Optimizing Red Soil-Based Geopolymer Bricks: A Sustainable Approach towards Environmentally Friendly Construction Materials

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Abstract - In the whole world, construction activities are happening rapidly as a result of the population increase and also due to the lifestyle of people in the 20th century, intensifying the pressure on resources needed for construction. It also causes bad effects on the environment, such as the carbon footprint associated with cement production and the waste management of emission waste like fly ash in thermal power plants. Counteracting and stabilizing the adverse environmental consequences, this study adopts an experimental approach to utilize thermal power plant waste Class C Fly ash (pozzolanic), locally available red soil, and stone dust, along with geopolymer precursors, to manufacture bricks, which are the most demanding material for infill masonry work. The mechanical, durability, and microstructural characterization of the bricks were studied for various mix proportions, along with various concentrations of geopolymer precursors, cured at elevated temperatures and ambient curing. An optimum methodology was obtained to develop a red soil-based geopolymer brick.

Key-Words: - Red Soil, Fly Ash, Stone Dust, Geopolymer brick, pozzolanic, microstructural characterization.

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1 Introduction

In the present scenario, the utility of concrete across the globe is placed in the second position next to water. As of date, only cement is predominantly used as a principal binder to produce concrete. However, environmental concerns associated with the production of cement are seriously viewed, [1]. Production of one ton of cement releases almost one ton of carbon dioxide (CO_2 Due to a rapid increase in the infrastructure sector, the production of cement leads to acute depletion of non-renewable resources like natural lime rock, coal, etc, [2]. The hydration of cement which is an exothermic reaction emits a huge amount of heat energy thereby increasing the atmospheric temperature. On the other hand, CO_2 is the prime greenhouse gas and it contributes significantly to environmental pollution and ozone depletion. Based on the above factors, enormous efforts have been made to minimize cement usage and invent an eco-friendly alternative binder, [3].

The amply stockpiled fly ash from thermal power plants posed a nuisance at its disposal. However, the fly ash exhibited excellent cementitious properties and showed a potential replacement for cement, [4]. This has sparked the idea of involving fly ash in the cement and concrete manufacturing process. The physical and chemical properties of fly ash also confirmed its possible utility in concrete by replacing cement partially or completely, [5].

Geopolymers are acknowledged as a potential alternative binder to OPC, for decreasing carbon dioxide emissions and accomplishing effective waste recycling. This cement-free geopolymer composite is budding as an exceptionally sustainable building material, [6]. Despite these advantages over Portland

Cement Concrete (PCC), Geo Polymer Concrete (GPC) possesses certain limitations in its application due to the lack of knowledge in its microstructure formation and non-standardized mix design procedures. Because of this knowledge gap, researchers tend to formulate, mix proportions, and adapt their manufacturing practices, [7]. The parameters involved in the synthesis of geopolymer composites are highly sensitive. They depend on the physical, chemical, and mineralogical compositions of constituents such as aggregates, fly ash, water, NaOH, and Na2SiO3 solutions. Also, the prevailing temperature during solution preparation, mixing, casting, and curing phases influences the parameters, [8]. Moreover, the need for elevated temperature curing has also confined their usage in precast applications. The use of low calcium content fly ash-based geopolymer concrete mandatorily requires curing by elevated temperature for the effective polymerization process, [9]. Hence, an effective breakthrough is essential for expanding the use of GPC in different applications. If the fly ash-based geopolymer concrete could be developed with an appropriate mix design, it could demonstrate enhanced mechanical and chemical properties of concrete on par with Portland cement concrete, [10]. Latent cementitious materials like Class C Fly Ash (CFA) and Ground Granulated Blast Furnace Slag (GGBS) contain adequate calcium to form cementitious compounds when they interact with water. The dormant hardening energy becomes active only under the stimulus of an activator like calcium hydroxide or strong alkaline such as sodium hydroxide or potassium hydroxide, [11]. When these latent cementitious materials are blended with Portland cement and water, the calcium hydroxide produced during the hydration of the brick plays the activator role. This is an exothermic reaction and emits a significant amount of heat energy. The evolved heat energy can be utilized for inducing the polymerization process in a geopolymer brick, [12]. Therefore, this study targets the ambient curing of geopolymer bricks and their suitability under various loading conditions in different environmental factors.

2 Literature Survey

The building sector has a big influence on the environment, hence research into sustainable building materials is essential. [13], examine the use of fly ash (FA) geopolymer binder in the manufacturing of unburned bricks. The goal of the study is to optimize the ratio between FA and alkaline activator solution (AAS) in blocks, with several ratios being examined. Properties including flexural tensile strength, compressive strength, and water absorption were measured when the blocks were tested at room temperature and 60°C. The analytical methods employed were Fourier Transform Infrared (FTIR) and Scanning Electron Microscope (SEM The required quantity of AAS was 8%, however, the results indicated that blocks with 20% AAS had the highest compressive strengths. The ratio of quasi-dry to saturated compressive strength was greater than 0.5, in compliance with current norms.

The environmental impact of red mud and waste foundry sand is significant, while natural clay for brick manufacturing is scarce. In a study, [14], provided a method for using red mud in clay bricks without pretreatment and calcination to replace natural clay in bricks using red mud, waste foundry sand, and fly ash. It utilized a polymeric approach, avoiding calcination. The bricks with varying concentrations utilized 12M bricks. To minimize heavy efflorescence over time, the caustic concentration was reduced to 5 M using red mud, the bricks eventually decreased efflorescence providing a strength of $3.27\ N/mm^2$. However, this study does not provide sufficient data on factors such as weathering effects, resistance to environmental stresses, and potential degradation over time.

A study, [15], focused on examining the early ages of precursor-activator suspension structures in alkali-activated ground granulated blast furnace slag and fly ash mixtures through mechanical and chemical evolution. The study found that the setting time of these mixtures is prolonged and the heat of hydration decreases with fly ash content. Also found that weight loss due to hydrate decomposition is around 30% of weight loss at 28 days, while in the OPC system, it is less than 10%. The quick setting of alkali-activated slag mixtures is due to rapid coagulation and rigidification of the network, while OPC binders setting is due to a network formed by partially hydrated or anhydrous cement particles.

As a result of climate change, more people are using wood pellets as a sustainable energy source; nevertheless, this increased use results in the generation of wood pellet fly ash (WA) by-products. Their study, [16], created wood pellet fly ash blended binder (WABB), a new sustainable building material composed of 20% cement, 30% GGBS, and 50% WA. A battery of experiments is used to evaluate the material's stabilizing ability in weathered granite soil (WS The average qu climbed by 1.88 to 11.77 as the WABB dose rate increased, according to the data, which is greater than compacted WS without a binder. It was also established that novel cementitious minerals exist. The function of cement in the early strength development and the latent hydraulic capabilities of ground granulated blast-furnace slag (GGBS) are thought to be responsible for the combined hydration process of WABB.

Cement, which adds to air pollution and greenhouse gas emissions, might be replaced with lateritic soils found in Bolivia's wet tropical regions. The compressive strength, chemical composition, and mineralogy of geo-polymers derived from lateritic clays have all been investigated. Research on Bolivia's lateritic clays and their combined mechanical, mineralogical, and chemical characteristics in a geo-polymer, however, is lacking. The goal of the study, [17], was to assess a geo-polymer derived from laterite clays. On mortar and geo-polymer cubes and prisms, compression, and flexural tests were performed along with mineralogical and chemical studies. The laterite clay-based geo-polymer exhibited a marginally higher flexural strength but a lower compressive strength when compared to Portland cement IP mortar, according to the results.

In the study, [18], used the plastic damage model of Weibull distribution and the energy dissipation mechanism to investigate the deformation and damage laws of solidified soils during compression failure. It looks at how the qualities of the soil are affected by curing ages, moduli, cement, ground granulated blast furnace slag (GGBS), and alkali-activator contents. According to the study, energy dissipation occurs when a specimen is damaged under stress, and the dissipation energy ratio (Ud/U) and damage variable are used to characterize soil damage. The brittleness index (BI) is determined, demonstrating that when the modulus and curing age drop, the BI and Ud/U rise while the dissipation energy ratio and dissipation energy fall.

3 Materials and Methodology

This research focuses on utilizing deteriorated red soil, locally available, in Karnataka, in union with stone dust and fly ash. An alkali solution serves as a binder to create geopolymer bricks. The mix design, optimizing the red soil-based geopolymer brick preparation, involves varying ratios of red soil to stone dust, with a fixed percentage of fly ash. The alkali solution is fine-tuned by adjusting molarity and alkali-to-silicate ratio under different curing temperatures. The resulting bricks undergo comprehensive evaluation, considering physical and durable parameters, alongside a scrutiny of structural integrity.

3.1 Materials Used

Red Soil, fly ash, Stone Dust, and aluminum silicate gel as a binder was used in this research to make the specimen for experimentation. This section in detail explains the physical and chemical properties of the materials being utilized.

3.1.1 Red Soil

The locally available red soil is used for this study, the soil is procured from Tumakuru, Karnataka, India. The red soil sourced from Tumakuru, Karnataka, India, exhibits specific physical and chemical properties.

Table 1. Physical properties of red soil

Physical Properties	
Specific gravity	2.62
Neutral pH	7.24
Electrical conductivity	96 µS/cm
Liquid limit	34.12
Plastic limit	34.12
Dry density	1.99 gm/cc

As shown in Table 1, the soil exhibits a specific gravity of 2.62 and a neutral pH of 7.24, the soil's electrical conductivity is measured at 96 µS/cm. Its liquid limit and plastic limit are determined to be 34.12 and 34.12, respectively, while the dry density stands at 1.99 gm/cc.

Table 2. Chemical composition of red soil

Chemical Composition	
Silicon dioxide (SiO2)	74.23%
Aluminium oxide (Al2O3)	19.07%
Calcium oxide (CaO)	1.2%
Magnesium oxide (MgO)	0.8%
Iron oxide (Fe2O3)	5.9%

Analyzing the chemical composition, the soil comprises 74.23% silicon dioxide (SiO2), 19.07% aluminum oxide (Al2O3), 1.2% calcium oxide (CaO), 0.8% magnesium oxide (MgO), and 5.9% iron oxide (Fe2O3) as shown in Table 2. These findings offer a broad thoughtful of the red soil's characteristics, crucial for measuring its suitability in various applications, such as construction.

3.1.2 Fly-Ash

Class C Fly ash (pozzolonic) which was acquired from the Raichur thermal power plant was utilized in this research to stabilize the red soil.

Table 3. Physical properties of fly ash

Physical Properties	
Specific gravity	2.15
Neutral pH	8.4
Electrical conductivity	225 µS/cm

Karnataka, which was characterized and the outcomes are tabulated in Table 3, has a Specific gravity of 2.15, pH 8.4, and Electrical Conductivity (µS/cm) 225.

Table 4. Chemical composition of fly ash

Chemical Composition	
Silicon dioxide (SiO_2)	55%
Aluminium oxide (Al_2O_3)	24%
Calcium oxide (CaO)	0.98%
Magnesium oxide (MgO)	0.47%
Iron oxide (Fe_2O_3)	7.8%
Potassium oxide (K_2O)	1.75%
Titanium oxide (TiO_2)	1.45%

Chemical composition SiO2(%) 55, Al2O3(%) 24, CaO (%) 0.98, MgO (%) 0.47, K2O(%) 1.75, Fe2O3(%) 7.8, TiO2(%) 1.45, Loss on ignition(%) 5.25, as shown in Table 4.

3.1.3 Stone Dust

Stone dust (SD) is a finely crushed material. After double washing, it is procured from the available nearby quarry of Tumakuru. Karnataka, India. As per the unified soil classification system (USCS), the stone dust may be categorized as mineral sediment with truncated compressibility. Quarry dust and rock dust are other names for SD. SD is a by-product produced by stone crusher operations. The use of stone dust in concrete can help preserve ordinary gravel for imminent peers while also improving concrete quality. It has an SG of 2.67. Table 5 and Table 6 provides the physical and chemical composition of quarry dust.

Table 5. Physical properties of quarry dust

Physical Properties	
Specific gravity	2.67
Bulk relative density	1820 kg/m3
Absorption	1.55 %

Quarry dust has a specific gravity of 2.67, significantly greater than water density, and a bulk relative density of 1820 kg/m3, with a moisture absorption rate.

Table 6. Chemical composition of quarry dust

Chemical Composition	
Silicon dioxide (SiO_2)	62.48%
Aluminium oxide (Al_2O_3)	18.72%
Calcium oxide (CaO)	4.83%
Magnesium oxide (MgO)	2.56%
Iron oxide (Fe_2O_3)	6.54%
Potassium oxide (K_2O)	3.18%
Titanium oxide (TiO_2)	1.21%

The chemical composition of quarry dust is shown in the table, along with the percentages of the different oxides. The majority, or 62.48%, is made up of silicon dioxide (SiO2), which is followed by aluminum oxide (Al2O3), magnesium oxide (MgO), calcium oxide (CaO), iron oxide (Fe2O3), potassium oxide (K2O), titanium oxide (TiO2), and magnesium oxide (MgO) at 18.72%, 4.83%, and 2.56%.

3.1.4 Geopolymer Solution

Geopolymer was created by combining an alumina silicate source with a strong alkali solution such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), which forms an alumina silicate gel that acts as binding material.

3.1.4.1 Sodium Hydroxide (NaOH)

The physical appearance of sodium hydroxide is in the form of pellets. Its basic alkali solution has a molar mass of 39.997 gms/mol, and it's an inorganic compound, also known as caustic soda, that was procured in the form of crystalline.

3.1.4.2 Sodium Silicate (Na2SiO3)

It's a silicate solution procured in the form of liquid which is heavy and also known as water glass.

3.1.5 Potable Water

The potable drinking water available in the locality is utilized for the development of dilution of sodium hydroxide to the essential clarification. Tap water conforming to IS 456 was used to mix brick material.

3.2 Methodology

All necessary materials were acquired, including red soil, fly ash, stone dust, NaOH, and Na2SiO3, and a thorough characterization of each material was conducted to assess their individual properties.

3.2.1 Solution Preparation

With a molarity of 6M NaOH was mixed with distilled water for at least 24 hours to make a solution. Na2SiO3 liquid was prior mixed with the dry materials. Both NaOH solution and Na_2 SiO_3 were kept to mix in the next process. The hydroxide solutions with varying molarity, ranging from 6M to 14M, with a 2M increment. Four different ratios of mixing NaOH with Na2SiO3 were considered in this research as shown in Table 7.

Table 7. Various NaOH to Na2SiO3 ratios

Ratio	NaOH	Na2SiO3
Ratio -1	1	1
Ratio -2	1	1.5
Ratio -3	1	2.0
Ratio -4	1	2.5

3.2.2 Dry Mix Preparation

To make a homogenous mixture, binders, and fine aggregates are mixed one after the other. First, a part of fly ash (FA) is mixed with a blend of red soil and stone dust. Then, for three minutes, the mixture is completely mixed until it has a uniform color.

Table 8. Various Mix ratios

Mix	Red Soil	Stone Dust	Fly Ash
Mix-1	100	0	0
Mix-2	90	0	10
Mix-3	80	10	10
Mix-4	70	20	10
Mix-5	60	30	10
Mix-6	50	40	10
Mix-7	40	30	10

The crush resistance analysis of different mix ratios (mix-1 to mix-7) combined with a constant alkali activator ratio 1: 2.5 as shown in Table 8, cured in an oven for 24 hours at 60°C, to reveal noteworthy findings.

3.2.3 Wet Mixing

The brick samples were prepared for various mix ratios and molarities while maintaining a consistent 1:2.5 NaOH to Na2SiO3 ratio. The samples are cured for 24 hours in an oven at a high temperature of 60°C. The NaOH to Na2SiO3 ratio is adjusted in increments of 0.5 while maintaining the ideal ratios, and these specimens are also cured for 24 hours at 60°C. As the ideal values are recognized, specimens are made and cured at temperatures between 60°C and 120°C in steps of 10°C. The proper mix ratio, molarity, NaOH to Na2SiO3 ratio, and oven curing temperature are determined by analyzing all test data to make red soil-based geo-polymer bricks.

4 Experimentation

Fig. 1: Red mud-based Geopolymer Bricks

The study makes use of materials from thermal power plants, quarry dust, and specific geopolymer ingredients. Red soil's mineral composition and physical properties were studied, and the chemical composition and fineness of class C fly ash were investigated. Stone dust was screened for particle size distribution and chemical composition. Geopolymer ingredients, such as activators and silicates, were chosen for their compatibility with the red soil and fly ash compositions. Figure 1 represents the red mud geopolymer bricks. The brick's resistance to environmental factors and durability over time is evaluated through mechanical and durability for strength and flexibility and also for moisture resistance and resilience in harsh conditions, which ensure their suitability for sustainable construction projects.

5 Test Results

This paper identifies the ideal curing conditions, specimens were cured at various temperatures and their temperature-dependent behavior was examined. By performing various tests, the behavior of geopolymer mixes was studied to obtain better results by optimizing mix design and curing processes.

5.1 XRD Analysis

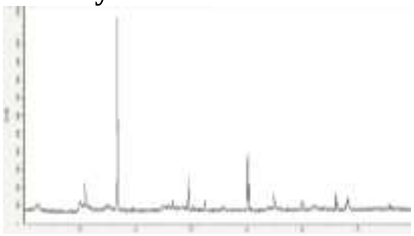


Fig. 2: XRD Image of Red Soil

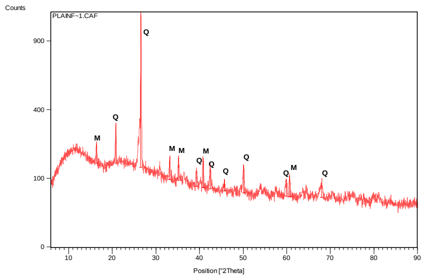


Fig. 3: XRD image of Fly Ash

The diffraction pattern that results from the XRD examination shows the composition, crystal structure, and phase purity of the brick material. As illustrated in Figure 2 and Figure 3, we can understand the diffraction characteristics, uses, and possible applications of red soil and fly ash.

5.2 SEM Analysis

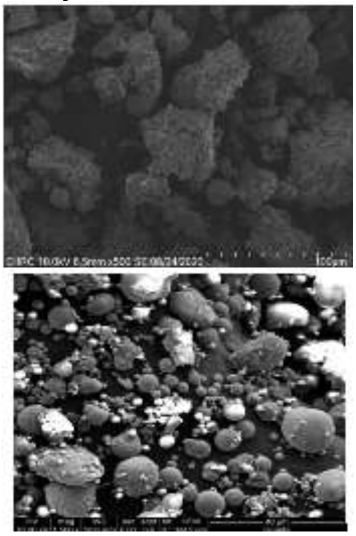
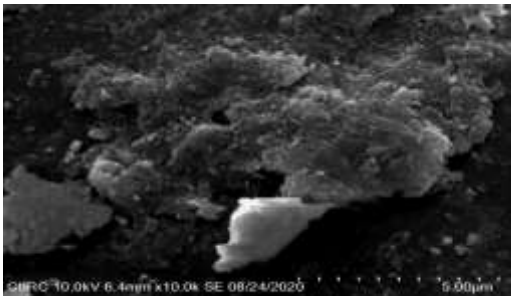
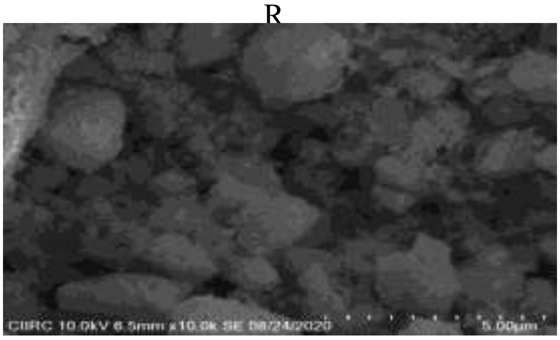


Fig. 4: SEM image of Red Soil and Fly Ash (Class C)

Scanning Electron Microscopy (SEM) is a significant way to assess how exposure to sulfate and various dry and wet cycles impact the internal structure of the brick specimens. Figure 4, shows the SEM image of red soil and Fly Ash. Understanding the mechanical properties, strength, and durability is made easier with the help of the visual information provided by the microstructural analysis. The microstructural behavior of damaged specimens after exposure to different conditions is depicted in Figure 5 and Figure 6. It aids in identifying defects or weaknesses in brick structures like voids, cracks, or poor bonding, thereby optimizing the manufacturing process and enhancing the quality and performance of bricks.

	R 
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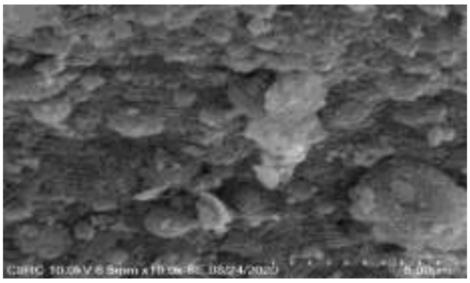	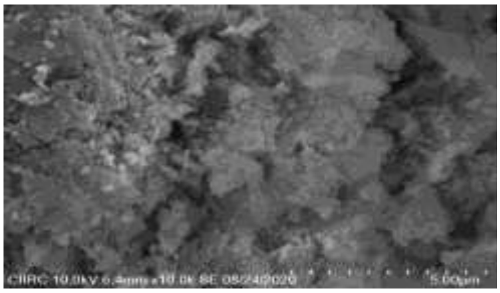
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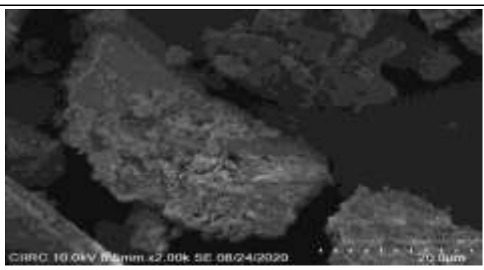	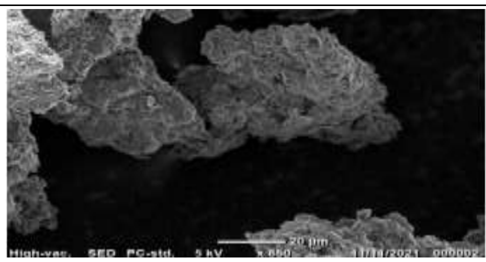
60^0 C	120^0 C

Fig. 5: A mix of red-based geopolymer bricks cured at 600 C and 1200 C shows different alkali activator ratios

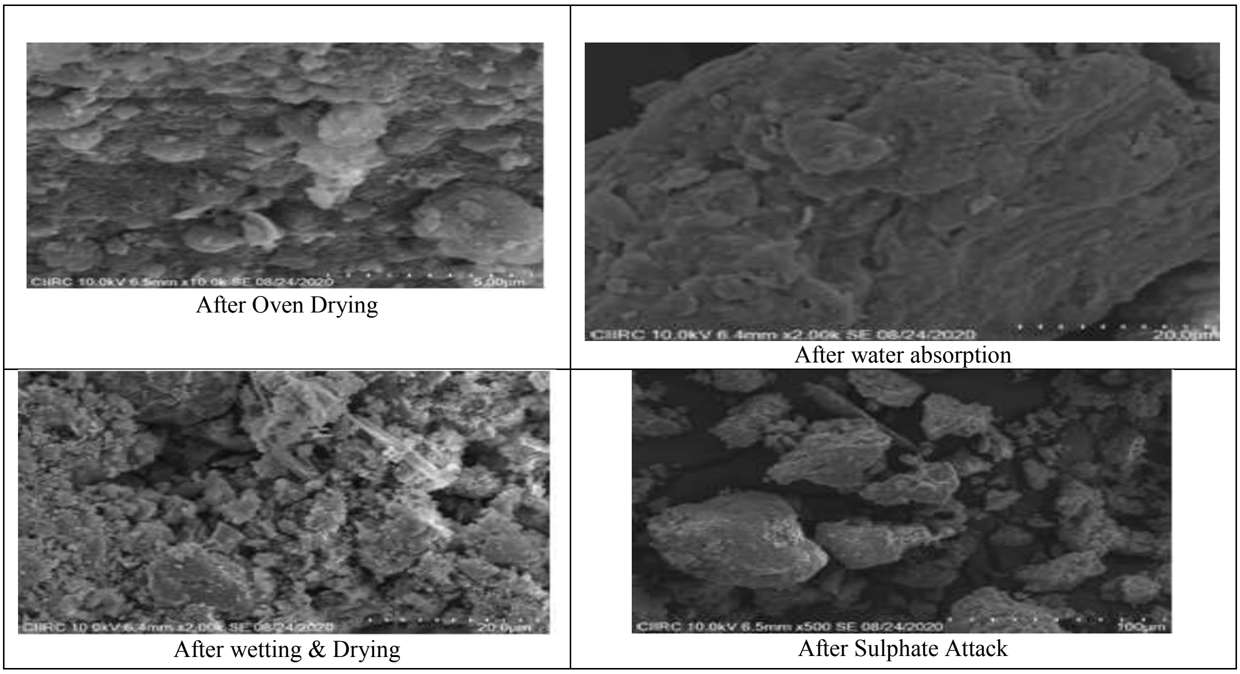

Fig. 6: SEM image of brick of 60:10:30 mix proportion at 1: 2.5 alkali activator ratio subjected to various conditions

It also provides a visual narrative of the material's response to different conditions, facilitating a more comprehensive understanding of its performance and behavior under diverse environmental challenges. The investigation extends to mix 5, utilizing an 8M hydroxide solution with a ratio of 3. Specimens are cast and cured in an oven for 24 hours at varying elevated temperatures, ranging from 60°C to 120°C, with increments of 10°C. Crush resistance assessments are conducted on the specimens, and the results are analyzed.

For the obtained optimum mix ratio of 60:10:30 (Red Soil: Fly Ash: Stone Dust), the study aims to optimize the NaOH to Na2SiO3 by varying the NaOH to Na2SiO3 ratio. The investigation spans a range from 1:1 to 1:2.5, with increments of 0.5. This systematic variation is designed to identify the ideal mix ratio that balances the cost considerations while maintaining desirable properties in the geopolymer material.

The observed trend in the study reveals that the strength of the specimens increases proportionally with a rise in the alkali activator ratio, specifically from 1:1 to 1:2.5. However, noteworthy insight is gained by recognizing that the rate of increase becomes marginal between the ratios of 1:2 and 1:2.5.

5.3 Compressive Strength Analysis of Various Mix Ratios for Different Molarities

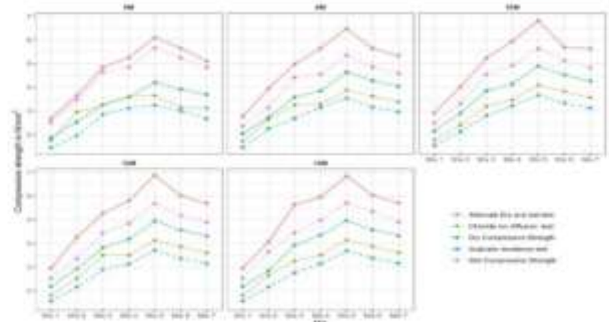

Fig. 7: Compressive Strength behavior of various mix ratios for different Molarities

According to Figure 7, mix 5 consistently demonstrates superior strength across all molarities studied. The analysis from Graph.1 consistently highlights the superior performance of mix 5 across various molarities. Notably, the crush resistance after alternative dry and wet cycles exhibits a substantial increase of 22 to 25% compared to the dry compressive strength after oven curing. This enhancement is attributed to the removal of leaching during wetting and drying, contributing to the overall strength improvement, as observed and documented by Preethi and Venkatarama Reddy in 2020.

However, it's noteworthy that the strength of the brick experiences a reduction of 20 to 25% during both sulfate and chloride resistance tests when compared to the dry compressive strength. This decline is expected due to the challenging environmental conditions posed by these corrosive agents. Considering these outcomes, the combination of an 8M NaOH concentration and mix 5 emerges as the optimal choice for further studies. This selection is supported by a robust performance across various tests and conditions, setting the stage for in-depth investigations into the specific characteristics and applications of this geopolymer mix.

5.4 Compressive Strength Results of Various Alkali Activator Ratio

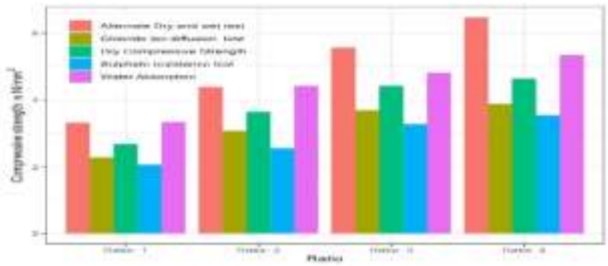

Fig. 8: Compressive strength results of various Alkali activator ratio

Based on the previous evaluation and report from Table 7, 1:2 f NaOH to Na2SiO3 ratio is selected as optimal and the respective compressive test results are shown in Figure 8. As a noticeable increase in compressive strength is seen and all values fall within the permissible range, this ratio is regarded as very suitable. Adopting the 1:2 ratio offers an appropriate balance between improving strength and ensuring that the geopolymer brick material remains within permitted performance restrictions. This optimal ratio is a reasonable proposition in terms of achieving cost-effectiveness along with efficiency standards.

5.5 Compressive Strength Results of Various Oven Curing Temperature

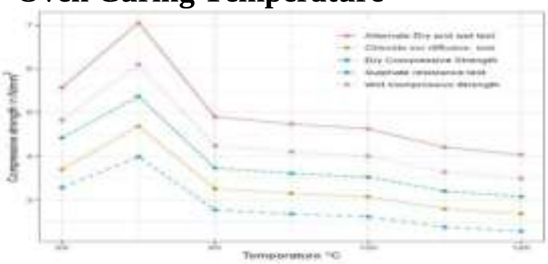

Fig. 9: Compressive strength results of varying oven curing temperature

Examining the behavior of the geopolymer material at varying temperatures is crucial to determining the ideal curing conditions that optimize the sample's strength. This understanding improves the production process and optimizes the curing parameters for the geopolymer mix, ensuring efficiency and effectiveness in identifying the optimum brick specimen. From the Figure 9, illustrates a distinct trend, indicating that the crush resistance of the specimens experiences an increase up to 70°C. Beyond this temperature, there is a noticeable reduction in strength with further temperature increases. This observation suggests that the geopolymer material reaches its optimal strength at 70°C, and elevated temperatures beyond this point may induce a decline in compressive strength.

5.6 Sulphate and Chloride Attack Results based on Mix 5

The investigation was extended to mix 5, utilizing an 8M hydroxide solution with a ratio of 3. Specimens are cast and cured in an oven for 24 hours at varying elevated temperatures, ranging from 60°C to 120°C, with increments of 10°C. Crush resistance assessments are conducted on the specimens, and the results are analyzed.

Table 9. Compressive strength in N/mm2 for mix 5

Molarity	Dry	Wet	Alternative dry and wet	Sulphate Resistance	Chloride resistance
6M	4.20	5.65	6.10	3.25	3.65
8M	4.64	5.36	6.48	3.54	3.88
10M	4.90	5.63	6.82	3.67	4.09
12M	4.94	5.69	6.88	3.71	4.13
14M	4.57	5.34	6.02	3.38	3.87

Upon closer examination, Table 9, which specifically focuses on the crushing strength behavior of mix 5 for various molarities, highlights that an 8M molarity of NaOH results in the desired strength. Notably, a further increase in molarity does not yield a significant additional enhancement in compressive strength.

6 Conclusion

In summary, the research findings emphasize the exceptional performance of Mix-5, characterized by the mix ratio (60:10:30) and cured at 70 degrees Celsius. Notably, Mix-5 consistently demonstrates superior compressive strength across varying molarities and alkali activator ratios. The optimization study further discloses that, while increasing the alkali activator ratio enhances strength, the rate of improvement becomes marginal between the ratios of 1:2 and 1:2.5. As a result, a NaOH to Na2SiO3 ratio of 1:2 is identified as optimal, striking a steadiness between strengthened properties and cost-effectiveness. Additionally, the temperature-dependent behavior of the specimens indicates that curing at 70 degrees Celsius results in peak compressive strength. Beyond this temperature, there is a noticeable decline in strength. These insights contribute to the refinement of geopolymer mix design and curing conditions. The findings of the research are as follows:

- This study was conducted to develop Red Soil-Based Geopolymer Bricks using industrial wastes such as fly ash and locally available red soil which is achieved using different mix ratios.
- From the physical and chemical characterization study, it was concluded that Raichur flash and locally available soil samples had better chemical composition suitable for the study.
- The microstructural studies conducted using XRD and SEM analysis indicated the peaks of mullite (calcium aluminum silicate) and quartz for fly ash. Sem analysis of fly ash showed a distinct formation of special hollow cenospheres. The XRD of red soil showed peaks of quartz, whereas the SEM of red soil showed aggregation of soil particles.
- The research findings emphasize the exceptional performance of Mix-5, characterized by the mix ratio (60:10:30) and cured at 70 degrees Celsius. Notably, Mix-5 consistently demonstrates superior compressive strength across varying molarities and alkali activator ratios.
- The optimization study further discloses that, while increasing the alkali activator ratio enhances strength, the rate of improvement becomes marginal between the ratios of 1:2 and 1:2.5. As a result, a NaOH to Na2SiO3 ratio of 1:2 is identified as optimal, striking a steadiness between strengthened properties and cost-effectiveness.

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