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EXPERIMENTAL ANALYSIS OF BRICK WASTE INCORPORATED FLY ASH–GGBS GEOPOLYMER MORTAR

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Abstract
The present investigation focuses on the effective utilization of Construction and Demolition Waste (CDW), particularly brick waste, as a substitute for fine aggregates in geopolymer mortar prepared using fly ash and Ground Granulated Blast Furnace Slag (GGBS). The study aims to address environmental concerns associated with conventional cement production, which emits nearly one ton of CO_2 for every ton of cement manufactured, along with the increasing problem of construction waste disposal. Experimental work was carried out by varying the proportions of fly ash and GGBS from 0% to 100%, changing the molarity of sodium hydroxide solution, and replacing natural sand with brick waste in the range of 10% to 30%. Sodium hydroxide and sodium silicate solutions were used as alkaline activators while maintaining a constant ratio of 2.5. Preliminary tests such as normal consistency, final setting time, and flowability were conducted to evaluate the fresh properties of the geopolymer mortar mixes. Compressive strength tests were performed on cube specimens after 28 days of ambient curing. The results indicated that geopolymer mortar containing 100% GGBS exhibited superior compressive strength and overall performance compared to other mix combinations.

Keywords
CDW, Geopolymer mortar, Fly ash, GGBS

1. Introduction

Rapid industrialization and urbanization have increased the use of conventional materials such as cement and natural sand, causing environmental issues like CO_2 emissions, resource depletion, and construction waste generation. Cement manufacturing alone contributes nearly 5% of global CO_2 emissions [17], while disposal of waste clay bricks has also become a serious concern.

Geopolymer concrete (GPC), introduced by Davidovits in 1978, has emerged as a sustainable alternative to conventional concrete. It utilizes alkali-activated materials such as fly ash and GGBS instead of cement, reducing carbon emissions while improving strength and durability. The binding process in GPC is based on aluminosilicate polymerization rather than cement hydration.

Geopolymer concrete provides benefits including improved durability, fire resistance, faster strength development, and reduced shrinkage. Brick waste, due to its high silica and alumina content, can also be effectively used as a replacement for natural aggregates. The performance of geopolymer mortar mainly depends on factors such as fly ash–GGBS ratio, NaOH molarity, sodium silicate ratio, and curing temperature. Overall, geopolymer mortar with brick waste offers an eco-friendly and sustainable alternative to conventional cement mortar.

2. Experimental Program

The present experimental investigation focuses on the preparation and evaluation of geopolymer mortar produced using industrial waste materials such as fly ash and Ground Granulated Blast Furnace Slag (GGBS), along with recycled brick waste as a partial replacement for fine aggregates. The experimental work was planned to study the influence of different parameters, including brick waste replacement percentage, fly ash–GGBS binder composition, and the molarity of alkaline activators, on the performance characteristics of geopolymer mortar. The compressive strength after 28 days of curing was considered the primary parameter for assessing the effectiveness of the developed mixes.

2.1 Materials

The materials used for the preparation of geopolymer mortar in the present study and their important properties are described in this section. Fly ash (FA) was procured from a local fly ash supplier located at Uchgaon, Kolhapur, while Ground Granulated Blast Furnace Slag (GGBS) was obtained from UltraTech Cements, Kolhapur, India. These industrial by-products were used as the primary binder materials for the geopolymer mortar mixes. The chemical composition and major properties of fly ash and GGBS are presented in Table 1.

Table 1- Chemical composition of fly ash and GGBS (wt. %)

Oxide	**Fly Ash**	**GGBS**
SiO_2	60.11	34.06
Al_2O_3	26.53	20
Fe_2O_3	4.25	0.8
CaO	4	32.6
MgO	1.25	7.89
SO_3	0.35	0.9
Na_2O	0.22	NIL
LOI	0.88	NIL
Specific Gravity	2.17	2.9

2.1.1 Alkaline Activators

A mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solution was used as the alkaline activator for the geopolymer mortar mixes. Sodium hydroxide pellets having 98% purity were utilized for preparing the alkaline solution. The sodium silicate solution used in the investigation possessed a SiO_2/Na_2O mass ratio of approximately 2.61 and consisted of 30.0% SiO_2, 11.5% Na_2O, and 58.5% water by mass. NaOH solutions with molar concentrations of 4M, 6M, and 8M were prepared by dissolving the required quantity of sodium hydroxide pellets in distilled water. After preparation, the solution was allowed to stabilize for one hour, and additional distilled water was added up to the 1-liter mark to compensate for any evaporation losses. The prepared NaOH solution was then mixed with sodium silicate solution while maintaining a constant Na_2SiO_3-to-NaOH mass ratio of 2.5. Before use in the mortar preparation, the combined alkaline activator solution was stored for 24 hours at a controlled room temperature of 25 ± 2°C.

2.1. 2 Mix Proportions

The experimental program was carried out by varying two important parameters affecting the performance of geopolymer mortar mixes:

- Brick Waste (BW) Replacement: Natural fine aggregate was partially replaced with brick waste at replacement levels of 0%, 10%, 20%, and 30% by volume.
- Binder Composition (GGBS:FA): Different combinations of Ground Granulated Blast Furnace Slag (GGBS) and fly ash (FA) were adopted in the ratios of 0:100, 30:70, 50:50, 70:30, and 100:0.

Based on preliminary trial investigations, a constant solution-to-binder ratio of 0.55 was maintained for all geopolymer mortar mixes to achieve suitable workability and consistency.

Table 2: Experimental matrix parameters

Variable	**Levels**
Brick Waste (%)	0, 10, 20, 30
GGBS:FA Ratio	0:100, 30:70, 50:50, 70:30, 100:0
NaOH Molarity (M)	4, 6, 8
Na_2SiO_3:NaOH Ratio	2.5 (fixed)

2.2 Methodology

2.2.1Specimen Preparation and Curing

The geopolymer mortar mixes were prepared at a temperature of 29 ± 2°C. Initially, the dry materials, including fly ash, GGBS, fine aggregates, and brick waste, were thoroughly mixed to obtain a uniform blend. Subsequently, the prepared alkaline activator solution was gradually added to the dry mixture and mixed properly until a homogeneous mortar consistency was achieved. The fresh geopolymer mortar was then poured into cube moulds of size 70.6 mm × 70.6 mm × 70.6 mm. Proper compaction was carried out using a vibrating table to eliminate entrapped air voids, and the top surface of the specimens was finished smoothly using a trowel. After casting, the specimens were allowed to remain in the moulds for 24 hours. However, mixes containing a higher percentage of fly ash required an extended demoulding period of approximately 36 hours due to slower setting characteristics. Following demoulding, all specimens were cured under ambient environmental conditions at a temperature of 25 ± 2°C and relative humidity of nearly 65% until the completion of the 28-day curing period prior to testing.

2.2.2 Testing Methods

The physical characteristics of fine aggregates and recycled brick waste, such as specific gravity, water absorption, bulk density, and particle size distribution, were determined according to the relevant Indian Standard codes. Both fresh and hardened properties of the developed geopolymer mortar were evaluated using standard testing procedures. The normal consistency of the geopolymer binder was determined in accordance with IS 4031 (Part 4) – 1988 using a Vicat apparatus. The setting time test was carried out as per IS 4031 (Part 5) – 1988. Workability of the fresh mortar mixes was evaluated through the Flow Table Test following the procedure specified in IS 4031 (Part 7) – 1988. The compressive strength of the geopolymer mortar specimens was determined according to IS 4031 (Part 6) – 1988. Compression testing was conducted using a compression testing machine at a loading rate of 140 $kg/cm^2/min$. The final compressive strength value reported for each mix represents the average strength obtained from three identical specimens.

2.3 Characterization of Aggregates

The physical properties of natural sand and recycled brick aggregate (RBA) used in the present investigation were evaluated prior to mix preparation. Important characteristics such as specific gravity, water absorption, bulk density, and particle size distribution were determined to assess the suitability of the materials for geopolymer mortar production. The experimentally obtained properties of natural sand and recycled brick aggregate are summarized in Table 3.

Table 3: Physical properties of natural sand and recycled brick aggregate (RBA)

Property	Natural Sand	Recycled Brick Aggregate (RBA)
Specific Gravity	2.95	2.06
Water Absorption (%)	0.24	9.5
Bulk Density (kg/m^3)	1573	1161
Fineness Modulus	2.40 (Fine Sand)	2.95 (Coarse Sand)
Grading Zone (IS 383)	Zone II	Zone I

The experimental results revealed that recycled brick aggregate (RBA) possessed lower specific gravity and bulk density values compared to natural sand, while exhibiting considerably higher water absorption characteristics. These observations indicate the porous and lightweight nature of RBA. Furthermore, particle size distribution analysis showed that the recycled brick aggregate was relatively coarser and exhibited a gap-graded behavior. Such characteristics may affect the packing arrangement of particles and increase the void content within the geopolymer mortar matrix.

3. Results and Discussion

3.1 Fresh Properties of Geopolymer Mortar

3.1.1 Normal Consistency

The alkaline solution required to achieve normal consistency was influenced by both binder composition and NaOH molarity, as shown in Fig. 1(a). Mixes with higher GGBS content required more solution because of the angular and flaky nature of

GGBS particles compared to the spherical fly ash particles. An increase in NaOH molarity also increased the solution demand due to higher solid concentration.

3.1.2 Setting Time

The final setting time was strongly dependent on the binder composition (Fig. 1(b)). Mixes containing 100% GGBS showed rapid setting behavior (35–44 min), whereas mixes with 100% fly ash required significantly longer setting times (105–195 min). This difference is mainly due to the faster reaction kinetics of GGBS in alkaline conditions. Higher NaOH molarity further increased the setting time of all mixes.

3.1.3 Flow Value

A constant solution-to-binder ratio of 0.55 was maintained for all mixes to achieve a uniform flow value of approximately 110%, ensuring comparable workability.

3.2 Compressive Strength

The compressive strength at 28 days was considerably influenced by NaOH molarity, binder composition, and recycled brick aggregate (RBA) replacement percentage.

3.2.1 Effect of NaOH Molarity

Compressive strength increased with the increase in NaOH molarity from 4M to 8M. Higher molarity improved the dissolution of silica and alumina, enhancing the geopolymerization process and resulting in a denser mortar matrix.

3.2.2 Effect of Binder Ratio

Mixes containing higher GGBS content exhibited superior strength performance. The 100% GGBS mix produced the maximum compressive strength due to the formation of additional C-A-S-H gel along with geopolymeric N-A-S-H gel, resulting in a stronger structure.

3.2.3 Effect of RBA Replacement

An optimum RBA replacement level of 20% was observed. Strength increased up to this level due to the pozzolanic contribution of crushed brick particles. However, at 30% replacement, strength decreased because of the porous nature and higher water absorption of brick aggregates, which increased void formation in the mortar. The optimum mix consisted of 100% GGBS, 8M NaOH solution, and 20% RBA replacement, achieving nearly 65 MPa compressive strength.

3.3 Cost Analysis

A preliminary cost comparison for 1 m^3 of mortar indicated that conventional cement mortar cost approximately ₹7,900, whereas geopolymer mortar cost nearly ₹6,700. Thus, geopolymer mortar showed around 15% cost reduction. The use of industrial by-products and construction waste also enhances the sustainability of the material.

4. Summary and Conclusions

This study evaluated the use of recycled brick aggregate (RBA) as a partial replacement for natural sand in fly ash and GGBS-based geopolymer mortar. The effects of binder ratio, NaOH molarity, and RBA replacement on fresh and hardened properties were experimentally investigated.

The major conclusions are summarized below:

- Fresh properties of geopolymer mortar were significantly affected by the binder composition. GGBS accelerated setting and increased solution demand, while fly ash delayed setting due to its spherical particle shape.
- Compressive strength improved with higher NaOH molarity and increased GGBS content.
- The optimum mix was obtained with 100% GGBS binder, 8M NaOH solution, and 20% RBA replacement.
- Utilization of fly ash, GGBS, and recycled brick waste provides an eco-friendly and economical alternative to conventional mortar.
- Recycled brick waste can be effectively incorporated into geopolymer mortar for sustainable construction applications.
- Further studies are recommended to evaluate long-term durability and structural performance of the developed mixes.

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