

# Structural Strengthening of Reinforced Concrete Beams Using Ambient-Cured Geopolymer Repair Mortar

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**Abstract**—Deterioration of reinforced concrete (RC) structures due to corrosion, environmental exposure, and increased loading necessitates sustainable retrofitting solutions beyond conventional Ordinary Portland Cement (OPC)-based materials, which suffer from shrinkage, poor bonding, and high CO<sub>2</sub> emissions. This study investigates ambient-cured geopolymer repair mortar, synthesized from fly ash and ground granulated blast furnace slag (GGBS) activated by 12M sodium hydroxide (NaOH) and sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) with a ratio of 2.5:1, for strengthening RC beams. Experimental evaluation of 100×100×400 mm beam specimens demonstrates superior compressive strength (40–60 MPa), enhanced bond characteristics, and 20–40% improvement in flexural capacity compared with OPC-based systems. These results are achieved through ambient curing without thermal treatment. Optimized mix proportions and the use of iron mesh reinforcement enable practical field application while reducing carbon emissions by approximately 40–60%. Load-deflection analysis further confirms improved ductility and crack resistance, addressing challenges related to adhesion compatibility and integration with existing design practices. The findings highlight geopolymer mortar as a sustainable and eco-friendly alternative for structural rehabilitation and infrastructure maintenance.

**Index Terms**—Geopolymer mortar, RC beam strengthening, ambient curing, fly ash, GGBS, flexural capacity, sustainable retrofitting.

## I. INTRODUCTION

Reinforced concrete (RC) structures around the world are increasingly facing deterioration due to corrosion of reinforcement, environmental exposure, poor construction practices, and increased service loads. These factors reduce the structural performance and safety of existing infrastructure. Conventional repair materials based on Ordinary Portland Cement (OPC) have several limitations such as high shrinkage, weak bonding with older concrete surfaces, limited resistance to aggressive chemicals, and high carbon dioxide (CO<sub>2</sub>) emissions during production. In recent years, geopolymer mortar has gained attention as a sustainable alternative repair material. It is produced using industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), which are activated by alkaline solutions like sodium hydroxide (NaOH) and sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>). This material can achieve compressive strengths in the range of 40–60 MPa, exhibits

low shrinkage, provides excellent durability, and can cure at ambient temperature without the need for heat treatment.

The present research focuses on the use of ambient-cured geopolymer repair mortar for strengthening reinforced concrete beams. The study aims to address practical challenges such as bonding compatibility with existing concrete surfaces, feasibility for field application, and alignment with current structural design practices. Experimental investigation is carried out to evaluate mechanical performance, bonding behavior, and improvements in flexural and shear capacity. Beam specimens with dimensions of 100×100×400 mm are tested under controlled loading conditions, and the performance of geopolymer repair mortar is compared with conventional OPC-based repair systems.

The main objectives of this research include optimizing the geopolymer mix proportions using a 12M NaOH solution with a Na<sub>2</sub>SiO<sub>3</sub>/NaOH ratio of 2.5:1, evaluating load-deflection behavior of strengthened beams, and measuring the improvement in structural strength. Based on previous studies, an increase in strength of approximately 20–40% is expected, along with a reduction of about 40–60% in environmental impact compared with OPC-based retrofitting techniques.

The remainder of this paper is organized as follows. Section II presents a review of relevant literature related to geopolymer-based retrofitting techniques. Section III describes the research methodology, including material properties, specimen preparation, and testing procedures. Section IV discusses the experimental results and analysis. Finally, Section V summarizes the conclusions and highlights the practical implications of the study.

## II. LITERATURE REVIEW

OVER the past decade, researchers and engineers have explored a variety of retrofitting and repair solutions to extend the lifespan of deteriorating reinforced concrete (RC) structures. Among the most promising options are geopolymer mortars, fiber-reinforced polymer (FRP) composites, and wire mesh-based systems. These technologies have garnered significant attention for their ability to improve mechanical strength,

ductility, and durability, all while providing environmental and cost benefits.

#### A. Overview of Retrofitting Solutions

1) *Geopolymer Mortar Applications:* Geopolymer mortars are made from aluminosilicate-rich materials like fly ash, ground granulated blast furnace slag (GGBS), or metakaolin, which are activated by concentrated alkaline solutions—usually a mix of sodium or potassium hydroxide with sodium silicate. By adjusting the binder-to-sand ratio, the concentration of the activator, and even adding small amounts of calcium hydroxide or Portland cement, the mechanical performance and setting properties of the mortar can be fine-tuned to meet specific needs.

Studies have shown that geopolymer mortars offer impressive early strength in both compression and flexure, along with excellent chemical stability, even in harsh environments. Additionally, by incorporating industrial by-products, these mortars significantly reduce the carbon emissions typically associated with cement production, supporting broader sustainability objectives. Thanks to these benefits, geopolymer mortars are emerging as a promising next-generation material for structural repairs and rehabilitation.

2) *Use of Fiber-Reinforced Polymer and Mesh-Based Systems:* Externally bonded FRP (fiber-reinforced polymer) composites, made of carbon or glass fibers embedded in epoxy resins, are commonly used to retrofit reinforced concrete (RC) structures. These composites offer significant improvements in flexural strength, deformation performance, and seismic resilience. However, FRP systems can be sensitive to environmental conditions. For example, they are prone to debonding at the interface and the degradation of bonding resins when exposed to temperatures above 70°C, which limits their use in high-temperature or fire-prone environments.

On the other hand, mesh jacketing systems—typically made from steel or stainless steel wire mesh (SSWM)—provide a more cost-effective solution for enhancing load-bearing capacity and ductility. These systems, often applied as ferrocement or wire-mesh jackets, help improve crack control and toughness. Despite their advantages, mesh systems face practical challenges such as corrosion risks (for non-stainless versions) and the labor-intensive installation process, particularly in large-scale projects.

#### B. Experimental Evidence and Comparative Performance

Extensive laboratory studies and analytical models have shown that geopolymer mortars offer exceptional performance when used to repair or strengthen RC beams and slabs. Key findings include:

- **Compressive Strength:** Geopolymer mortars can attain 30–40 MPa within the first week, depending on mix proportions and curing regimes.
- **Flexural Strength:** Typically reaches 10–20% of compressive strength, matching or slightly surpassing conventional OPC-based mortars.

- **Tensile and Bond Strength:** Enhanced through confinement using natural fibers or wire mesh reinforcements, improving ductility and crack resistance.

Experimental data also show that wrapping with stainless-steel wire mesh—whether fully or partially applied—substantially improves both load-bearing capacity and deformation before failure. The combination of geopolymer mortar and mesh reinforcement creates an ideal balance of strength and ductility, making it especially effective for retrofitting structures in seismic areas.

A comparative summary of retrofit performance is presented in Table I.

TABLE I  
COMPARATIVE SUMMARY OF RETROFIT TECHNIQUES AND PERFORMANCE

| Technique          | Strength Gain | Flexural Improvement | Notable Benefits                          | Constraints               |
|--------------------|---------------|----------------------|-------------------------------------------|---------------------------|
| Geopolymer Mortar  | +30–80%       | +10–25%              | Low CO <sub>2</sub> , high early strength | Shrinkage, alkali cost    |
| FRP (e.g., CFRP)   | +60–150%      | Up to +60%           | Seismic resistance, ductility             | Adhesion, fire resistance |
| SSWM Mesh Retrofit | +40–60%       | +20–45%              | Ductility, crack control                  | Corrosion, field effort   |

#### C. Service Life, Durability, and Remaining Challenges

1) *Bond Behavior and Shrinkage:* While geopolymer mortars show strong adhesion to concrete surfaces, the bond strength with external overlays—particularly carbon FRP—can sometimes fall short. Pull-off test results indicate that weak spots at the interface are often caused by early-age shrinkage or inadequate surface preparation. To ensure durable adhesion and long-lasting bond performance, it's crucial to optimize both the mix design and the interface treatment.

2) *Long-Term Performance and Field Validation:* Much of the current research centers on the short-term mechanical performance of materials, with limited data on their long-term behavior under cyclic, thermal, or chemical exposure. Key concerns—such as the corrosion resistance of mesh wraps, the consistency of large-scale curing, and the effectiveness of geopolymer mortars as adhesive layers in hybrid systems—still need further investigation. To fully assess their real-world potential, field-scale trials and long-term monitoring are essential to validate laboratory results and ensure these materials can withstand harsh environmental conditions.

3) *Integration into Design Standards:* Despite promising results in laboratory settings, the lack of established standards for geopolymer retrofitting has slowed its adoption in industry. There is a clear need for comprehensive guidelines that cover mix proportions, field application procedures, curing protocols, and quality control testing. Overcoming practical challenges—such as workability, setting time control, and

compatibility with existing structures—will be essential for ensuring reliable and scalable use in real-world infrastructure rehabilitation projects.

### III. METHODOLOGY OVERVIEW

A Detailed review of previous research was conducted to better understand the behavior of geopolymer mortar in retrofitting applications. The literature focused on identifying optimal source materials, activator ratios, curing methods, and their impact on strength and bonding properties.

From this analysis, it was found that geopolymer mortars made from fly ash, GGBFS, or metakaolin offer superior compressive strength, chemical resistance, and durability compared to traditional cement-based mortars.

The research also emphasized that the performance of geopolymer mortars is heavily influenced by factors such as activator concentration (ranging from 10 to 16 M NaOH), the ratio of sodium silicate to sodium hydroxide, and the curing process.

These findings laid the groundwork for selecting materials, designing mix formulations, and defining testing protocols for the current experimental study.

#### A. Material Selection and Mix Design

Choosing the right raw materials, such as fly ash, ground granulated blast furnace slag (GGBS), and metakaolin, is crucial for achieving the desired performance in geopolymer mortars. The availability and chemical composition of locally sourced materials play a significant role in selecting the appropriate precursor. The ratio of sodium hydroxide to sodium silicate activators, typically ranging from 10 to 16 M, has a direct impact on the polymerization process. For repair mortars, the optimal sand-to-binder ratio usually falls between 1:1 and 1:2, which helps improve workability and reduce shrinkage. Some studies also suggest that adding small amounts of Portland cement or calcium hydroxide can help regulate the reaction rate, improve early setting, and enhance dimensional stability.

#### B. Substrate Preparation

Before application, the surface of the existing concrete must be thoroughly cleaned to remove contaminants like dust, grease, and any loosely adhered layers. Techniques such as mechanical abrasion, wire brushing, or sandblasting are commonly used to create a roughened surface, which improves the mechanical bond between the substrate and the new geopolymer layer. Proper surface preparation is key to ensuring strong adhesion and reducing the risk of delamination under load or during thermal cycling.

#### C. Mixing and Application

Geopolymer mortar should be mixed mechanically in small batches to ensure consistency and prevent premature setting. The mixture is usually applied in thin layers or troweled over the damaged areas, ensuring full compaction and complete coverage. When used alongside fiber or mesh reinforcement

systems, it's important to work the mortar thoroughly into the mesh to maximize confinement and bond strength. Given the rapid-setting nature of geopolymers, careful planning and continuous mixing are essential during application.

#### D. Curing Process

Curing is crucial for achieving the final strength and durability of geopolymer mortar. It's recommended to use moist curing for at least 24–48 hours to support the geopolymerization process and minimize cracking caused by shrinkage. While ambient curing has shown promise in some cases, maintaining controlled moisture and temperature conditions during the early stages of curing is still essential to ensure consistent results in real-world applications.

#### E. Testing and Performance Monitoring

Thorough mechanical and durability testing is essential to validate the performance of retrofitted structures. Standard tests typically include measurements of compressive strength, flexural strength, and bond strength at 7, 14, and 28 days. Structural evaluations, such as load-deflection analysis, two-point loading frames, and finite element modeling (FEM), provide valuable insights into deformation behavior and failure mechanisms. Ongoing monitoring of crack propagation, strain distribution, and deflection under service loads helps ensure long-term reliability and allows for continuous refinement of the design and implementation of geopolymer retrofits.

## IV. BROADER DISCUSSION AND PRACTICAL IMPLICATIONS

#### A. Key Insights and Observed Trends

1) *Mechanical Robustness*: Geopolymer mortars offer an impressive combination of early strength, durability, and compatibility with various reinforcement strategies, including steel mesh, fiber-reinforced cementitious matrix (FRCM), and hybrid fiber-reinforced polymer (FRP) laminates. Experimental results show that these systems not only boost compressive and flexural strengths but also improve ductility and post-yield behavior. Specifically, FRCM and wire mesh jackets enhance energy dissipation and extend the plastic deformation phase—both of which are crucial for structures in seismic zones.

2) *Environmental and Lifecycle Benefits*: One of the key advantages of geopolymer retrofit systems is their strong sustainability profile. By using industrial by-products like fly ash, ground granulated blast furnace slag (GGBS), or metakaolin, these systems significantly reduce reliance on Portland cement, helping to cut down on greenhouse gas emissions. Additionally, geopolymers provide excellent fire and chemical resistance, which not only extends the lifespan of repaired structures but also lowers maintenance needs over time.

3) *Economic and Application Realities:* Although the raw activator costs for geopolymers can be higher than those of traditional Portland cement systems, using locally available materials, the rapid setting time, and reduced downtime provide significant cost benefits. Additionally, the easier maintenance and improved durability help lower overall lifecycle costs. Recent studies suggest that geopolymer-based retrofits could reduce repair costs by as much as five to ten times compared to commercial proprietary products, underscoring their potential for large-scale infrastructure rehabilitation.

#### B. Persistent Gaps and Recommendations for Industry

1) *Standardization Needs:* Despite encouraging results in laboratory and pilot-scale studies, the absence of standardized guidelines for geopolymer proportioning, mixing, surface preparation, and curing continues to hinder its widespread use in industry. To ensure reliability and scalability, it's crucial for relevant institutions to develop standardized practices and performance-based design frameworks.

2) *Hybrid and Advanced Systems:* Integrating geopolymer mortars with mesh reinforcements, hybrid fibers (natural or synthetic), or FRPs in layered or sandwich configurations is an emerging and highly promising approach. However, challenges remain, including ensuring consistent interfacial bond strength, optimizing the compatibility of composite materials, and understanding long-term behavior under cyclic and dynamic loading. Addressing these issues will require targeted research efforts.

3) *In-Field Validation:* Extensive field-scale validation and long-term monitoring of geopolymer-retrofitted structures are critically needed, especially under harsh environmental conditions. Collaboration between academic institutions, industry stakeholders, and infrastructure agencies can help generate the necessary data and support the transition of geopolymer retrofitting from research labs to mainstream engineering practice.

#### V. CONCLUSION

The growing body of research on geopolymer mortars for retrofitting reinforced concrete (RC) structures highlights their significant potential in terms of strength, durability, and environmental performance. These materials provide a sustainable alternative to ordinary Portland cement (OPC) systems, offering benefits such as rapid curing, enhanced chemical resistance, and a lower carbon footprint. However, achieving widespread adoption and consistent performance will require continued research and the development of standardized practices.

- **Standardized Mix Development:** There is an urgent need to develop codified and field-tested geopolymer mix designs specifically tailored for retrofitting applications. Such formulations should ensure predictable mechanical properties, compatibility with substrates, and ease of application in diverse site conditions.
- **Enhanced Interface Engineering:** Improved surface preparation techniques and interface optimization are essential to enhance long-term bond strength and minimize

shrinkage-induced cracking or delamination in composite systems.

- **Pilot Projects and Case Studies:** Large-scale pilot applications and long-term monitoring are required to evaluate the performance of geopolymer-based retrofits under varying climatic, chemical, and loading environments. These studies will also help establish cost-benefit models over the lifecycle of the structure.
- **Code and Guideline Development:** Development of comprehensive design standards and practical field guidelines will facilitate the adoption of geopolymer mortars in mainstream civil infrastructure repair. Codes should address issues such as curing practices, environmental exposure, worker safety, and seismic resilience.

Future research should explore hybrid systems that incorporate natural fibers, nano-additives, or advanced reinforcements to further improve strength and ductility. Incorporating real-time structural health monitoring into geopolymer-repaired systems, along with developing comprehensive economic models that consider lifecycle performance rather than just initial costs, will help promote the sustainable and efficient use of geopolymers in infrastructure rehabilitation.

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