Influence of Metakaolin and Glass Fiber on the Properties of Sustainable Geopolymer Bricks

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Abstract. The demand for sustainable and eco-friendly construction materials has led to interest in geopolymer bricks as an alternative to conventional clay bricks. This current study investigates the impact of metakaolin and glass fibre on the compressive strength, water absorption, microstructural behaviour, and EDX analysis of geopolymer bricks manufactured from red soil. Various mixtures were prepared, and partially replaced red soil with metakaolin from 10% to 50%, followed by the addition of glass fibre at varying percentages from 0% to 3 %. The compressive strength of the geopolymer bricks was evaluated after 7 and 14 days of curing, and the findings showed a considerable increase in strength. Water absorption tests show a clear reduction in porosity as Metakaolin concentration increased, and this notes the even greater improvement due to the addition of glass fibre. SEM and EDX tests clearly demonstrated a deeper and more compact microstructure in the optimum mix. The SEM analysis showed very few apparent cracks and reduced porosity. The EDX analysis showed the presence of essential components in the geopolymer brick. The results show that the presence of Metakaolin with glass fibre improves the compressive strength, durability, and water absorption of geopolymer bricks, which shows a promising material for sustainable construction applications.

1 Introduction

The increasing demand for sustainable construction materials has sparked prevalent interest in geopolymer bricks, which provide an environmentally friendly alternative to typical cement-based products. This study looks into the possibility of improving the characteristics of geopolymer bricks by using Metakaolin as a partial replacement for red soil and glass fibre as a reinforcing material. Metakaolin is a pozzolanic substance that enhances the chemical bonding and strength of the geopolymer matrix, whilst glass fibre is

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known for reducing cracking, improving mechanical qualities, and increasing durability. Combining these elements is to improve the performance of geopolymer bricks and contribute to the creation of long-lasting, high-strength construction materials that are also energy efficient and environmentally benign.

This paper aims to stabilize the compressed earth brick (CEB) using an alkali-activated binder for supporting sustainable construction. To create the third stabilizer, flyash and sodium hydroxide (NaOH) are combined. In order to achieve an acceptable CEB that complied with the compressive strength and water absorption, the project team used soil that was close to the project site. To reduce the construction industry's carbon footprint, sustainable construction methods include using alternative building materials and their components.[1]. In addition to give solution by an alternative to burnt clay bricks, acid and sulfate-resistant bricks and stabilized mud blocks, this combination increases the strength and durability of the brick. This mixture increases compressive by 5.94 MPa and flexural strength by 3.44 MPa [2]. The impact of polypropylene fibers improves the strength, ductility and deformability of CEBs and this would overcome the shortcomings of earthen building materials [3-4]. This study focused on the manufacturing of compressed stabilised earth blocks with lime stabilization for soil with low contents of clay and silt [5-6]. With and without stabilisers, the purpose of this work is to examine the design of clay matrices with the best granulometry for usage in compressed earth blocks [7]. Previous studies have focused on fly ash as the base material and examined the influence of different binding materials, curing methods, and alkaline activator solutions on strength development, demonstrating its potential as an alternative to conventional fired clay bricks. [8]. The mix enhances the compressive strength (upto 75 MPa), more stable microstructure low demand for energy [9]. Investigated the mix combined with ferrochromium slag, zeolite, the mechanical strength where higher 7 MPa compared to conventional brick, thermal conductivity to sample decreases 42.3% [10]. The mix combined with red mud (iron oxide) and fly ash, NaOH concentration improvement in setting, compressive strength etc. Paving bricks using 10% to20% red mud has increased mechanical strength [11]. Investigated the mix design with clay, fly ash, alkaline activator solution avoids the microwave caused by very high temperature and also increases compressive strength [12]. This effective technique enhances potential and has little negative economic effects while being feasible for the recycling and valorization processes. It is a substitute material for making geopolymer [13]. Given that the procedure doesn't require high temperatures like traditional brickmaking does, the microstructure and phase composition of copper mine bricks made of geopolymer are very significant and have positive environmental effects [14]. That mix design with metakaolin traces increasing setting and mechanical properties of geopolymer with long term indicator of geopolymer performance [15].

2 Materials Used

2.1 Locally available soil

The test soil was collected from a nearby location that was easy to access during the field visit (Fig.1). Basic tests, such as hand pressure, smell, plasticity, and cohesion, were carried out to check whether the soil is suitable for making geopolymer earth bricks. The top layer of soil is removed because of containing impurities and organic matter. 0.45 m below the depth of the soil is taken out for testing. The collected sample was then examined to understand the properties presented in Table 1 and to confirm whether it can be replaced with river sand and combined with geopolymer mix production as per IS 2720 part5.

Fig. 1. Removal of the top soil layer

Table 1. Soil test characteristics

Soil Properties	Results
Gravity Specific	2.56
Dispersion of grain size	
Sand	57.7%
Clay	14.3%
Silt	27.9%
Liquid limit	32.6%
Plastic limit	25%
Natural moisture content(w)	2.36%
Compaction characteristics	
Maximum dry density (γdmax)	1.66 g/cm^3
Optimum moisture content	10%

2.2 Metakaolin

Metakaolin is obtained from the mineral kaolinite, which is naturally available and commonly used in many construction applications, especially in cement-based materials (Fig. 2). It is prepared by heating kaolin clay at temperatures between 600°C and 800°C. When kaolinite is heated within this range, it changes into an amorphous form with good pozzolanic properties. If the temperature goes too high, the material starts to sinter and forms a non-reactive phase containing mullite and poorly developed Al–Si spinel.

To get the best pozzolanic performance, the calcination temperature has to be controlled carefully. Although activation can happen anywhere between 550°C and 850°C, the most effective range is generally considered tobe 650°C to 750°C. Kaolinite is preferred for producing reactive pozzolans because it has a wider temperature range between its dehydroxylation and recrystallization stages compared to many other clay minerals. Also, unlike T-O-T clays such as smectite, the structure of kaolinite exposes its octahedral layer directly to the interlayer space, which makes it easier for the structure to break down when heated.

Fig. 2. Metakaolin

2.3 Alkaline liquid

Sodium silicate solution is readily available and was directly used in the experimental work. NaOH flakes were purchased locally and dissolved in water to prepare the required alkaline solution. For the study, sodium hydroxide solutions at 6M, 8M, and 10M were prepared to examine their effect on the mix performance. Sodium-based activator solutions are preferred because they provide good results at a lower cost when compared to calcium-based systems. The chemical reaction involved in geopolymerization is given in Equation 1. The chemical composition of the sodium silicate is presented in Table 2.

$$Al_2O_3 + SiO_2 + NaOH + Na_2SiO_3 \rightarrow Na_2O \cdot Al_2O_3 \cdot SiO_2 \cdot H_2O \quad (1)$$

Table 2. The chemical makeup of sodium silicate

Constituents	Measurement (%)
Na2O	25.86
SiO2	34.54
H2O	39.6

2.4 Glass fiber

The properties of glass fiber (Fig. 3) are given in Table 3. Glass is a non-crystalline substance having a short-range network structure, and the materials that are created from its very fine fibers are known as glass fibers.

Table 3. Properties of glass fiber

Properties	Results
Length	12 mm
Diameter	11 to 13 µm..
Specific gravity	2.68
Colour	sandal or white

Fig. 3. Glass fiber

3 Methodology

The manufacture of geopolymer bricks involved varying the percentage replacement of red soil with metakaolin at levels of 10%, 20%, 30%, 40%, and 50% to identify the optimum mix based on mechanical and physical performance. Once the optimum metakaolin content was determined, glass fiber was added to the mix in incremental percentages of 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% to further enhance the properties of the bricks. The ingredients, including alkaline activator solution (a combination of sodium hydroxide and sodium silicate), red soil, and metakaolin, were thoroughly mixed, and the composite mix was molded into standard brick dimensions. These molded bricks were then cured under ambient or thermal conditions as per standard practices, and subsequently tested for various properties to determine the best-performing mix. The microstructural behavior has been examined for geopolymer bricks. The mix ratios for geopolymer bricks are presented in Table 4, and the mix ratios of fiber-reinforced geopolymer bricks are given in Table 5.

Table 4. Mix ratios for geopolymer bricks

Name of Mix	Red soil	Metakaolin
SM0	100%	0%
SM1	90%	10%
SM2	80%	20%
SM3	70%	30%
SM4	60%	40%
SM5	50%	50%

Table 5. Mix ratios of fiber reinforced geopolymer bricks

Name of Mix	Red soil	Metakaolin	Glass Fiber
SMF1	70%	30%	0
SMF2	70%	30%	0.5%
SMF3	70%	30%	1%
SMF4	70%	30%	1.5%
SMF5	70%	30%	2%
SMF6	70%	30%	2.5%
SMF7	70%	30%	3%

4 Casting of Specimens

The raw materials, such as red soil, metakaolin, and the alkaline activator solution prepared using sodium hydroxide and sodium silicate, were mixed thoroughly to obtain a uniform geopolymer paste. . Fig. 4 presents the casting and testing of specimens. This paste was then placed into standard brick moulds of size 19 cm × 9 cm × 9 cm and compacted evenly. For every mix, three brick samples were cast. The moulded bricks were kept for ambient curing as per the standard procedure.

Fig. 4. Casting and testing of specimens

5 Results and Discussion

5.1 Sieve analysis test for red soil

Dry sieve analysis was adopted because the soil had low clay content and negligible cohesion, making dry sieving appropriate (Fig. 5). Sieve analysis test for red soil was performed to determine the particle size distribution of the soil sample using a standard set of sieves. A total of 1000 grams of soil was taken and passed through the sieves ranging from 4.75 mm to 75 µm. The results showed that 29.45% was retained on the 150 µm sieve, which indicates that a major portion of the soil consists of fine sand. The cumulative percentage retained increased steadily as the sieves became finer, reaching 100% at the pan. The percentage finer calculated by subtracting the cumulative retention from 100 showed that 79.57% of the soil particles are finer than 1.18 mm. The fineness modulus of the sample was calculated as 4.65, placing the soil in the medium sand category. This indicates that the soil is suitable for common construction uses such as concrete and mortar production.

Fig. 5. Sieve analysis test for red soil

Table 6. Sieve analysis test for red soil

S.No	Sieve size	Soil Weight Retained (gm)	% Weight retained in each sieve (%)	Cumulative % weight retained in each sieve	% Finer
1	4.75mm	1.4	0.14	0.14	99.86
2	2.36mm	9.7	0.97	1.11	98.89
3	1.18mm	193.2	19.32	20.43	79.57
4	600µm	169.3	16.93	37.36	62.64
5	425mm	141.3	14.13	51.49	48.51
6	300µm	129.4	12.94	64.43	35.57
7	150µm	294.5	29.45	93.88	6.12
8	75µm	30.8	3.08	96.96	3.04
9	Pan	30.4	3.04	100	0
	Total	1000		465.8	
Finess Modulus = 465.8/100 = 4.65					

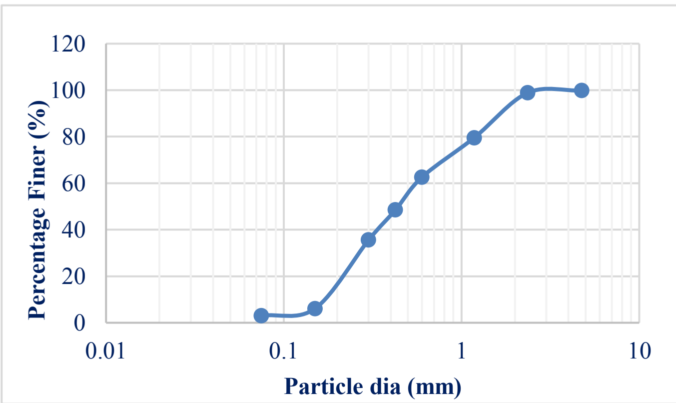

Fig. 6. Gradation curve for red soil

5.2 Proctor Compaction Test

Compaction test presented in Table 7 and corresponding chart in Fig. 8. The soil was compacted in three layers within the standard Proctor mould using a standard rammer, and the dry density was determined at different moisture contents. As the moisture content increased, the dry density of the red soil increased and reached a maximum value, then decreased, forming the typical compaction curve. From the test results, the dry density increased from 1.00 g/cc at 8% moisture content to a maximum of 1.66 g/cc at 10% moisture content. Beyond this point, the dry density gradually reduced with further increase in moisture content. This clearly shows that the soil attains its Maximum dry density (MDD) of 1.66 g/cc at an optimum moisture content (OMC) of 10%. Up to the OMC, the added water helps by lubricating the soil particles, enabling them to rearrange and pack more closely during compaction. When the moisture content exceeds the OMC, additional water occupies the voids between particles, reducing the achievable dry density. Identifying the MDD and OMC is important for field compaction control because it ensures that the soil is compacted to its best possible density.

Fig. 7. Proctor compaction test for red soil

Table 7. Proctor compaction test results for red soil

S.No	Description	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
1.	Weight of mould+ compacted wet soil W2 (gm)	7490	7540	7520	7480	7410
2.	Weight of compacted wet soil W=W2-W1 in (gm)	1810	1840	1800	1780	1750
3.	Wet density of soil (g/cm^3)	1.81	1.83	1.80	1.78	1.75
4.	Moisture content (%)	8	10	12	14	16
5.	Dry density (g/cm^3)	1.00	1.66	1.60	1.56	1.50

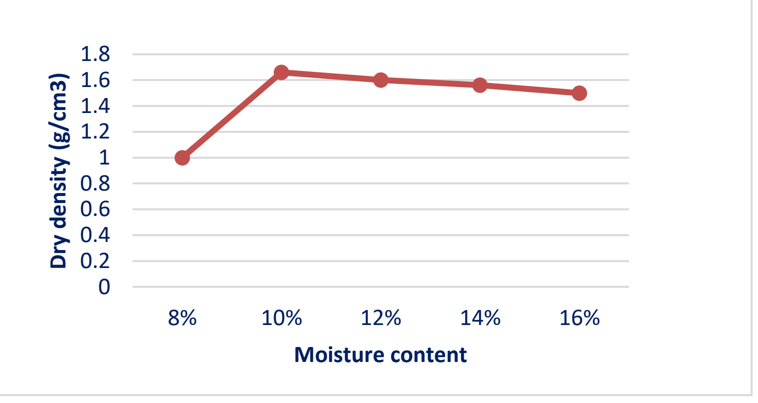

Fig. 8. Dry density of red soil

5.3 Compressive Strength of Geopolymer Bricks

The compressive strength test results of the geopolymer bricks determined in accordance with IS 3495 (Part 1): 1992 are shown in Table 8, which presents the performance of bricks produced using red soil partially replaced with different proportions of Metakaolin. Strength increases steadily as the percentage of metakaolin increases. 30% Metakaolin provides the most effective improvement in strength. Table 10 gives the compressive strength values for bricks prepared with the optimum 30% Metakaolin content and further modified with glass fibres ranging from 0% to 3%. The addition of glass fibre showed a marginal increase in strength, with the best performance recorded at 2%. The corresponding graphs are shown in Figures 9 and 10.

The reference mix SM0, containing no Metakaolin, achieved strengths of 7.1 N/mm² at 7 days and 7.3 N/mm² at 14 days. In SM1, there was a slight reduction at 7 days but a small improvement at 14 days, indicating slower early strength gain in the concrete. As the Metakaolin content increased, the strengths also increased, SM3 recording the highest values of 8.1 N/mm² at 7 days and 8.6 N/mm² at 14 days. The strength increases up to 30 % of metakaolin due to enhanced geopolymer gel formation and improved bonding. Beyond this level, excessive formation leads to reduced workability and incomplete geopolymerization, causing a slight drop in strength at SM4. The marginal increase at SM5 is attributed to improved filler effects but remains lower than the optimum SM3 mix. From the results, it was confirmed that the effectiveness of Metakaolin enhances the structural performance of geopolymer bricks.

The strength results of bricks containing glass fibre show clear variations at both 7 and 14 days. The control mix with 0% fibre recorded strengths of 8.1 N/mm² at 7 days and 8.7 N/mm² at 14 days. When 0.5% glass fibre was added, the 7-day strength increased slightly to 8.3 N/mm², while the 14-day value showed a small reduction to 8.6 N/mm². As the fibre content increased, minor fluctuations were observed. The highest 7-day strength of 8.4 N/mm² occurred at 2% fibre content, with the 14-day strength reduced to 8.7 N/mm². SMF 5 having optimum value, SMF 6 slightly decreased, and SMF 7 showed improved strength. This behavior is attributed to fiber dispersion and fiber–matrix interaction. At low to moderate fiber contents (up to 2%), fibers help control microcracks and improve stress transfer. At higher fiber contents, fiber agglomeration and poor dispersion reduce matrix continuity, leading to minor strength reduction. This suggests 2% glass fibre helps improve early strength by controlling microcracks and enhancing bonding. However, increasing the fibre content to 2.5% and 3% did not yield further benefits and instead caused slight reductions in strength. While the compressive strength improvement is marginal, glass fibers primarily help in crack control, toughness, and durability, which are important for handling, transportation, and service life.

Table 8. Strength of geopolymer bricks

S.No	Name of Mix	Compressive Strength (MPa)	
		7 Days	14 Days
1.	SM0	7.1	7.3
2.	SM1	6.9	7.2
3.	SM2	7.2	7.9
4.	SM3	8.1	8.6
5.	SM4	7.9	8.1
6.	SM5	8.0	8.3

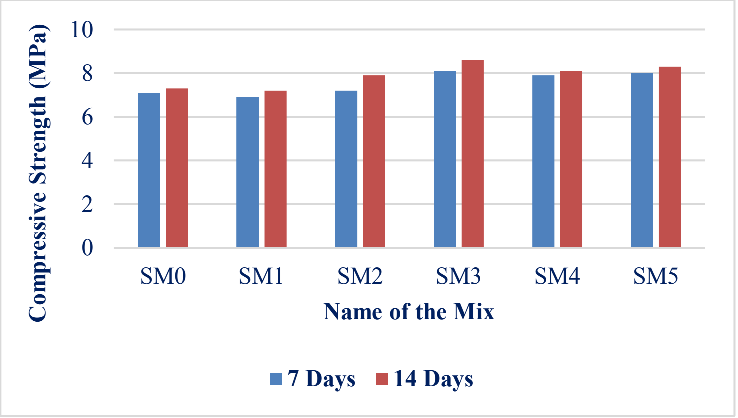

Fig. 9. Characteristic strength of geopolymer bricks

Table 9. Strength of geopolymer bricks with glass fiber

S.No	Name of Mix	Compressive Strength (MPa)	
		7 Days	14 Days
1.	SMF1	8.1	8.7
2.	SMF2	8.3	8.6
3.	SMF3	8.2	8.4
4.	SMF4	8.1	8.5
5.	SMF5	8.4	8.7
6.	SMF6	8.0	8.4
7.	SMF7	8.1	8.6

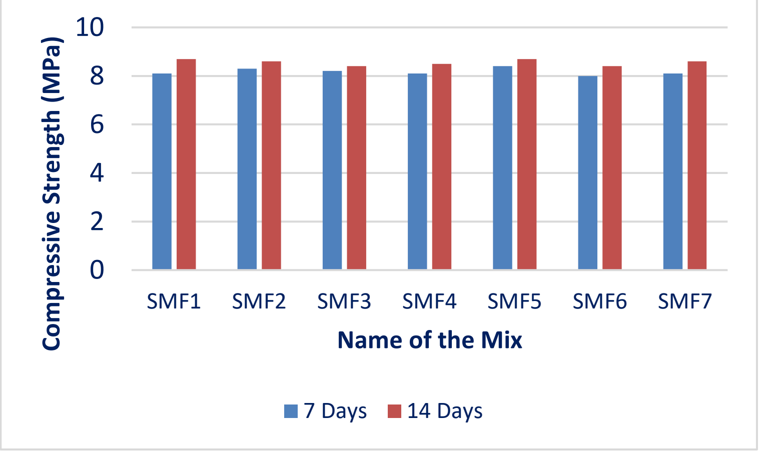

Fig. 10. Strength of geopolymer bricks with glass fiber

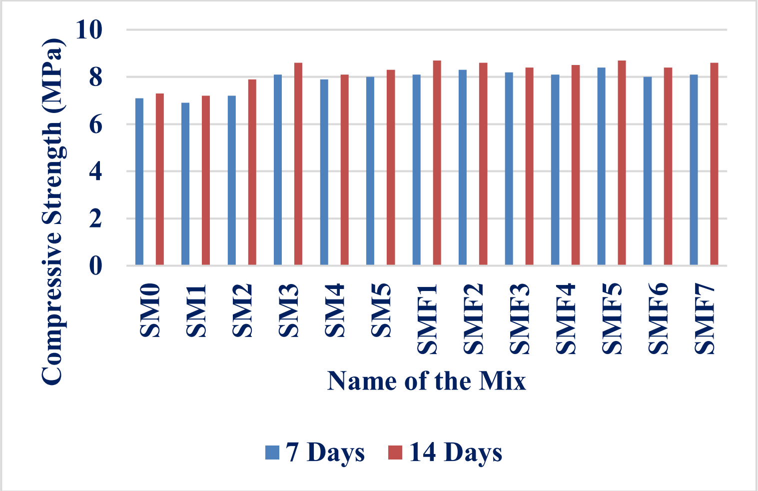

Fig.11. Comparison of geopolymer bricks and geopolymer bricks with glass fiber

5.4 Water Absorption Test of Geopolymer Bricks

The water absorption test results for the geopolymer bricks are presented in Table 10, showing the effect of replacing soil with various percentages of metakaolin and the graphical representation is given in Fig. 12 and Fig. 13. The results clearly demonstrate that absorption decreases when the percentage of metakaolin increases. The control mix SM0 recorded the highest absorption values of 12.02% at 7 days and 11.05% at 14 days, showing higher porosity. The mix containing 30% Metakaolin showed the lowest absorption values of 6.5% at 7 days and 6.16% at 14 days, indicating better resistance to water penetration. When the metakaolin content in 40 % and 50 %, a slight increase in water absorption was noted, which may be due to reduced compactness or minor inconsistencies in the matrix.

Table 11 summarizes the water absorption behaviour of geopolymer bricks containing various percentages of glass fibre, with tests conducted at both 7 and 14 days. The comparison of geopolymer bricks and geopolymer bricks with glass fiber is presented in Fig. 14. A constant steady reduction in water absorption is observed as the fibre content increased up to 2%. The mix without any glass fibre showed relatively 11.69 % higher water absorption at 7 days and 10.95% at 14 days. With the addition of glass fibre, water absorption gradually decreased, reaching the lowest levels of 8.5% at 7 days and 6.9% at 14 days for the mix with 2% glass fibre. These results suggest that 2% glass fibre provides the most effective improvement in water resistance by lowering porosity.

Table 10. Absorption test of geopolymer bricks

S.No	Name of The Mix	Water Absorption (%)	
		7 Days	14 Days
1.	SM0	12.02	11.05
2.	SM1	11.13	10.33
3.	SM2	8.56	7.33
4.	SM3	6.5	6.16
5.	SM4	6.9	6.5
6.	SM5	7.12	6.66

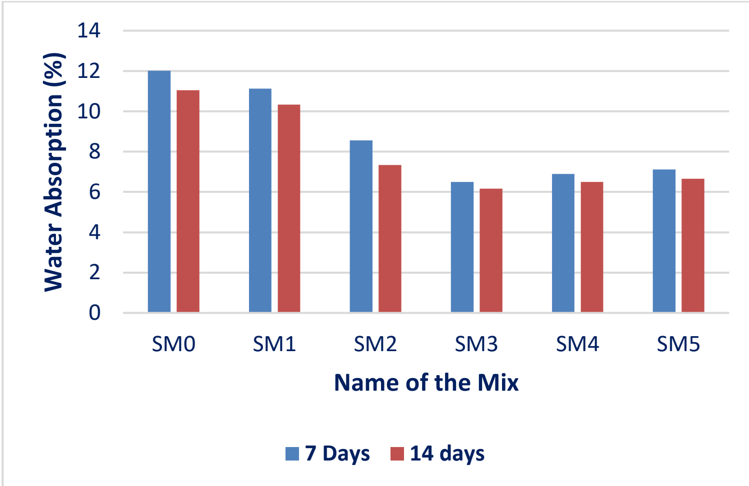

Fig. 12. Water absorption of geopolymer bricks

Table 11. Absorption of geopolymer bricks with glass fiber

S.No	Name of The Mix	Water Absorption (%)	
		7 Days	14 Days
1.	SMF1	11.69	10.95
2.	SMF2	10.88	9.6
3.	SMF3	9.65	8.26
4.	SMF4	9.1	7.5
5.	SMF5	8.5	6.9
6.	SMF6	8.9	7.23
7.	SMF7	9.23	7.75

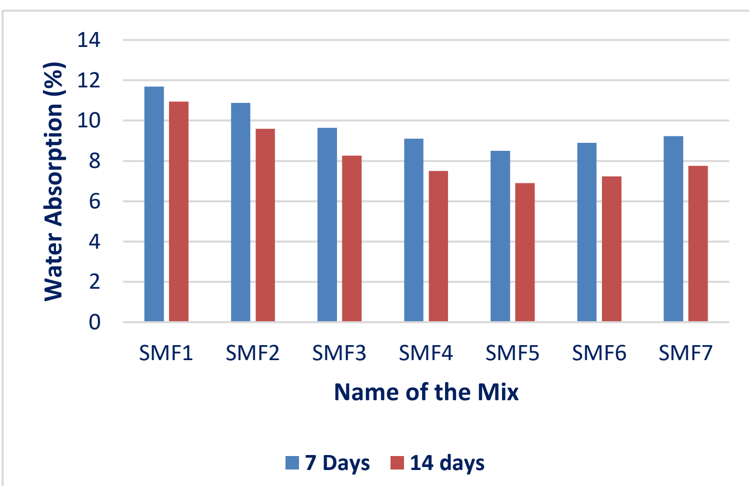

Fig. 13. Absorption of geopolymer bricks with glass fiber

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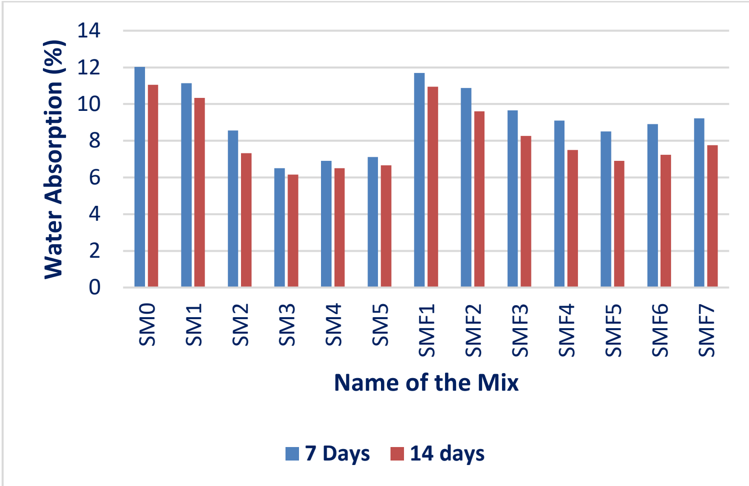

Fig. 14. Comparison of geopolymer bricks and geopolymer bricks with glass fiber

5.5 SEM and EDX Analysis

Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy were performed to study the microstructural and elemental characteristics of the geopolymer bricks. Fig. 15 shows SEM morphology and EDX analysis of red brick clay material, and Fig. 16 shows the EDX spectrum showing the elemental composition of the geopolymer brick of SM3. The SEM images showed that the mix containing 30% Metakaolin and 2% glass fibre developed a much denser and more compact matrix compared to the control mix. This image shows fewer pores and microcracks, which indicates improved bonding and reduced porosity due to the result of the pozzolanic reaction and the reinforcing effect of the fibres. This shows the improved compressive strength and lower water absorption for this geopolymer mix. Fig. 17 to Fig. 20 show the SEM image of various mix ratios. The presence of key elements such as Silicon-Si, aluminium- AI, and oxygen-O identified in the EDX results supports the SEM results. These key elements are the primary constituents of the geopolymer gel, N-A-S-H. The EDX results further detect the few amounts of calcium which suggests the possible formation of secondary binding that contributes to the additional strength. From these SEM and EDX results, SMF5 shows a significant improvement in the microstructure and performance.

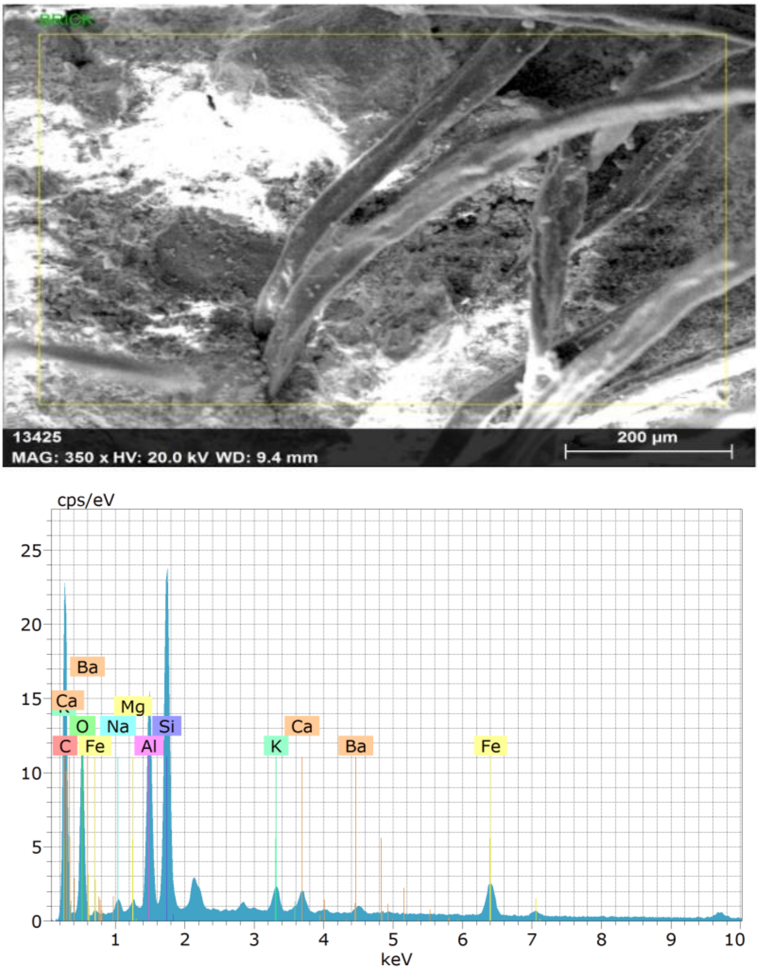

Fig. 15. SEM morphology and EDX analysis of red brick clay material

Spectrum: BRICK

Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (3 Sigma) [wt.%]
Carbon	K-series	19.75	53.03	65.30	7.50
Oxygen	K-series	10.65	28.61	26.44	4.29
Aluminium	K-series	1.74	4.67	2.56	0.33
Silicon	K-series	2.55	6.84	3.60	0.41
Potassium	K-series	0.14	0.36	0.14	0.09
Calcium	K-series	0.15	0.41	0.15	0.09
Iron	K-series	1.71	4.60	1.22	0.23
Sodium	K-series	0.21	0.56	0.36	0.12
Magnesium	K-series	0.10	0.26	0.16	0.10
Barium	L-series	0.25	0.66	0.07	0.11
	Total:	37.24	100.00	100.00	

Fig. 16. EDX spectrum showing elemental composition of geopolymer brick -SM3

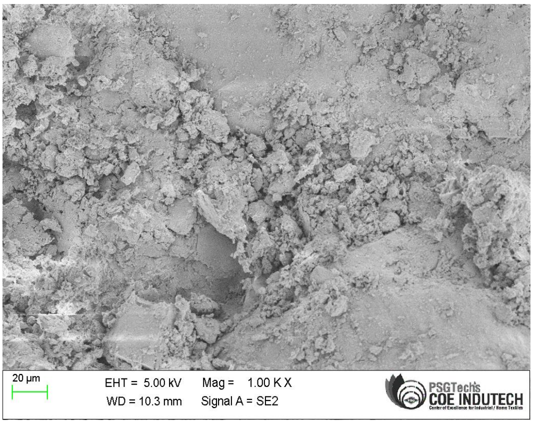

Fig. 17. SEM image for SMF1

Fig. 18. SEM image for SMF2

Fig. 19. SEM image for SMF3

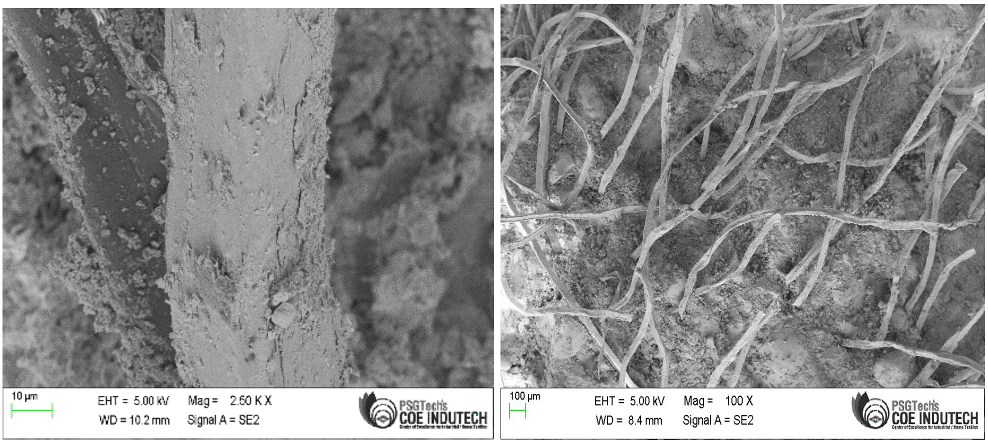

Fig. 20. SEM image for SMF5

6 Conclusion

Based on the experimental and microstructural investigations carried out, the following conclusions are drawn regarding the performance of geopolymer bricks incorporating metakaolin and glass fiber. The following conclusions were derived:

- The presence of Metakaolin as a partial replacement for red soil significantly improves the strength and reduces the absorption of geopolymer bricks.
- The replacement of 30% Metakaolin with the addition of 2% glass fiber is taken as optimum, which has the highest strength and the lowest water absorption capacity at both 7 and 14 days. This indicates that the replacement of metakaolin enhances the bonding and density of the geopolymer matrix, which results in improved mechanical and durability performance. The addition of glass fibre improves the behavior of geopolymer bricks.
- The addition of 2% fibre content was found to be most effective, and this will improve the crack width reduction and maintain the balance between strength increase and the reduced water absorption.
- The addition of glass fibre also reduces the porosity and enhances the overall structural performance.
- The SEM Image from the mix SMF5 has minimum visible cracks and pores compared to the Control and other mix.
- The SEM result is further confirmed by the EDX analysis due to the presence of main elements that form the strong and stable geopolymer gel formation. This improves the performance of the mixes.
- The replacement of 30% Metakaolin with the addition of 2% glass fiber from the geopolymer bricks shows the high strength, durability, and water absorption capacity, which makes them suitable for sustainable construction applications.

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