of AAM containing varying proportions of SF and FA as partial replacements for SSA-GGBS binders under ambient curing conditions. In series C (SSA-GGBS), the maximum compressive strengths at 7 and 28 days, 40.59 MPa and 42.80 MPa, respectively, were achieved at 12M, with a gradual decrease in strength observed at higher molarities (14M and 16M). In series S (SSA-GGBS-SF), the maximum 7-day compressive strength of 30.57 MPa was recorded for the mix with 10% SF at 12M, while the highest 28-day strength of 36.68 MPa was achieved with 14% SF at the same molarity. A slight decline in compressive strength was observed at higher molarities. In series F (SSA-GGBS-FA), the mix with 20% FA achieved the highest 7-day strength of 29.05 MPa at 12M. In comparison, the mix with 10% FA reached the maximum 28-day compressive strength of 39.58 MPa at 14 M.

Compressive strength decreased at higher NaOH molarities in all series, which may be attributed to factors such as excess $Na^+$ ions. Other reasons for the decrease in compressive strength may include reduced dissolution of silica and alumina particles from the binder as NaOH molarity increases. The excessive congestion of hydroxide ions at higher molarities (more than 12M) can hinder effective geopolymerization, as investigated in previous literature, the influence of concentration of NaOH on fresh and compressive strength in FA-GGBS-based geopolymer mortar. Under ambient curing, higher GGBS content accelerates early strength development while enhancing 28-day strength due to its slower dissolution and delayed geopolymerization.

SF initially consumes activators, slowing early reactions and increasing porosity, but over time, it contributes to gel formation, densifying the material by 28 days. However, compressive strength decreases when SF percentages increase from 10% to 20% due to relatively low $Al_2O_3$ and CaO concentrations, reduced alkalinity, and excessive gel formation that can lead to microvoids or cracking. It may be due to binder chemical composition, sources, and fineness and also concentration of alkaline activator. To prevent excessive gel formation in geopolymers, it is crucial to regulate the molarity of the alkaline activator, the particulate size distribution, and the binder composition. In addition to lowering internal stresses and microvoid formation, balanced gel formation produces a more homogenous material and prevents it from cracking during curing and hardening.

FA promotes both early and long-term strength through its cohesive microstructure and long-term reactivity. However, excess FA reduces GGBS content, increases the extra water demand, and slows geopolymerization, which is also due to the presence of $P_2O_5$ in SSA, which hinders dissolution and gel formation, becoming a key reason for strength reduction.

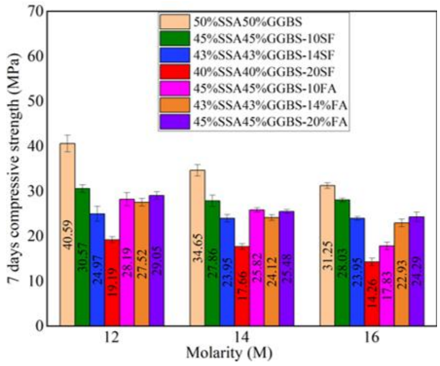

Fig. 1 7 days compressive strength at molarity

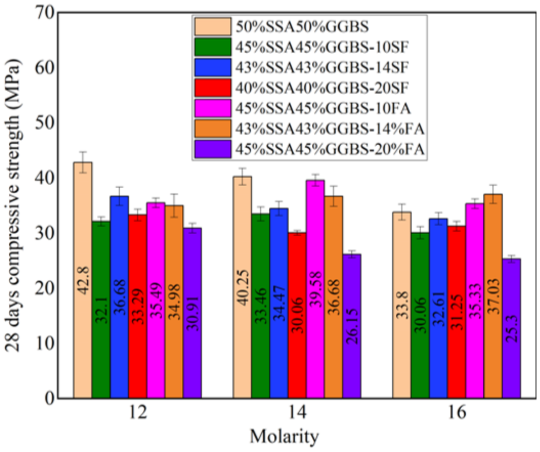

Fig. 2 28days compressive strength at molarity

### 3.2 Comparison of Molarity Effects on Compressive Strength

Fig.3 and 4 illustrate the influence of molarity on compressive strength, with 12M acting as the control. All mixtures exhibit considerable strength gains at 12M when compared to 16M. At 16M, compressive strength falls for most mixes, especially those with higher SF or FA content. This may be due to excess $Na^+$ ions interrupting geopolymerization. The formation of porosity is influenced not solely by the alkalinity molarity but also by the interactions with the binder composition, the fineness of precursors, and the water content. Unreacted particles and heterogeneous gel formation are the result of a low Si/Al ratio and a high CaO content, which increases porosity. To increase porosity, excess water generates capillary pores and rapid dissolution, and fast gelation contains unreacted particles and air, leading to increased porosity.

It is thought that the optimal molarity enhances aluminosilicate dissolutions, promoting strong gel formation, which causes strength improvement. However, in this study, the influence of molarity was investigated negatively. Still, in some previous studies, FA/GGBS-based geopolymer compressive strength decreased due to the chemical reactivity of aluminosilicate binder (Si/Al), fineness, and also source of binders. Higher alkaline activator molarity results in increased compressive strength for geopolymers because of increased chemical reactivity. The hardened material is enormously improved by the formation of strong gels such as N-A-S-H (low calcium) and C-A-S-H (high calcium) as a result of the increased dissolution of silica and alumina with higher molarity. Furthermore, increased molarity accelerates the geopolymerization process, resulting in faster dissolution, hardening, and homogeneous solidification. In this research, the rapid development of gels occurred at an early age using SSA-GGBS.

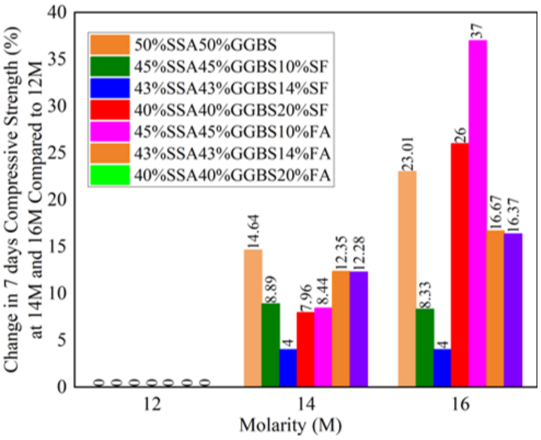

Fig. 3 Effect of molarity on strength (%)

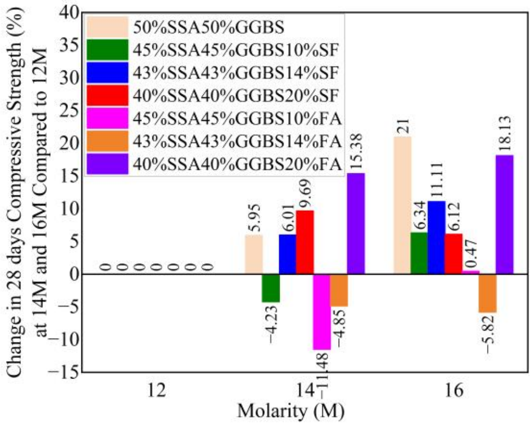

Fig. 4 Effect of molarity on strength (%)

### 3.3 Microstructure Analysis and Hardening Mechanism

SEM analysis shown in Fig.5 reveals the microstructural characteristics of AAM, focusing on gel formation, porosity, cracks, and unreacted precursors. In this study, SSA binder properties such as chemical composition, particle size, water absorption, and inclination temperature are important. The aluminosilicates ($SiO_2$ and $Al_2O_3$) dissolved in solution play a key role in the reactivity of SSA when mixed with GGBS and other additional binders like SF and FA, as well.

Due to its stability within the Si-Al framework, the N-A-S-H gel (low calcium, formed by SSA and FA) is more resistant to high temperatures as a result of the critical role played by these supplementary binders. However, the C-A-S-H gel (high calcium generated from GGBS) is prone to breakdown at lower temperatures, lowering thermal stability. Inclination temperature in geopolymers or their binders refers to the temperature range at which their pozzolanic activity increases, allowing them to maintain structural integrity and performance.

At 12M NaOH molarity, compressive strength is higher due to the better balance of optimal aluminosilicate dissolution, efficient N-A-S-H gel formation as compared to 14M and 16M. Because excessively high molarity can disrupt gel formation due to oversaturation of $Na^+$ ions, early precipitation of gels, and incomplete silica dissolution. According to previous studies, increased $Na_2O$ levels (more than 4%) and excess sodium silicate ($Na_2SiO_3$) can hinder geopolymerization by reducing air release and water evaporation, negatively impacting gel formation and compressive strength [10].

The inclusion of C-S-H and C-A-S-H gels enhances microstructure and mechanical properties. Still, excess calcium from GGBS can interfere with N-A-S-H polymerization by disrupting Si-O-Al and Si-O-Si bonds, leading to weaker C-S-H gels. Geopolymerization efficiency is influenced by precursor properties such as particle size, Si/Ca composition, and reactivity. Si- and Ca-rich materials require moderate alkalinity, while Si- and Al-rich materials need higher alkalinity.

Precursor characteristics, including particle size, chemical composition, $SiO_2/CaO$ ratio, $SiO_2/Al_2O_3$ ratio, and $Na_2O/SiO_2$, significantly influence the geopolymerization process. Binders that contain high Si and Ca require moderate alkalinity, while Si and Al-rich materials need higher alkalinity[11]. According to the previous study, the dissolution of FA accelerates the release of silicate and aluminate species, increasing the polymerization rate and improving gel production [12]. However, excessive reactivity of GGBS under high alkalinity can lead to calcium leaching, reducing compressive strength. These findings highlight the need to balance molarity and precursor composition to optimize geopolymer performance [13].

To improve the dissolution of SF, FA, SSA, and GGBS in alkaline environments, optimize the alkaline activator composition by balancing NaOH and $Na_2SiO_3$ ratios, and use mechanical or thermal pre-treatment to promote reactivity. The reaction kinetics and polymer formation are enhanced by the combination of highly reactive binders, such as FA or GGBS, with less reactive binders, like SF and SSA, and elevated curing temperatures (60–90°C). Calcium sources, such as $Ca(OH)_2$, improve matrix stability by producing C-S-H gels. Optimized mix design with water-to-binder and $SiO_2/Na_2O$ ratios reduces porosity and leaching. Together, these techniques increase the reactivity of all binders, resulting in better geopolymer performance and durability. Increasing GGBS content in a geopolymer made from sewage sludge ash (SSA) and phosphorus pentoxide ($P_2O_5$) enhances reactivity due to its calcium-rich properties, which help control the extra water demand absorbed by SSA. However, increasing the alkaline molarity from 12M to 16M reduces compressive strength, as higher alkalinity causes excessive dissolution of aluminosilicate materials, leading to excess gel formation and weaker bonding. Therefore, optimal alkaline molarity is crucial for achieving the best geopolymer mortar mix design performance, which is suitable for practical application in different environments.

In this study, GGBS increases the reactivity of SSA aluminosilicates because of the extra water used by GGBS reactive materials containing high CaO content. But SSA contains $P_2O_5$, which increases the demand for additional water, so its reactivity gel formation and solidification are very low with a low FA binder.

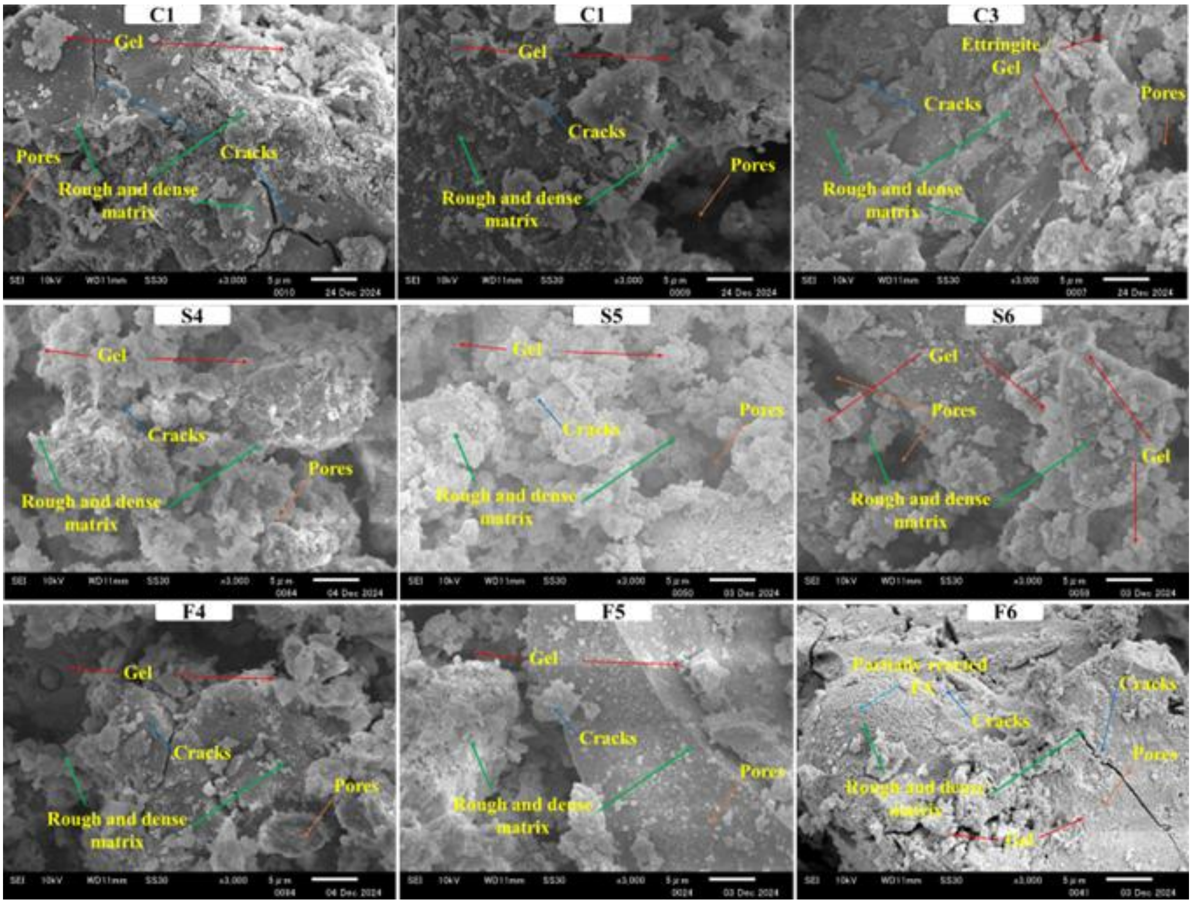

Fig. 5 SEM of SSA-GGBS AAM, control mix, 14%SF,14%FA at 12M to 16M NaOH.

## 4. CONCLUSIONS

This study proposed a twenty-one mix design for AAM using SSA to examine the effects of NaOH molarity, binder types, and ratios on compressive strength. Based on the experiment results, the following conclusions are drawn:

(1) The highest 28-day compressive strength of 42.80 MPa was achieved with SSA-GGBS at 12M NaOH, while 36.68 MPa and 39.58 MPa were obtained with 14% SF at 12M and 10% FA at 14M, respectively.
(2) An increase of NaOH molarity from 12M to 16M reduced compressive strength, probably due to excess $Na^+$ ions and incomplete aluminosilicate dissolution.
(3) SF replacement caused slower reactivity and delayed strength development in the presence of SSA, which demands more extra water. At the same time, FA demonstrated improved long-term reactivity and a denser microstructure.
(4) GGBS played a critical role in early strength gain, but excessive calcium reactivity at high alkalinity led to calcium leaching, reducing overall strength.

These findings highlight the importance of optimizing NaOH molarity and binder ratios, confirming SSA-GGBS mortars as a sustainable alternative for eco-friendly construction.

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