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Research Article

Enhanced Durability and Strength of Interlocking Geopolymer Mud Blocks Incorporating Industrial By-products for Sustainable Construction

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ABSTRACT

Geopolymers have drawn much interest in sustainable building because of their exceptional mechanical strength, longevity, chemical resistance, and less environmental impact. Using less mortar and requiring less labour, Interlocking Pressed Earth Stabilized Blocks (IPESB) provide increased structural integrity, quicker construction, and cost savings. This research investigates the creation of Interlocking Geopolymer Mud Blocks (IGMB) using fly ash, ground granulated blast furnace slag (GGBS), M-sand and red soil as essential components. The investigation of IGMB's characteristics included its mechanical and thermal aspects alongside microstructural and physical properties because it incorporated local aluminosilicate sources (ASS) and alkaline-activated materials (AAM) with fly ash and GGBS to substantially boost strength levels. The material received its characterization through Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and Transmission Electron Microscopy (TEM). Research indicates IGMB showed superior results against traditional IPESB through its remarkable 5–6 multiple enhancement which delivered excellent compressive strength of 48.45 N/mm². The strength performance of IGMB was enhanced when AAM solution concentration increased from 8M to 12M showing promise for long-term earthquake protection of this potential building material. Research indicates that IGMB serves as a promising eco-friendly alternative to traditional masonry units, offering both enduring structural stability and environmental benefits.

Keywords: Geopolymer; Interlocking Geopolymer Mud Blocks (IGMB); Mechanical strength; Alkali-Activated materials (AAM); Sustainable construction; Structural integrity.

1. INTRODUCTION

Geopolymers have developed as a sustainable option in construction industry owing to their superior strength, durability, and low environmental effect. IPESB improves structural stability and cost efficiency through the reduction of mortar usage and labor demands. This research investigates the advancement of IGMB through the utilization of industrial by-products to enhance mechanical performance and long-term durability (Preethi and Venkatarama, 2020). Local natural soil combined with stabilizers allows the creation of blocks through manual or semi-automated production methods. (Saidi et al. 2018). Common stabilizers include cement and lime, which are cost-effective and enhance the quality of the indoor environment (Assi *et al.* 2018). Production of cement leads to substantial environmental problems because greenhouse gas emissions remain high when considering the annual worldwide concrete output at 10 billion tons (Khale and Chaudhary, 2007). Geopolymerization is when aluminosilicate sources react with alkali activators, forming an alkali-activated structure. This process requires silica- and aluminium-rich materials, including industrial byproducts like fly ash, red mud, metakaolin, GGBS, and rice husk ash (Davidovits, 1989; 2008). The reaction involves polycondensation with alkali activators such as NaOH or KOH combined with Na_2SiO_3 or K_2SiO_3 (Preethi and Venkatarama, 2020). Experimental studies have assessed the strength of IGMB, evaluating the impact of fly ash, GGBS, alkali concentration, and clay content. Results indicate that kaolinite-rich natural soils lack sufficient compressive strength, but adding fly ash and GGBS enhances it. GGBS provides more strength than fly ash, and increasing alkali solution molarity from 8M to 12M improves strength by 30–50%. However, using soil with more than 30% clay at 12M NaOH results in a lumpy mixture, affecting compaction.

Aluminosilicate sources (ASS) play a crucial role in manufacturing geopolymers, ceramics, and refractory materials due to their thermal stability and mechanical strength. They are key raw materials in zeolite synthesis with catalysis, adsorption, and ion exchange applications. ASS also supports sustainable construction by producing eco-friendly binders that reduce cement dependency and carbon emissions. The range of applications for high-temperature processes includes furnace linings along with insulation which leads to enhanced energy efficiency and longevity. These materials serve environmental remediation because they enable wastewater treatment and heavy metal adsorption purposes. (Abhilash *et al*. 2021). Several studies have been carried out based on the IGMB. Here an attempt had been made by adding ASS and AAM in Mud blocks.

New research about Interlocking Concrete Block Paving (ICBP) proves the benefits of waste materials from industrial and agricultural sources because they boost structural qualities and longevity while supporting sustainability initiatives (Bilir *et al*. 2022). The research team continues to face difficulties in creating a uniform surface layer because they require enhanced analytical tools consisting of finite element modelling together with modified slab analysis *(Mohd et al*. 2022). The strength and durability and chemical resistance capabilities of geopolymer concrete equal those of traditional Portland cement (OPC) therefore making it an acceptable alternative to OPC in rigid pavement applications. Additional research goals exist to improve workability alongside setting time and performance stability when implementing the material within pavement structures. Recent advancements in geopolymer-based hybrid materials highlight their potential as protective coatings and structural consolidates in construction and cultural heritage preservation. Their performance factors include substrate properties, alkaline activator dosage, and curing conditions (Giacobello *et al.* 2022).

Kandasamy and Priya (2023) examined how moulding moisture content influences the compressive strength of unstabilized compressed earth blocks, emphasizing its role in optimizing construction quality. They critically analyze stabilized mud blocks by discussing their benefits in sustainable construction and material efficiency.

Vivek and Mangai (2023) evaluated various mix proportion amounts to determine their effectiveness in geopolymer interlocking blocks production. The 14 M sodium hydroxide solution was prepared through sodium hydroxide flakes dissolution in water with 24 hours of resting time before its application. The ratio for mixing sodium hydroxide with sodium silicate solution used a sodium silicate quantity that was 2.5 times greater than the sodium hydroxide amount. The mixture required a material-to-fluid ratio of 6.5 for achieving ideal workability together with strength characteristics. Each block had a total weight of 10.35 kg so the fluid content amounted to 1.576 kg. The specified ratio between sodium hydroxide and sodium silicate allowed researchers to calculate needed solution amounts at 0.45 kg and 1.126 kg.

Nagajothi *et al*. (2022) explored geopolymer concrete, which is formed through the polycondensation of aluminosilicate materials with alkaline activators. Their research highlighted its superior durability and mechanical properties compared to conventional concrete while contributing to lower CO_2 emissions. Additionally, geopolymer concrete exhibited enhanced resistance to acid attacks, sulfate exposure, and water absorption, reinforcing its potential as a sustainable alternative for construction.

A comprehensive review of Geopolymer Mud Blocks (GMB), focusing on their composition, structural properties, and environmental impact has been done to explore the material qualities, longevity, and environmental advantages of GMB. They critically examine them and highlight the importance of GMB in sustainable building. These blocks minimize environmental problems through their implementation of industrial by-products as well as local materials for waste reduction along with resource efficiency. GMB construction blocks require additional attention because of inconsistent raw materials use and expensive alkaline activators and limited technological recognition. The successful deployment of GMB needs focused scientific investigations together with production process innovations as well as enhanced recognition from both the public sector and industries. The solution of these challenges will help GMB achieve its complete potential for building a sustainable resilient built environment (Kandasamy and Ramesh, 2025).

Table 1. Physical properties of materials

S. No.	Physical properties	Red soil	GGBS	Flyash
1	Specific gravity	2.56	2.95	2.19
2	Liquid limit	30.86	-	-
3	Plastic limit	18.49	-	-
4	Shrinkage limit	16.15	-	-
5	BET surface area ($\frac{m2}{g}$)	34.27	0.51	0.35
6	Lime reactivity (Mpa)	1.82	9.49	2.74

There is still a need to optimize IGMB utilizing industrial by-products to improve sustainability and durability, despite a wealth of research on stabilized mud blocks and geopolymer concrete. Few studies have examined the impacts of ASS and AAM in IGMB; most have concentrated on geopolymerization and the function of alkali activators. Furthermore, little attention has been paid to how different clay contents and alkali concentrations affect workability and mechanical qualities. Although previous research has shown the advantages of geopolymer concrete for pavement and construction applications, achieving a uniform and compact IGMB structure is still tricky. By using industrial waste materials, the current work seeks to close this gap and enhance IGMB performance while lessening its environmental effect. This study aims to improve IGMB's compressive strength, durability, and shrinkage resistance by combining ASS and AAM, supporting environmentally friendly and sustainable building practices.

2. EXPERIMENTAL METHODS

2.1 Material

Natural Redsoil (RS), M-Sand (MS), GGBS, and Flyash (FA) with Sodium hydroxide (NaOH) and Sodium silicate (Na_2SiO_3) in the ratio of 1:1.5. The molarity of the solution is 8 Molar. Different properties of materials tested during this research project can be found in Table 1.

The specific gravity for the RS and MS was determined using pycnometer apparatus. The soil's chemical composition and Atterberg's limitations are provided in Table 1. The red soil had a liquid limit of 30.86%, a plastic limit of 18.49%, and a shrinkage limit of 16.15%. The red soil had a specific gravity of 2.56 and a lime reactivity of 1.82 MPa. The Msand's chemical composition and Atterberg's limitations are provided in Table 1. Laboratory grade NaoH and Na_2SiO_3 were used as the AAS in this experimental investigation with 98% purity. As per the standard calculations, AAM was prepared by mixing NaoH and Na_2SiO_3 in the ratio of 1:1.5. The molarity used in this study is 8 molars. The AAM was utilized after 1 day of its preparation since the reaction is exothermic.

Table 2. Details of mixed proportions

Mix	RS	Msand	Flyash	GGBS	AAM (Geopolymer materials) 8M
Mix 1	60	20	15	5	-
Mix 2	57	20	15	5	3
Mix 3	56	20	15	5	4
Mix 4	55	20	15	5	5
Mix 5	54	20	15	5	6

2.2 Characterization of Materials

Analyses of elemental composition and microstructure for RS, MS and FA used SEM. The model used for determining SEM was JSM-IT800, JEOL, Tokyo, Japan. Energy-dispersive X-ray spectroscopy (EDX) is used to find the elemental composition of raw materials. The photographs were acquired under operational conditions of 25 kilovolts (kV). The morphological analysis of RS, MS and FA was conducted through HR-TEM using JEOL JEM-2100. The FT-IR spectra received analysis through the combination of Everest Diamond ATR accessory operated with Thermo Scientific Nicolet Summit FTIR Spectrometer.

2.3 Method of Making IGMB

Table 2 shows the procedure for making the GMBs: The red soil is ball-milled for 15-20 minutes to remove soil lumps. Then, it was sieved using the 4.75mm sieve to remove the stone and gravel particles. Then, the batching process was performed based on the standard calculations. Utilizing a pan mixer ensured a consistent mixture of the ingredients. Mixing the RS, MS and GGBS in dry conditions for 5 minutes resulted in a uniform mix. Subsequently, the necessary alkaline solution, such as NaOH and Na_2SiO_3 in the ratio of 1:1.5, which was prepared 24 hours before, was mixed with the uniform mix done previously. The laboratory maintained the dry density value of compressed earth bricks at 1.8 g/cc. Operation control by mass measurement directed the processed mix to enter the machine mould (Al-Jabri *et al.* 2021; Kasinikota and Tripura, 2022). Automatic brick casting took place through the operation of the interlocking brick-making machine. The machine pushed out the brick from compaction after which it rested on the platform. The specimens began air curing on the fifth day after their 24-hour casting period. Here is a visual of the IGMB in Figure 1, Figure 2 and Figure 3 showing the Fabrication of different blocks in different proportions.

Fig. 1: IGMB kept for ambient curing

2.4 Size and Weight of the Block

Each of the blocks utilized in this research weighs 14.5 kg and measures 292.1 mm length, 203.2 mm width, and 127 mm height. The blocks' composition changes according to the mix proportions, including RS, flyash, GGBS, m-sand, and AAM in geopolymer formulations. AAM content rises from 0% to 6% in the five mixtures examined in an 8M alkaline environment, whereas RS concentration gradually decreases from 60% in Mix 1 to 54% in Mix 5. While the different quantities of AAM affect the overall geopolymer properties, the consistent presence of Msand (20%), fly ash (15%), and GGBS (5%) in all blends guarantees consistency.

Fig. 2: IGMB kept for ambient curing

Fig. 3: IGMB ejected from the machine

3. RESULTS AND DISCUSSIONS

3.1 Water Absorption Test

The water absorption test performed per IGMB methods provides data about how much water blocks absorb while submerged in water. The water absorption evaluation uses the procedures described in ASTM C642 together with IS 3495 (Part 2):1992. A selection of IGMB blocks from each mixture will receive oven drying at 105–110°C for a period of 24 hours. The testing period ends when all samples reach room temperature allowing you to record their weights as W_1 (oven-dry weight). Soak the dried blocks under 27 ± 2°C water for a period of 24 hours. Take away the blocks before carefully removing excess water with a damp cloth at the surface. A scale should be used to determine the weight of blocks immersed in water for 24 hours (W_2 = wet weight after 24 hours). The procedure to evaluate water absorption depends on the following mathematical equation. The analysis confirmed through Table 3 and Figure 4 that mix 5 exhibits the lowest water absorption level *(Teixeira et al*. 2020).

$$\text{Water Absorption} = (W_2 - W_1) / W_1 \times 100$$

W_1 = Dry weight of the block in grams
W_2 = Wet weight of the block in grams

Table 3. Water absorption test

Mix	Initial weight	Final weight	Water Absorption %
Mix 1	14.40	16.49	14.5
Mix 2	14.30	15.58	8.98
Mix 3	14.25	15.33	7.58
Mix 4	14.35	15.39	7.26
Mix 5	14.90	15.97	7.1

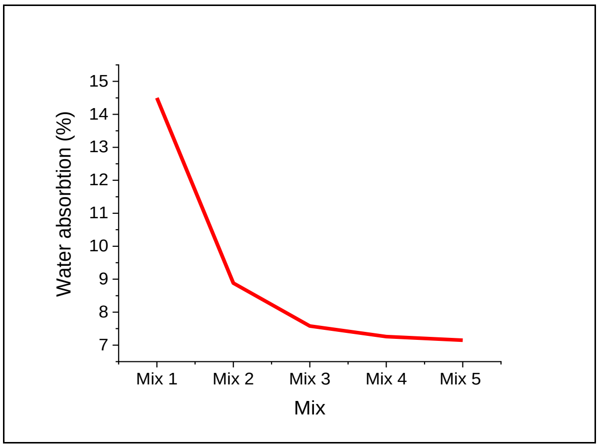

Fig. 4: Water absorption

Table 4. Compressive strength of individual IGMB

Mix	Compressive strength @ 7 days (MPa)	Compressive strength @ 14 days (MPa)	Compressive strength @ 28 days (MPa)
Mix 1	7.3	10.56	14.56
Mix 2	10.5	14.33	19.75
Mix 3	19.56	23.67	28.9
Mix 4	23.20	29.78	35.78
Mix 5	31.45	38.78	48.45

3.2 Compressive Strength of Individual IGMB

The compressive strength of various IGMB mixtures at 7, 14, and 28 days is shown in Table 4. The findings demonstrate a steady rise in strength over time, suggesting enhanced geopolymerization and curing. At 28 days, mix 5 reached 48.45 MPa, the maximum strength, while Mix 1 showed the lowest. According to the statistics, improving the mix proportions or adding more stabilizers improves IGMB's mechanical performance (Vignesh *et al*. 2020). Figure 5 shows the compressive strength analysis test equipment.

Fig. 5: Compressive strength analysis test

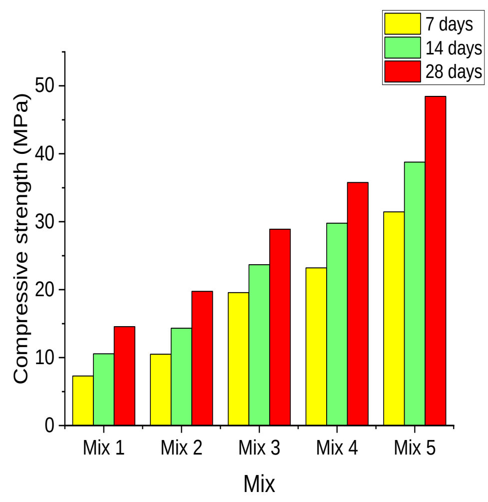

Fig. 6: Compressive Strength test results

The test results for IGMB compressive strength during 7 days, 14 days and 28 days appear in Figure 6. All compressive strength measurements demonstrate that Mix 5 achieves the maximum strength values at each curing stage. Every bar in the red series displays greater strength after 28 days of curing. This demonstrates substantial strength development during extended curing times. The result shows that mixed design effectively boosts the mechanical characteristics of IGMB.

Table 5. Compressive strength of IGMB prism

Mix	Compressive strength (Mpa)		
	7 days	14 days	28 days
Mix 1	8.15	11.67	12.90
Mix 2	10.67	12.5	15.55
Mix 3	13.18	15.12	18.24
Mix 4	15.31	18.13	23.23
Mix 5	16.46	25.88	35.52

3.3 Compressive Strength of IGMB Prism

The compressive strength of IGMB prisms at 7, 14, and 28 days is shown in Table 5, demonstrating a steady rise over time. Mix 5 had the most potent strength, measuring 35.52 MPa after 28 days, whereas Mix 1 had the lowest. The findings suggest that strength is improved by optimized mix designs or increased stabilizer content. The findings show that IGMB prisms have the potential to be used in structural applications with increased endurance (Manjunath *et al*. 2021). Figure 7 shows the compressive strength analysis test equipment.

Figure 8 presents the compressive strength test results for IGMB prisms at 7, 14, and 28 days. The graph indicates a consistent increase in compressive strength over time, with Mix 5 showing the highest strength across all curing periods. The 28-day strength (brown bars) is significantly higher, demonstrating the enhanced durability of Mix 5. This trend confirms the effectiveness of different mix compositions in improving structural performance.

Fig. 7: Compressive strength test for IGBM prism

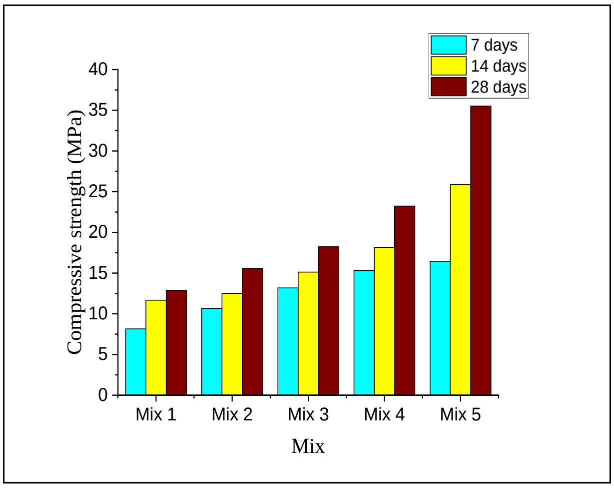

Fig. 8: Compressive strength test for IGBM Prism results

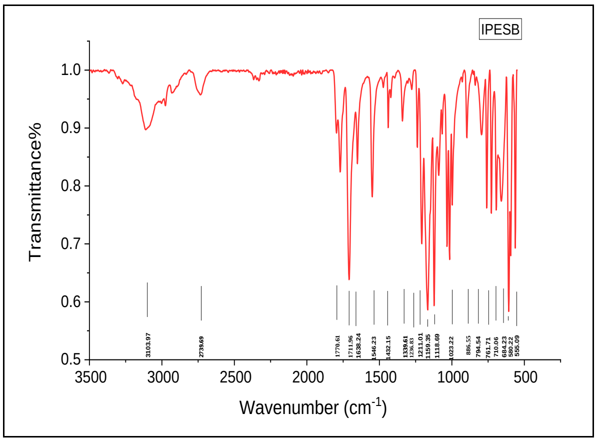

Fig. 9: FTIR analysis

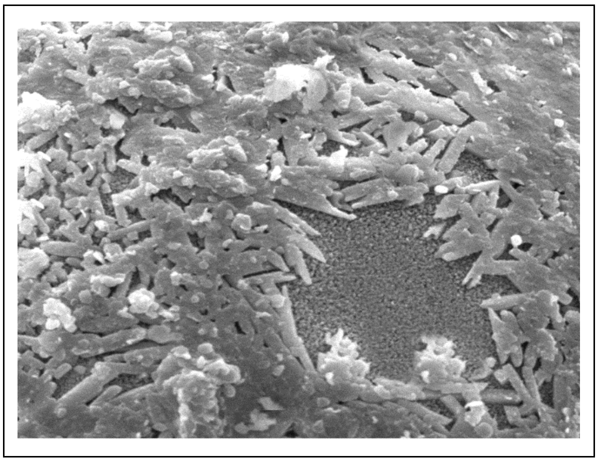

Fig. 10: SEM analysis of mix 1

3.4 FTIR Analysis

IPESB's FTIR spectrum displays distinctive absorption bands representing various functional groups. O-H stretching is seen in the wide band between 3000 and 3500 cm^{-1}, suggesting hydroxyl groups or moisture. Aluminosilicate structures are confirmed by the 1000–1200 cm^{-1} range peaks, which are linked to Si–O–Si and Si–O–Al stretching vibrations. Sharp peaks below 800 cm^{-1} indicate metal-oxygen linkages, which suggest the existence of clay minerals or geopolymeric phases.

3.5 SEM Analysis

The SEM image (Figure 10) of the first proportion (Mix 1), which consists of 60% Red Soil, 20% M-sand, 15% Fly Ash, and 5% GGBS without AAM, reveals a loosely packed microstructure with visible porosity. The absence of an alkaline activator results in poor bonding between particles, leading to a weak matrix with significant voids. The unreacted fly ash and GGBS particles are dispersed without effective gel formation, indicating limited geopolymerization. This suggests that without AAM, the material lacks strength and durability compared to other mixes with activators (Rivera *et al.* 2020).

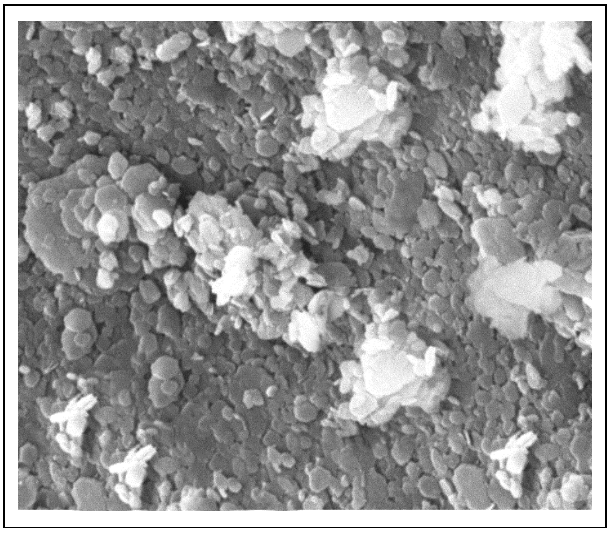

Fig. 11. SEM analysis of mix 3

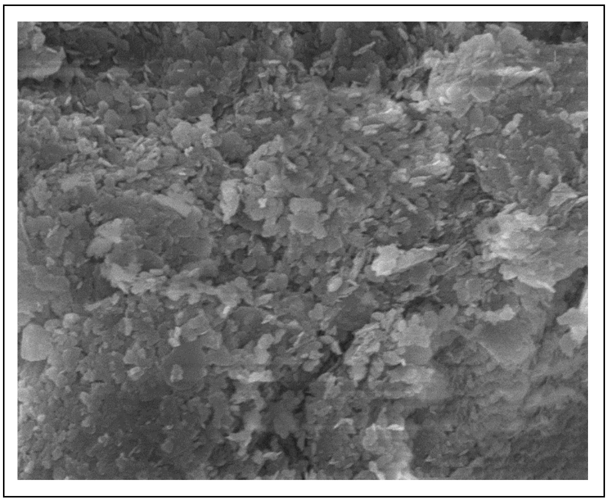

Fig. 12: SEM analysis of Mix 5

The SEM image (Figure 11) of Mix 3 (56% Red Soil, 20% M-sand, 15% Fly Ash, 5% GGBS, and 4% AAM) reveals moderate geopolymerization with visible unreacted particles. The surface appears relatively rough with dispersed white patches, indicating partial formation of geopolymeric gel. Some microvoids are present, suggesting that the alkaline activator concentration is not optimal for full densification. However, compared to lower AAM mixes, the bonding between particles improves, contributing to better structural integrity and strength development (Muñoz *et al.* 2015).

SEM microstructure analysis of Mix 5 shows a tighter and denser structure than AAM amounts below 6% where Mix 5 contains 54% Red Soil, 20% M-sand, 15% Fly Ash, 5% GGBS and 6% AAM. Enhanced particle bonding occurs due to the elevated amount of alkaline activator which produces well-formed geopolymeric gel in the image. An improved density rate leads to better material strength and durability which provides environmental resistance for the material. Effective geopolymerization processes can be validated by observing the uniform matrix structure which counts toward substantial improvements in interlocking block stability (Ahmad *et al.* 2022).

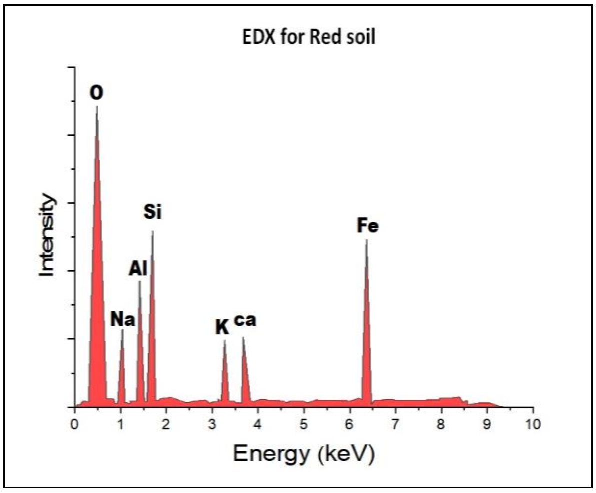

Fig. 13: EDX analysis of red soil

3.6 EDX Analysis

The spectroscopic (EDX) analysis of red soil elemental composition utilizes Dispersive Energy X-ray to provide results. Possible spectrum peaks indicate elemental compounds that include oxygen (O) alongside iron (Fe) and silicon (Si) and aluminium (Al) when oxides exist within the sample. High levels of iron in the soil cause its crimson color. Soil mineral composition evaluation helps researchers understand whether the geological material would be suitable for geopolymer applications.

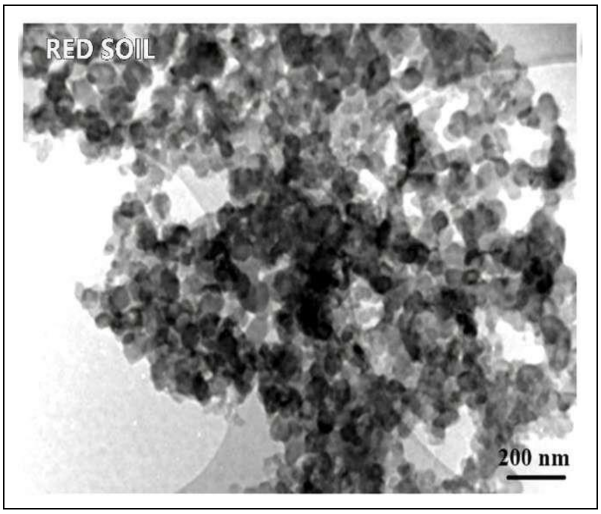

Fig. 14: TEM analysis of RED soil

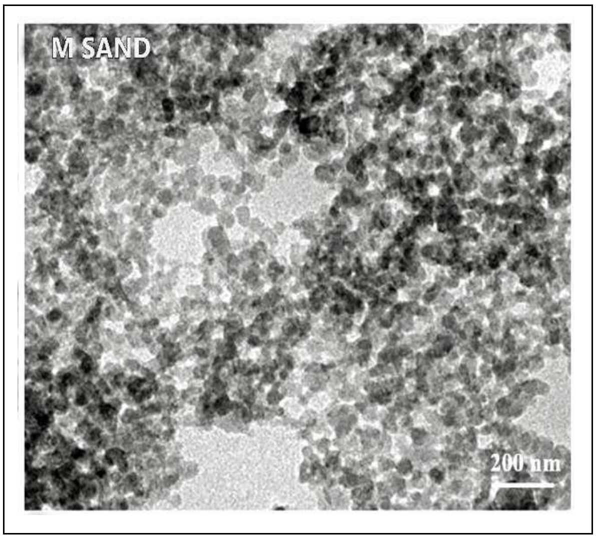

Fig. 15: TEM analysis of M sand

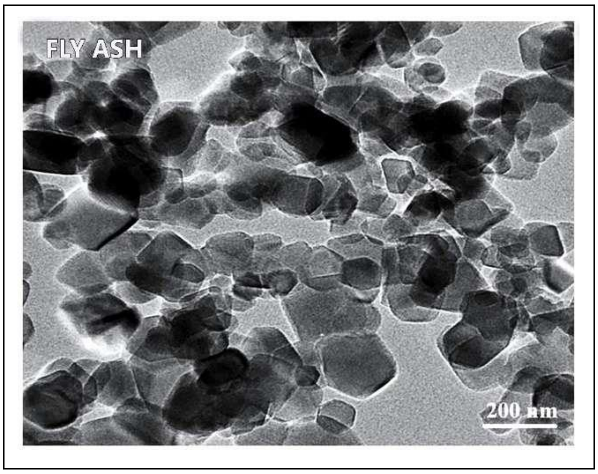

Fig. 16: TEM analysis of Flyash

3.7 TEM Analysis

Transmission Electron Microscopy (TEM) research of red soil shows nanoscale features in Figure 14. The network of small particles in the image demonstrates extensive surface area together with likely pore space. The distribution pattern among the particle points to clay mineral existence that modifies soil reactivity while affecting its stabilization potential. Understanding the nanostructured character of the material remains vital for achieving knowledge about its role in the geopolymerization process.

The TEM analysis in Figure 15 displays m -sand with fine particles dispersed irregularly while exhibiting a large surface area. The nanoscale structure indicates m-sand could improve bonding strength of geopolymer systems (Murthy and Pandurangan, 2019).

Figure 16 shows the TEM analysis of fly ash, revealing its spherical and irregular-shaped particles with a smooth texture. The fine particle size and morphology enhance its pozzolanic reactivity in geopolymer applications.

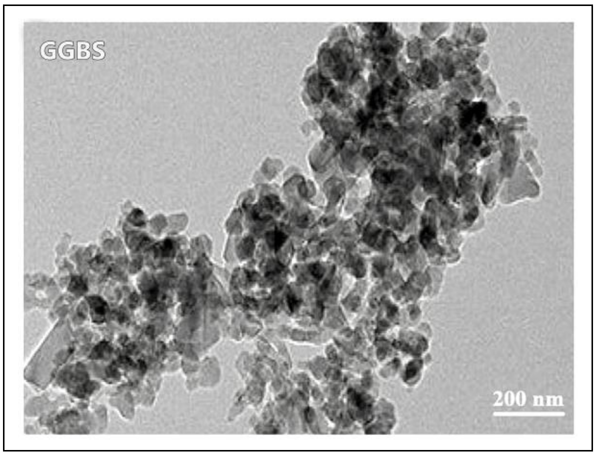

Fig. 17: TEM analysis of GGPS

Figure 17 presents the TEM analysis of GGPS, showing agglomerated Nano-sized particles with irregular morphology. The structure suggests a high surface area, which may enhance its reactivity in geopolymer applications(Oti, Kinuthia, and Bai 2009).

4. CONCLUSION

Adding an alkaline activator (AAM) significantly improves the material's microstructure by enhancing the geopolymerization process, leading to better bonding between particles and reduced porosity. Increasing the percentage of AAM results in higher compressive strength, with Mix 5 (6% AAM) achieving the highest strength (48.45 MPa at 28 days), demonstrating the positive impact of alkali activation. SEM analysis reveals that Mix 1 (without AAM) has a loosely packed structure with voids. At the same time, Mix 5 exhibits a denser, well-compacted matrix, confirming the effectiveness of alkaline activation in improving material properties. The presence of silicon (Si) and aluminum (Al) in red soil, fly ash, and M-sand contributes to the formation of geopolymeric gel, enhancing the overall durability and mechanical performance of the interlocking bricks. Higher alkaline activation levels lead to a reduction in microvoids, indicating improved densification and reduced permeability, which enhances the material's resistance to water absorption and environmental degradation (Alexandra *et al.* 2020).

Among all the tested mixes, Mix 5 (54% RS, 20% MS, 15% FA, 5% GGBS, and 6% AAM) exhibited the best combination of compressive strength and microstructural integrity, making it the most suitable for structural applications. The utilization of industrial byproducts such as fly ash and GGBS, combined with geopolymerization, reduces the reliance on cement-based binders, making the IGMB a more sustainable and eco-friendly construction material (Belayali *et al.* 2022).

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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