CHAPTER 30

Assessment and Optimization of Geopolymer-Based Stabilized Mud Blocks

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ABSTRACT

This research intends to examine and improve Stabilized Mud Blocks (GSMBs) through the utilization of Geopolymer to enhance mechanical and ecological properties via incorporation of clay, fly ash, and polypropylene (PP) fibers. Geopolymer binder synthesis involves a solution of sodium hydroxide (NaOH) combined with sodium silicate (Na_2SiO_3), at a ratio of Na_2SiO_3 to NaOH of 2.0-3.0. A Taguchi L9 orthogonal array (3x3) experimental design will be utilized to systematically analyze the influence of four independent variables, namely the percentage of clay used, the ratio of the alkaline activator, flyash percentage, and the content of PP fiber. Specimens are air-dried oven-cured at 24 hours at 60 o C and sun cured at 28 days to allow geopolymerisation. The test utilizes density, compressive strength, flexural strength, water absorption, and efflorescence characteristics. Multi-response optimization was employed to determine the optimal combination of mix parameters considering multiple performance criteria simultaneously. It is anticipated that the implementation of PP fibers will enable crack management and post-crack behavior moderation, while the adjustment of mixture ratios and activator concentrations will contribute to overall structural performance improvements. The findings of this analysis can support the validation of GSMBs as a viable alternative to conventional fired bricks and cement-based masonry, facilitating the adoption of low-carbon, resource-efficient construction practices.

Keywords: Geopolymer, Stabilized Mud Blocks, Fly Ash, Clay, Sustainable Construction.

1.0 Introduction

As we all know, construction industry has been a significant contributor to global greenhouse gases emissions due to its consumption of energy-intensive materials such as fired clay bricks and regular Portland cement.

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The urbanization is increasing rapidly, especially in developing countries like India, which is fast consuming material, environment and carbon emission. Additionally, the increased concentration of urban areas has contributed to the Urban Heat Island (UHI) effect, where conventional construction materials characterized by high thermal mass and low reflectivity exacerbate elevated ambient temperatures within metropolitan regions.

Stabilized Mud Blocks (SMBs) present an environmentally sustainable alternative, utilizing excavated soil from the immediate location and industrial by-products (fly ash), thereby reducing the impact of embodied energy and transportation. The application of geopolymer binders, generated via alkaline activation, also reduces carbon emissions relative to cement stabilization. Additionally, the implementation of polypropylene (PP) fiber is employed to mitigate the effects of shrinkage cracking, thereby enhancing both serviceability and durability.

2.0 Literature Review

Previous studies into earthen construction materials have demonstrated that the type of soil, soil stabilization method, and curing process are highly influential factors in the performance of blocks. Cement and lime are the traditional stabilizers that have been widely used for improving the compressive strength and durability of soil blocks but their carbon footprint is high hence not very sustainable. The remaining binders studied include fly ash and slag geopolymers, which exhibit high strength, low permeability, and enhanced chemical resistance. Empirical studies indicate that the application of geopolymer stabilization facilitates the formation of alumino-silicate gel networks, thereby improving particulate cohesion in the soil. The friable materials with soil bases have also been studied by the application of fiber reinforcement to surmount them. The best type of fiber in this case is polypropylene fiber, given that it is inert, inexpensive, and also moisture resistant. Literature indicates improvements in flexural strength, crack width, and toughness of fiber-reinforced stabilized blocks. Despite this advancement, limited research exists regarding the potential integration of geopolymer binders with polypropylene fiber reinforcement in stabilized mud blocks. This research addresses this gap by analyzing the synergistic impact of fiber reinforcement and stabilization on geopolymers.

3.0 Data and Methodology

3.1 Materials used

The following materials were used in the experimental investigation:

- Locally excavated soil obtained from a construction site.

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- Fly ash as an alumino-silicate precursor.
- Geopolymer binder prepared using sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).
- Polypropylene (PP) fibers.
- Potable water for preparation of alkaline solution.

3.2 Soil Characterization

To assess the suitability of the excavated soil for stabilized mud block production, laboratory tests were conducted in accordance with relevant Indian Standards.

3.2.1 Grain Size Analysis

The determination of the grain size distribution was according to IS 2720 (Part IV). Table 1 contains the results.

Table 1: Grain Size Distribution of Excavated Soil

IS Sieve Size	% Retained	Cumulative % Retained	% Finer
4.75 mm	22.93	22.93	77.07
2.36 mm	27.72	50.65	49.35
1.18 mm	27.3	77.95	22.05
600 µ	7.89	85.84	14.16
300 µ	7.05	92.89	7.11
150 µ	2.93	95.82	4.18
75 µ	2.19	98.01	1.99
Pan	1.88	99.89	0.11

Source: Created by authors

The sampled soil in the Baner region of Pune is that of non-plastic coarse grain soil that is mostly composed of sand with a small percentage of gravel and very little percent of fine soil (silt or clay). Therefore, the soil tends to be predominantly sand sized and with low fines (0.1%). According to the system of Indian Standard Soil Classification System (IS 1498), the soil is classified as Gravelly Sand (SG). It is a coarse soil which is typical to the soils which are formed out of weathered basalt at the Deccan Trap region. Such kind of soil is not naturally coherent and cannot accommodate SMBs without any modifications. Therefore, the lack of the clay component was removed, and geopolymer binders were utilized, with the inclusion of the PP fibers to control the cracks that appeared after the shrinkage.

3.2.2 Atterberg Limits and Shrinkage Limit

The tests performed according to IS 2720 were liquid limit, plastic limit, plasticity index and shrinkage limit tests. Table 2 summarizes the results.

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Table 2: Atterberg Limits and Shrinkage Characteristics

Property	**Value**
Liquid Limit (LL)	37.48%
Plastic Limit (PL)	5.37%
Plasticity Index (PI)	32.11%
Shrinkage Limit (SL)	4.4%

Source: Created by authors

Interpretation: The analysis of grain size reveals that the soil is coarse-grained and contains low level of fines hence it is classified as Gravelly Sand (SG) according to IS 1498. Atterberg limit tests on the fraction passing the 425 µm sieve were made as per IS 2720 (Part 5). The findings suggest that the fines fraction have plastic behavior but the quantity of the fraction in the bulk soil is very small; hence, the soil behavior is not plastic and is coarse-grained. The plastic limit range of fines of the soil was determined as rather low. The plastic limit was not used in soil classification and interpretation because it was not easy to obtain a constant 3 mm thread during the rolling process. Low shrinkage value refers to the volumetric shrinkage of the soil fines in isolation. However, in spite of a low shrinkage limit of the fines fraction of the soil, the shrinkage cracking in stabilized soil blocks is largely determined by shrinkage binder-induced by the soil block and moisture loss during curing. The polypropylene fibers were thus used to contain the formation of micro-cracks and enhance crack resistance and not to diminish the inherent soil shrinkage. And geopolymer binders provided sufficient bond and strength.

3.3 Soil Preparation by Sieving to 2.36 mm

The sieved soil was filtered using a 2.36 mm sieve to filter away any large gravel particles. This assisted in making the mix more even, easier to compact during block casting and created a smoother surface finish. Although the soil had few fine particles hence, they lacked natural cohesiveness. Because of this, geopolymer binders and fiber reinforcement were added to provide bonding and crack resistance in the blocks.

3.4 Mix Design and Experimental Plan

An orthogonal array of L9 (3×3) was taken to ensure that the proportions of materials were optimized to a minimum number of experimental trials. There were three parameters that were varied:

- Clay percentage.
- Alkaline Solution Ratio ($Na_2SiO_3/NaOH$ = 2.0, 2.5, 3.0).
- Polypropylene fiber content.
- Flyash percentage.

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The mix proportions for block casting are presented in **Table 3**.

Table 3. Taguchi L9 Mix Proportions for GSMBs

Sr. No.	Date of Casting	% Clay	% Fly Ash	Alkanline Solution Ratio (ASR)	Polypropylene Fibre %	Alkanline Solution	NaOH (Kg)	Na_2SiO_3
1	17-12-2025	40%	60%	2	1.50%	L/S = 0.4	1.46	2.94
2	19-12-2025	40%	60%	2.5	2%	L/S = 0.4	1.25	3.14
3	19-12-2025	40%	60%	3	2.50%	L/S = 0.4	1.1	3.3
4	18-12-2025	60%	40%	2	2%	L/S = 0.4	1.46	2.94
5	07-01-2026	60%	40%	2.5	2.50%	L/S = 0.4	1.25	3.14
6	07-07-2026	60%	40%	3	1.50%	L/S = 0.4	1.1	3.3
7	16-12-2025	80%	20%	2	2.50%	L/S = 0.4	1.46	2.94
8	09-01-2026	80%	20%	2.5	1.50%	L/S = 0.4	1.25	3.14
9	09-01-2026	80%	20%	3	2%	L/S = 0.4	1.1	3.3

Source: Created by authors

3.5 Casting and curing procedure

- Dry materials were mixed thoroughly.
- Alkaline activator solution was prepared separately and added gradually.
- Blocks were cast using a hand-operated compression press in the construction laboratory.
- The oven-cured at 60°C for 24 hours.
- Subsequently, blocks were ambient cured under sun exposure for 28 days to allow complete geopolymerisation.

Therefore, the development of geopolymer-based stabilized mud blocks is explored in this project as a viable solution to address environmental concerns, reduce construction-related emissions, and contribute to climate-resilient and resource-efficient construction practices.

4.0 Empirical Results and Testing Procedures

Stabilized mud blocks (GSMBs) made of geopolymer were tested on their physical and mechanical properties as well as durability upon the standard testing procedures. Experimental procedures were conducted in compliance with ASTM C67 05: Standard Test Methods of Sampling and Testing Brick and Structural Clay Tile with no exceptions. Following are the results for compressive test, water absorption test, efflorescence test & initial rate of absorption test:

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Mix No.	Factor A (Clay: Fly ash)	Factor B (Alk. Sol Ratio)			Factor C (PP Fibers)	Comp. Strength (MPa)	Water Abs (%)	IRA	Efflorescence
		ASR	Required Na_2SiO_3	Required NaOH					
1	40:60	2	2.94 kg	1.46 kg	1.50%	9.71	2.96	0.14	Nil
2	40:60	2.5	3.14 kg	1.25 kg	2%	7.49	3.12	0.15	Nil
3	40:60	3	3.3 kg	1.1 kg	2.50%	6.7	3.28	0.2	Slight
4	60:40	2	2.94 kg	1.46 kg	2%	7.23	3.67	0.16	Slight
5	60:40	2.5	3.14 kg	1.25 kg	2.50%	6.8	4.02	0.18	Slight
6	60:40	3	3.3 kg	1.1 kg	1.50%	6.2	4.48	0.25	Moderate
7	80:20	2	2.94 kg	1.46 kg	2.50%	4.91	6.9	0.28	Heavy
8	80:20	2.5	3.14 kg	1.25 kg	1.50%	4.6	6.2	0.22	Heavy
9	80:20	3	3.3 kg	1.1 kg	2%	4.1	5.7	0.3	Slight

Source: Created by authors

The experimental results show that the mix composition significantly influences the mechanical and durability properties of the geopolymer stabilised mud blocks. The highest compressive strength of 9.71 MPa was obtained in Mix 1 (40:60 clay to fly ash ratio) with ASR = 2 and 1.5% PP fibres. This shows that an increase in fly ash content results in better geopolymerization and bonding, hence stronger blocks. When the content of clay increased from 80% (Mix 7-9), compressive strength decreased significantly to 4.1-4.91 MPa. Similar trends were observed for water absorption. Mixes with high fly ash content had low water absorption of 2.96-3.28%, while mixes with high clay content had high water absorption of 6.9%, indicating increased porosity.

The initial rate of absorption (IRA) also showed an increase with increases in clay content. The lowest IRA reading of 0.14 kg/m²/min was recorded when Mix 1 was used, while the highest reading of 0.30 kg/m²/min was recorded when Mix 9 was used.

For efflorescence, mixes with high percentages of fly ash content showed nil or low efflorescence, while mixes with high percentages of clay content showed moderate to heavy efflorescence due to the migration of soluble salts on the surface.

The findings showed that mixes with high percentages of fly ash content showed better strength and durability, while mixes with high percentages of clay content showed better results in terms of water absorption and efflorescence. Hence, mixes with 40% clay content and 60% fly ash content showed better results.

5.0 Multi-Response Optimisation

Multi-response optimisation is used when multiple performance parameters need to be optimised simultaneously.

In this study, the goal was to:

- Maximise compressive strength
- Minimise water absorption

- Minimise efflorescence
- Minimise initial rate of absorption

Minitab combines all these responses and determines the optimal mix proportion that satisfies all the objectives. The optimisation process results in a composite desirability value, which varies between 0 and 1.

A value closer to 1 indicates a highly optimal result. In this study, the composite desirability value obtained was 0.976, which indicates that the selected mix has excellent overall performance.

The following are the steps to perform in Minitab software for multi-response analysis:

Minitab Software > Stat > ANOVA > General Linear Model > Response Optimizer > Enter goals for the responses (ex. Water Absorption = Minimize).

Multi-response optimisation was performed in Minitab to determine the best combination of mix parameters that satisfies all performance requirements simultaneously. Since different properties have different goals, optimisation was carried out by setting:

- Compressive Strength → Target / Maximum
- Water Absorption → Minimum
- Efflorescence → Minimum
- Initial Rate of Absorption (IRA) → Minimum

Using these goals, Minitab analysed all responses together and identified the optimum mix combination.

Parameters						
Response	**Goal**	**Lower**	**Target**	**Upper**	**Weight**	**Importance**
IRA	Minimum		0.14	0.3	1	1
Efflorescence	Minimum		1	4	1	1
Water Absorption	Minimum		2.96	6.9	1	1
Compressive Strength	Target	4.1	7.5	9.71	1	1

Source: Created by authors

Clay	**ASR**	**PP Fibres**	**IRA**	**Efflorescence**	**Water Absorption**	**Compressive Strength**
40	2.5	2	0.132	0.667	2.768	7.706

Source: Created by authors

The optimal settings obtained were:

- Excavated Clay = 40%
- Alkali Solution Ratio (ASR) = 2.5
- PP Fibres = 2%

At this combination, the predicted performance values are:

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Property	Predicted Value
Compressive Strength	7.71 MPa
Water Absorption	2.77%
Efflorescence	0.67 (Nil)
IRA	0.132 kg/m²/min

Source: Created by authors

The following is the range of predicted performance values:

Response	Predictions with 95% CI
IRA	(0.0220, 0.2425)
Efflorescence	(-3.128, 4.461)
Water Absorption	(0.698, 4.838)
Compressive Strength	(5.118, 10.293)

Source: Created by authors

The composite desirability value calculated is 0.976, which is close to 1. This implies that the mix combination selected has a perfect balance of strength and durability properties. From the optimisation results, it is clear that a greater content of fly ash with a moderate content of alkaline solution ratio and fibre content improves the geopolymer stabilised mud blocks.

6.0 Conclusion

This study investigated the development and performance of geopolymer-based stabilized mud blocks (GSMBs) using locally available soil, fly ash, alkaline activator, and polypropylene (PP) fibers. The experimental results demonstrated that the mix composition significantly influences both mechanical and durability properties of GSMBs.

The highest compressive strength of 9.71 MPa was achieved for the mix with 40% clay and 60% fly ash (ASR = 2, 1.5% PP fibers), while mixes with higher clay content (80%) showed significantly lower strength in the range of 4.1–4.91 MPa. Water absorption varied from 2.96% to 6.9%, with lower values observed in fly ash-rich mixes, indicating improved durability and reduced porosity. Similarly, the initial rate of absorption (IRA) ranged between 0.14 and 0.30 kg/m²/min, with minimum values corresponding to optimal geopolymer composition. Efflorescence was observed to be nil to slight in mixes with higher fly ash content, whereas clay-rich mixes exhibited moderate to heavy efflorescence.

Multi-response optimization was performed to simultaneously maximize strength and minimize durability-related parameters. The optimal mix proportion was identified as 40% clay, alkaline solution ratio of 2.5, and 2% PP fibers, yielding predicted values of 7.71 MPa compressive strength, 2.77% water absorption, 0.132 kg/m²/min IRA, and negligible efflorescence, with a high composite desirability value of 0.976.

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Overall, the study confirms that geopolymer-based stabilized mud blocks can serve as a sustainable and high-performance alternative to conventional masonry units. The use of industrial by-products such as fly ash, combined with optimized mix design, can significantly reduce environmental impact while maintaining adequate structural performance, making GSMBs suitable for low-rise and affordable housing applications.

7.0 Implications

Geopolymer-stabilized mud bricks should be adopted to help to cut down the carbon emissions and save resources in the construction sector. They can be especially used in low rise buildings and affordable housing projects where cost-effectiveness and sustainability are of high importance.

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