

Retrofitting Using Geopolymer Mortar: A Strength Study

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Abstract—Abstract—One of the biggest challenges facing civil engineers today is improving the durability of deteriorating reinforced concrete (RC) structures. Conventional repair techniques that rely on Portland cement are energy-intensive and fall short in long-term durability and sustainability. Geopolymer mortar, produced from industrial by-products such as fly ash, ground granulated blast furnace slag, and metakaolin activated with alkaline solutions, has emerged as a promising eco-friendly alternative. This paper systematically reviews experimental and comparative research on geopolymer mortar used for structural retrofitting, including hybrid systems employing fiber-reinforced polymer and wire mesh reinforcement. The review synthesizes evidence on mechanical performance, sustainability benefits, and current limitations, and proposes directions for future research. Geopolymer mortars demonstrate high early compressive strength, favorable bond characteristics, and reduced carbon footprint relative to ordinary Portland cement mortars, though challenges related to shrinkage, standardization, and long-term field validation remain to be addressed.

Index Terms—fiber-reinforced polymer, geopolymer mortar, retrofitting, structural rehabilitation.

I. INTRODUCTION

As urban areas expand and infrastructure ages, ensuring the safety and functionality of concrete structures has become increasingly critical. Bridges, slabs, columns, and beams are susceptible to damage from unpredictable loads, steel corrosion, and harsh environmental exposure. Conventional repair techniques—including cement overlays—frequently prove inadequate in addressing cracking, debonding, and shrinkage, and they carry a significant environmental cost owing to the energy intensity of cement production.

Geopolymer mortar presents a sustainable alternative by utilizing industrial waste materials such as fly ash or slag, substantially reducing CO₂ emissions. Nevertheless, many practicing engineers remain in the early stages of understanding both the benefits and limitations of these materials. This paper provides a detailed, balanced review of how geopolymer mortars can be applied to structural repair and retrofitting, drawing on existing literature, practical applications, and current industry trends.

II. LITERATURE REVIEW

Over the past decade, researchers and engineers have proposed numerous retrofitting and repair techniques to ex-

tend the service life of deteriorating RC structures. Among the most promising are geopolymer mortars, fiber-reinforced polymers (FRP), and wire mesh systems—all of which enhance mechanical strength, ductility, and durability while remaining cost-effective and environmentally conscious.

A. I. Overview of Retrofitting Solutions

1) *Geopolymer Mortar Applications*: Geopolymer mortars are produced from aluminosilicate-rich materials—fly ash, ground granulated blast furnace slag (GGBFS), and metakaolin—activated by concentrated alkaline solutions, typically combinations of sodium or potassium hydroxide and sodium silicate. By varying the binder-to-sand ratio, alkaline concentration, and minor additions of calcium hydroxide or Portland cement, the properties of the mortar can be tailored for specific repair scenarios.

Investigations confirm that geopolymer mortars achieve high early compressive and flexural strength and exhibit excellent chemical stability, even under elevated exposure conditions. Because they incorporate industrial by-products, their carbon footprint is significantly lower than that of conventional cement-based systems, establishing geopolymer mortars as materials of choice for the next generation of structural rehabilitation.

2) *Use of Fiber-Reinforced Polymer and Mesh-Based Systems*: Externally bonded FRP composites—carbon or glass fibers set in an epoxy matrix—are among the most widely used materials for strengthening RC structures, delivering measurable improvements in flexural strength, deformation capacity, and seismic resistance. However, FRP systems are susceptible to environmental degradation: debonding at the interface and resin degradation become significant above approximately 70 °C.

Wire mesh jacketing—using steel or stainless steel wire mesh (SSWM)—offers a cost-effective means of increasing structural capacity and improving toughness. Challenges include corrosion risk in non-stainless meshes and the labor intensity of field installation.

B. II. Experimental Evidence and Comparative Performance

Laboratory research has consistently demonstrated the high performance of geopolymer mortars in the repair and strengthening of RC beams and slabs, with the following key findings:

- **Compressive Strength:** Geopolymer mortars attain 30–40 MPa within the first week of application, depending on mix proportions.
- **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 reinforcement, improving ductility and crack resistance.

Experimental data further show that stainless steel wire mesh wrapping—both full and partial—significantly raises the load capacity and deformation at failure. The combination of geopolymer mortar with wire mesh provides an optimal balance of strength and ductility, making it particularly suitable for structures in seismic zones.

A comparative summary of retrofit performance across the three principal techniques is presented in Table 1.

TABLE I
TABLE 1. COMPARATIVE SUMMARY OF RETROFIT TECHNIQUES AND PERFORMANCE

Technique	Strength Gain	Flexural Improve.	Notable Benefits	Constraints
Geopolymer Mortar	+30–80%	+10–25%	Low CO ₂ , high early strength	Shrinkage, alkali cost
FRP (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. III. Service Life, Durability, and Remaining Challenges

1) **Bond Behavior and Shrinkage:** Although geopolymer mortar generally adheres satisfactorily to concrete substrates, bond strength at the overlay interface—particularly for carbon FRP systems—can fall short of requirements. Pull-off testing identifies early-age shrinkage and inadequate surface preparation as primary sources of interfacial weakness. Careful surface preparation is therefore essential for achieving reliable adhesion.

2) **Long-Term Performance and Field Validation:** Much of the existing research is limited to short-term mechanical characterization; data on long-term behavior under cyclic, thermal, and chemical loading remain scarce. Open questions include the corrosion performance of mesh wraps, the reproducibility of large-scale curing, and the effectiveness of geopolymer mortars as adhesives in hybrid systems. Field-scale testing and ongoing structural monitoring are necessary to bridge the gap between laboratory observations and real-world durability.

3) **Integration into Design Standards:** The absence of codified standards for geopolymer retrofitting procedures—covering mix proportioning, application method, and curing—continues to impede widespread adoption. Standardized guidelines addressing workability, setting time control, and compatibility with existing substrates are urgently needed.

III. METHODOLOGY OVERVIEW

A comprehensive review of prior research was conducted to evaluate the performance of geopolymer mortar in retrofitting applications. The review focused on identifying optimal source materials, binder-to-sand ratios, alkaline activator concentrations, curing conditions, and their combined influence on strength development.

The review established that geopolymer mortars produced from fly ash, GGBFS, or metakaolin consistently outperform conventional OPC-based mortars in strength, chemical resistance, and durability. Activator concentration—typically ranging from 10 M to 16 M NaOH—and the ratio of sodium silicate to sodium hydroxide solution were identified as primary variables governing polymerization rate and final strength.

A. I. Material Selection and Mix Design

Selection of precursor materials—fly ash, GGBS, or metakaolin—depends on local availability and the target mechanical properties. A sodium hydroxide concentration of 10–16 M combined with sodium silicate solution is recommended for effective polymerization. A binder-to-sand ratio of 1:1 to 1:2 is advised for repair mortars to balance workability and shrinkage control. Minor additions of Portland cement or calcium hydroxide can moderate reaction rates and improve dimensional stability.

B. II. Substrate Preparation

The substrate concrete must be thoroughly cleaned to remove dust, grease, and loosely bound material. Mechanical abrasion, wire brushing, or sandblasting creates the surface roughness necessary for adequate mechanical interlock. Proper surface preparation is critical for preventing de-lamination and ensuring long-term adhesion.

C. III. Mixing and Application

Geopolymer mortar should be mechanically mixed in small batches to guarantee uniformity and prevent premature setting. The mixture is applied in thin layers, troweled onto the damaged area with full compaction and coverage. When used with fiber or mesh reinforcement, the mortar must be thoroughly worked into the mesh to achieve optimal confinement and bond strength. As a fast-setting material, geopolymer mortar demands careful scheduling and continuous mixing during application.

D. IV. Curing Process

Curing conditions directly influence the final strength and durability of the geopolymer mortar. Moist curing for a minimum of 24–48 hours is recommended. While ambient curing has yielded promising results, maintaining controlled temperature and moisture during the initial curing period is critical for producing consistent outcomes in field applications.

E. V. Testing and Performance Monitoring

Validation of retrofitted structures requires both mechanical and durability testing. Standard tests include compressive strength, flexural strength, and bond (pull-off) strength evaluated at 7, 14, and 28 days. Structural performance is assessed through load-deflection measurements, two-point loading frames, and finite element modeling. Continuous monitoring of crack propagation, strain distribution, and deflection is essential for comprehensive performance validation.

IV. BROADER DISCUSSION AND PRACTICAL IMPLICATIONS

A. I. Key Insights and Observed Trends

1) *Mechanical Robustness:* Geopolymer mortars exhibit strong early strength, excellent durability, and compatibility with a broad range of reinforcement systems including steel meshes, fiber-reinforced cementitious matrix (FRCM) composites, and hybrid FRP laminates. Laboratory evidence confirms that these reinforcement systems increase not only strength but also ductility; FRCM composites and wire meshes, in particular, enhance energy dissipation capacity and the extent of the plastic deformation phase—both critical attributes for earthquake-prone regions.

2) *Environmental and Lifecycle Benefits:* A key advantage of geopolymer-based retrofitting is its environmental performance. Replacing Portland cement with industrial by-products (fly ash, GGBS, metakaolin) substantially reduces greenhouse gas emissions. Additionally, the inherent fire and chemical resistance of geopolymers extends the service life of retrofitted structures and reduces lifecycle maintenance costs.

3) *Economic and Application Realities:* Although alkaline activators can elevate initial material costs relative to traditional OPC systems, the use of locally sourced precursors, fast setting times, and minimal structural downtime can yield significant overall savings. Current research indicates that geopolymer-based retrofits can achieve cost savings of five to ten times compared to commercial proprietary repair systems, underscoring their potential for large-scale infrastructure renewal.

B. II. Persistent Gaps and Recommendations for Industry

1) *Standardization Needs:* Despite promising laboratory and pilot-scale results, the absence of standardized guidelines for geopolymer proportioning, mixing, surface preparation, and curing continues to restrict industrial adoption. Development of recognized codes and design methods by relevant standards bodies is an immediate priority.

2) *Hybrid and Advanced Systems:* Geopolymer mortars combined with mesh reinforcement, hybrid fibers, or FRP composites in stacked or sandwich configurations represent a promising frontier. Unresolved issues include interfacial bond strength, composite material compatibility, and long-term performance under cyclic and dynamic loading—all requiring targeted research effort.

3) *In-Field Validation:* Field-scale validation of geopolymer-retrofitted structures, supported by long-term monitoring under realistic environmental conditions, is critically needed. Collaboration among academic institutions, industry partners, and infrastructure agencies will be essential to generate the evidence base required to translate laboratory findings into standard engineering practice.

V. CONCLUSION

The body of research reviewed confirms that geopolymer mortars hold substantial promise for the retrofitting of RC structures, offering improved strength, durability, and sustainability relative to conventional OPC-based systems. Rapid curing, enhanced chemical resistance, and a markedly reduced environmental impact position geopolymer mortars as a viable mainstream repair material. Realizing this potential, however, requires the following targeted actions:

- **Standardized Mix Development:** Codified geopolymer mix designs tailored to retrofitting applications are needed to ensure consistent mechanical properties and ease of field application across varying site conditions.
- **Enhanced Interface Engineering:** Improved surface preparation protocols and interface optimization techniques are essential for maximizing bond strength and mitigating shrinkage cracking or debonding in composite systems.
- **Pilot Projects and Case Studies:** Large-scale pilot projects with long-term observation programs are required to assess geopolymer retrofit effectiveness under diverse climatic, chemical, and loading conditions and to establish credible cost-benefit relationships.
- **Code and Guideline Development:** Comprehensive design standards and practical field guidelines—addressing curing practices, environmental exposure, worker safety, and seismic resilience—will accelerate mainstream adoption.

Future research should investigate hybrid systems incorporating natural fibers, nano-additives, or advanced reinforcements to further improve strength and ductility. Integration of real-time structural health monitoring into geopolymer-repaired elements, coupled with lifecycle economic models that move beyond initial cost comparisons, will further support the sustainable deployment of geopolymers in infrastructure rehabilitation.

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