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Enhancing Sustainable Geopolymer Concrete with The Use of Recycled Water and Blended Waste Powder

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Abstract
Rapid industrialization has led to the accumulation of hazardous waste materials, such as Red Mud (RM), Slag, and Fly Ash (FA), which present significant environmental challenges. The construction industry, particularly cement production, also contributes heavily to global CO_2 emissions. This research investigates the development of geopolymer concrete using RM, FA, Slag, and Recycled Water (RW) as sustainable alternatives to traditional cement. The objective is to optimize the mechanical properties of geopolymer concrete while minimizing its environmental impact. A series of trial mixes were developed, with mechanical tests for compressive, tensile, and flexural strength performed at various curing periods (7, 28, and 56 days). The results indicate that geopolymer concrete with recycled water performs comparably to that made with normal water, achieving compressive strengths up to 45 MPa and flexural strengths up to 10 MPa. While the workability of the geopolymer concrete was lower than that of conventional concrete, the overall performance shows that RM, FA, and Slag-based geopolymer concrete is a viable, eco-friendly alternative. The study concludes that geopolymer concrete can substantially reduce the environmental footprint of construction while offering mechanical properties suitable for structural applications. Further research is suggested to improve its workability for practical use.
Keywords: Red Mud, Slag, Fly Ash, Geopolymer Concrete, Sustainable Construction, Recycled Water

1. Introduction

Concrete is the most widely used construction material globally, prized for its strength, durability, and versatility. Its basic composition—aggregate, cement, and water—allows it to be molded into a wide range of shapes, meeting diverse construction demands [1]. However, the environmental consequences of concrete production are significant. The cement manufacturing process, in particular, is responsible for substantial greenhouse gas emissions, notably CO2 and NO2, which contribute to climate change and global warming [2]. In response to these challenges, researchers have been exploring sustainable alternatives, such as geopolymer binders. These binders, produced from aluminosilicate materials or industrial waste, provide an eco-friendlier solution compared to traditional Portland cement, while also offering faster setting times and improved durability [3].

Geopolymer concrete emerges as a promising alternative due to its ability to utilize silicon and aluminum-rich industrial by-products like Fly Ash (FA), Slag, and Red Mud (RM). The formation of a geopolymer involves the reaction of these materials with an alkaline solution, creating a strong binding phase that not only reduces the carbon footprint but also repurposes industrial waste, which would otherwise contribute to environmental degradation [4]. Among these materials, Red Mud is particularly noteworthy due to its high content of cementitious components such as calcium oxide, silicon dioxide, and iron oxide. Its properties make it an excellent candidate for replacing traditional raw cement [5]. Studies have shown that Red Mud-based geopolymer concrete exhibits improved durability and strength over conventional concrete, although its workability can be reduced. By incorporating methods like neutralization to address its alkalinity, Red Mud can be made safer for broader use, with its inert nature preventing environmental contamination. This research aims to further explore the potential of geopolymer concrete, incorporating Red Mud, Fly Ash, and Slag, and using both normal and recycled water, to develop a sustainable and high-performance construction material.

2. Literature Review

The environmental implications of traditional cement production, particularly its substantial carbon dioxide emissions, have driven the search for sustainable alternatives in construction. As cement plays a pivotal role in concrete, its environmental footprint necessitates the exploration of eco-friendly substitutes. Geopolymer concrete, utilizing industrial wastes such as Red Mud (RM), Slag, and Fly Ash (FA), has emerged as a viable alternative to conventional cement. According to [6] incorporating recycled materials in construction reduces dependency on virgin resources, while promoting environmental and economic benefits. Materials like quarry dust and foundry sand have been successfully integrated into concrete, providing sustainable alternatives to Portland cement and conserving natural resources.

One of the primary motivations for developing geopolymer materials is the mitigation of greenhouse gas emissions associated with Portland cement production. the potential of industrial waste, including RM, to produce geopolymer materials and Alkali-Activated Binders (AAB) [7]. These materials, derived from residual heavy metals, exhibit enhanced stability and contribute significantly to reducing environmental degradation [8]. The study noted that geopolymers not only offer improved mechanical performance but also align with environmental preservation efforts [9].

Red Mud, in particular, has gained attention due to its abundance of metallic oxides, high surface area, and stable dispersion properties, making it suitable for various industrial applications. Ongoing research has focused on incorporating RM into geopolymer binders, which has shown promising results in terms of mechanical and thermal properties. That geopolymer binders synthesized with Bayer Red Mud exhibited enhanced long-term strength, particularly with the addition of 20-30 wt. percentage silica fume (SF) [10]. The study observed that a lower solution-to-solid ratio further improved the strength of the material, achieving compressive strength of up to 31.5 MPa after 28 days. The geopolymerization of liquified aluminosilicate and silica produced condensed matrices, contributing to the material's overall strength and durability [11].

The integration of recycled water into geopolymer concrete further enhances sustainability by conserving freshwater resources [12-13]. The combination of industrial waste materials such as FA, Slag, and RM with recycled water not only addresses environmental concerns but also promotes the use of readily available and cost-effective alternatives [14]. This approach reduces carbon emissions and presents a practical solution for sustainable construction practices.

In summary, the reviewed literature demonstrates that the utilization of industrial wastes in geopolymer concrete provides a sustainable alternative to traditional Portland cement. The incorporation of RM, FA, and Slag, along with the use of recycled water, offers both environmental and economic advantages, making geopolymer concrete a promising material for the future of sustainable construction.

3. Materials used

The investigation made use of the following resources

- OPC – 43 Grade (in accordance with IS: 8112-2013)
- Natural Sand (in accordance with IS: 383-2016)
- Coarse aggregates (20 mm down) (in accordance with to IS: 383-2016)
- Red Mud (RM), Fly ash (FA), Slag
- Alkali Activator mixture.
- Recycled water from hostel and hotel is used in the geopolymer concrete work. The suitability of this recycled water for concrete is tested, with the results confirming its adequacy for concreting purposes.

A ratio of 2.0 was used for sodium Hydroxide to Sodium Silicate ratio ($NaOH/ Na_2SiO_3$). Where a solution is created by mixing one part of Na_2SiO_3 with two parts NaOH with NW and RW.

4. Methodology and Model Specifications

1. Material Preparation: Red Mud (RM), Fly Ash (FA), and Slag were collected and processed to ensure consistency in particle size for optimal geopolymerization [15].

2. Alkali Activator Solution: Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was prepared in a 2:1 ratio, using both normal water (NW) and recycled water (RW).
3. Mix Design: Various geopolymer concrete mixes were designed, incorporating RM, FA and Slag, with adjustments in activator concentration [16].
4. Casting and Curing: Specimens were cast in standard moulds and cured at ambient temperature for 24 to 48 hours.
5. Mechanical Testing: Compressive strength, flexural strength, and split tensile strength tests were conducted as per IS standards [17].
6. Results were analyzed to assess the mechanical performance and environmental impact of the geopolymer concrete.

5. Test Results of Mechanical Properties

Compressive Strength (MPa)

The graph shows that geopolymer concrete has slightly lower compressive strength than conventional concrete.

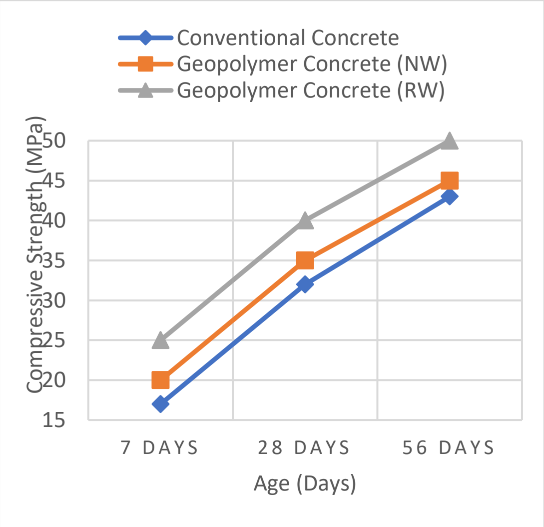

Figure 1: Compressive Strength values for Conventional, GPC with NW and RW

However, it is still a sustainable and viable option, particularly with recycled water. Geopolymer concrete with normal water consistently outperforms conventional concrete.

Spilt Tensile Strength (MPa)

The graph shows the split tensile strength comparison over 7, 28, and 56 days. Geopolymer concrete with normal water consistently outperforms conventional concrete.

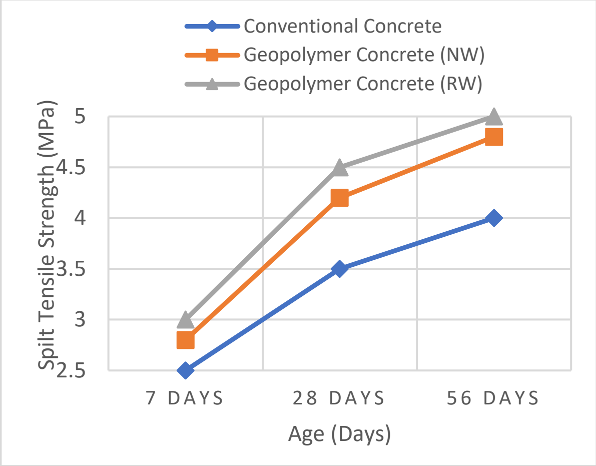

Figure 2: Spilt Tensile Strength values for Conventional, GPC with NW and RW

Flexural Strength (MPa)

The graph shows the flexural strengths of conventional and geopolymer concrete made from Fly Ash (50%), Red Mud (25%), and Slag (25%) over 7, 28, and 56 days. It compares the use of normal water (NW) and recycled water (RW).

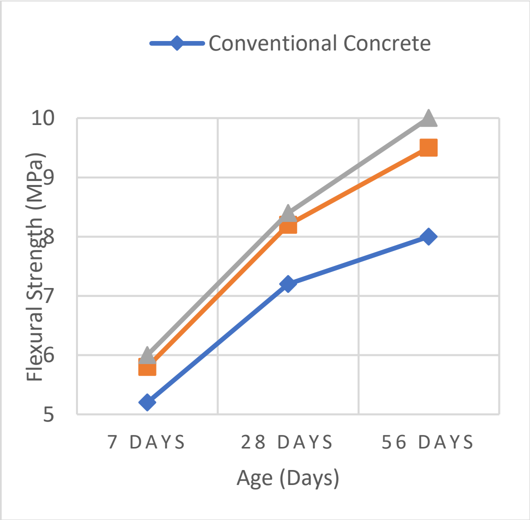

Figure 3: Flexural Strength values for Conventional, GPC with NW and RW

Geopolymer concrete has better flexural strength, especially at 56 days, making it a promising sustainable alternative to conventional concrete.

Conclusion

1) The incorporation of Red Mud (RM), Slag, and Fly Ash (FA) in the geopolymer concrete mix allows for the formulation of a more economical concrete alternative when compared to conventional concrete.

2) The workability of the geopolymer concrete developed in this study was found to be lower than that of conventional concrete, indicating a need for careful consideration in practical applications.
3) Mechanical strength tests revealed that the compressive strength of RM, Slag and FA-based geopolymer concrete utilizing both normal water (NW) and recycled water (RW) showed only marginal differences compared to the corresponding strengths observed in conventional concrete.
4) The target compressive strength of 43 N/mm² for geopolymer concrete was successfully achieved at 56 days, with the geopolymer concrete made with NW reaching 45 N/mm², indicating the effectiveness of the mix design ratios used.
5) The liquid-to-binder ratio was identified as a crucial factor in attaining the desired splitting tensile strength, with results of 4.8 N/mm² for geopolymer concrete with recycled water and 5.0 N/mm² for that with normal water, demonstrating only slight variation.
6) Flexural strength testing revealed that the geopolymer concrete with recycled water achieved a strength of 9.5 N/mm², while the strength for the concrete made with normal water was slightly higher at 10 N/mm² after 56 days, indicating comparable performance in both cases.

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