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Review on Structural Performance of Composite Structures with Geopolymer Concrete and FRP Reinforcement

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Abstract

Geopolymer concrete, utilizing industrial solid waste as raw materials, demonstrates low-carbon environmental friendliness and exceptional durability, making it an ideal alternative to traditional cement concrete. Fiber-reinforced plastic (FRP) bars possess advantages such as corrosion resistance, lightweight properties, and high strength, fundamentally addressing steel reinforcement corrosion issues. The composite structural system formed by these two materials shows broad application prospects in corrosive environments, underground engineering, and seismic-resistant structures. This article summarizes the interfacial bonding mechanisms between FRP bars and various concrete matrices, microscopic simulation methods, as well as the load-bearing and seismic performance of composite components. It identifies current research limitations in material stability, accelerator compatibility, specialized admixtures, interfacial mechanisms, and structural design. The study also outlines directions for multi-solid waste synergy, green activation techniques, interfacial modification, and engineering applications, providing references for future research and practical engineering in this field.

Keywords

Geopolymer Concrete; FRP Reinforcement; Interfacial Bonding; Mechanical Properties; Durability; Composite Structure.

1. Introduction

Conventional Portland cement production is characterized by high energy consumption and carbon emissions, while steel reinforcement corrosion significantly compromises the durability of concrete structures, particularly in marine, saline-alkali, and chemical corrosive environments [1,2]. Geopolymer concrete, prepared from alkali-activated fly ash, slag, coal gangue, and other silicoaluminous solid wastes, emits only 9% of carbon compared to traditional concrete while exhibiting superior acid/alkali resistance, freeze-thaw resistance, and alkali resistance [3,4,5]. Fiber-reinforced plastics (FRP) tendons (especially GFRP tendons) demonstrate high tensile strength and excellent corrosion resistance, making them ideal alternatives to steel reinforcement [1,2,6,7].

The integration of geopolymer concrete with FRP reinforcement enables complementary material advantages, facilitating the development of low-carbon and durable novel composite structures. Current research by scholars worldwide has extensively explored performance modulation of geopolymer concrete [3,8,9,10,11], interfacial bonding between FRP reinforcement and concrete [1,2,6,12,13], and load-bearing performance of composite components [7,14], yet systematic review outcomes remain lacking. This article adopts the "researcher–research content–core conclusions" paradigm to comprehensively present research advancements in this field.

2. Research Progress on Geopolymer Concrete

2.1 Raw Materials and Reaction Mechanism

Zhang Dawang and Wang Dongmin [3] conducted a systematic review of raw material systems for geopolymer concrete, highlighting that cementitious materials primarily consist of industrial solid wastes rich in silicon and aluminum, including fly ash, slag, coal gangue, and kaolinite. While fly ash is the most widely used material, it exhibits low early strength. Slag significantly enhances early strength and structural density, whereas solid wastes like coal gangue further reduce costs and carbon emissions [3,9,10]. Regarding accelerators, the NaOH-sodium silicate composite system is the most prevalent choice, offering high activation efficiency but poor workability. Tempest et al. proposed a silica fume-NaOH formulation that reduces energy consumption while improving concrete strength [3].

Regarding the reaction mechanism, Davidovits classified the alkali activation process into three stages: dissolution, monomer reconstruction, and polycondensation, ultimately forming a three-dimensional network structure composed of N-A-S-H and C-(A)-S-H gels [3]. Deventer, Fernandez-Jimenez, and others separately proposed a four-step mechanism and microstructural model for fly ash alkali activation, providing theoretical support for performance control [3].

2.2 Mixing Ratio and Workability

Lloyd, Anuradha, Pavithra, and others have successively proposed mix design methods for fly ash geopolymer systems, but a unified standard has yet to be established [3]. Provis et al. found that the Si/Al ratio, specific surface area, and accelerator/cement ratio of fly ash directly influence strength and workability, with geopolymer 7-day strength reaching 87% of 28-day strength—significantly faster than conventional concrete [3]. Geopolymer concrete exhibits rapid setting, poor workability, and poor compatibility with traditional admixtures. Chang and Bilim demonstrated that phosphate retarders effectively extend setting time, with K_2HPO_4 showing optimal performance without strength loss. Bakharev and Puertas observed unstable effects of lignosulfonate and naphthalene-based superplasticizers, while only modified polycarboxylate superplasticizers improved workability, indicating that specialized admixtures remain in the early stages of development [3].

2.3 Mechanical Properties

Zhang Dawang et al. [3] concluded that the fly ash-mineral slag composite system enables room-temperature curing with compressive and flexural strengths meeting engineering requirements. Lodeiro et al. pointed out that the early formation of large amounts of N-A-S-H and C-(A)-S-H gels is the core reason for rapid strength development [3]. Additional studies demonstrated that geopolymer concrete exhibits excellent dynamic splitting tensile energy absorption characteristics and superior impact resistance compared to conventional concrete [4]. Both fly ash-bioclinker and slag-fly ash composite systems demonstrate stable mechanical properties, making them adaptable to various strength grade requirements [8,9].

2.4 Durability Performance

Geopolymer concrete demonstrates significantly superior durability compared to conventional concrete. Bakharev and Puertas et al. demonstrated that low-calcium systems lack the $Ca(OH)_2$ decalcification process, resulting in enhanced carbonation resistance [3]. Shi and Fu et al. found that these systems exhibit well-developed gel pores with minimal capillary pores, achieving a mass loss of less than 6% after 300 freeze-thaw cycles and exhibiting excellent frost resistance [3]. Provis and Tennakoon et al. confirmed that low calcium content effectively inhibits alkali-aggregate reactions, with expansion rates far below regulatory limits [3].

Zhu Junmin [15] investigated the corrosion resistance of cement-silica fume-mineral slag-fly ash composite systems against carbonated water, determining the optimal formulation ratio of 19.39% silica fume + 10.61% mineral slag + 0% fly ash, which significantly reduces mass and strength loss. Wang Minglei [10] and Lin Jiachun [11] separately studied polymer-based materials derived from coal gangue and coal gangue-mineral slag-fly ash bases, respectively. Their research demonstrated that multi-solid waste compounding can synergistically enhance strength and durability while optimizing microstructure and interfacial effects.

3. Study on Bonding Performance of FRP Strips at Concrete Interfaces

3.1 GFRP tendon bonding with ordinary/resin concrete

Yan Shilin, Zhang Yan et al. [1] conducted pull-out tests and beam bending tests, with results demonstrating that GFRP reinforcement surface fiber wrapping treatment significantly enhances bonding strength, exhibiting superior bonding performance with furan resin concrete compared to ordinary concrete. The ultimate load capacity of GFRP reinforced beams is slightly higher than that of steel-reinforced beams, but they demonstrate greater deflection and excellent corrosion resistance, achieving comparable comprehensive cost-performance ratios to steel-reinforced beams.

3.2 Bonding of GFRP Reinforced Bars with Regenerated Concrete

Zhang Weidong, Wang Zhenbo et al. [2] conducted 12 pull-out tests and drew four key conclusions: (1) increased replacement rate of recycled coarse aggregate leads to reduced GFRP reinforcement bond strength; (2) higher concrete strength correlates with greater bond strength; (3) larger reinforcement diameters decrease bond strength due to shear lag effect; (4) failure modes predominantly involve pull-out damage, while low-strength concrete is prone to splitting failure.

3.3 Interface Micromechanical Simulation

Li Shuwei and Zhang Zihua [6] established a three-dimensional fully mesoscopic model of FRP-reinforced concrete, considering the surface morphology of reinforcement materials, random aggregate in concrete, and interfacial mechanical interlocking effects. The simulation showed peak strength errors of only 3.75% and peak slip errors of 2.45%. The study demonstrated that increasing aggregate volume fraction and mortar matrix strength can significantly enhance interfacial bonding performance.

3.4 Bonding of GFRP Ribbed Bars to Alkali-Activated Matrix

Wang Qixiu [13] demonstrated through experiments that the bond strength of GFRP ribbed bars is significantly higher than that of smooth bars, with rib geometric parameters directly influencing bond-slip behavior. Further research on the bond performance between alkali-activated concrete and FRP bars revealed a dense interface transition zone where bond strength met design requirements. However, long-term performance and constitutive model studies remain insufficient.

4. FRP-Performance Study of Concrete Composite Components

4.1 Stress Performance of Composite Beams

Xie Wenjie [14] conducted experimental studies on GFRP profile-concrete composite beams, demonstrating excellent synergistic performance that fully leverages the tensile strength of GFRP and compressive strength of concrete. This makes the composite beams suitable for large-span, lightweight, and corrosion-resistant structural engineering applications.

4.2 Seismic Performance of Restraining Columns

Fu Xin [7] conducted seismic tests on FRP-reinforced concrete columns with GFRP confinement. The results demonstrated that GFRP confinement significantly enhances column ductility and energy dissipation capacity, exhibits a full hysteresis curve, and causes slow load-bearing capacity degradation, resulting in excellent seismic performance suitable for structures in seismic fortification zones.

5. Summary

(1) Geopolymer concrete utilizes industrial solid waste as raw materials, featuring low-carbon environmental friendliness and excellent mechanical and durability properties. The addition of silica fume and slag can enhance early strength and corrosion resistance, while synergistic utilization of multiple solid wastes further optimizes performance.

(2) NaOH-sodium silicate is the most commonly used accelerator, while phosphate retarders and modified polycarboxylate superplasticizers demonstrate relatively optimal water-reducing effects. Traditional admixtures exhibit poor compatibility.

(3) The bond strength of FRP tendons is significantly influenced by surface treatment, matrix strength, aggregate substitution rate, and tendon diameter. Ribbed tendons outperform smooth tendons, and the full mesoscopic model enables high-precision simulation of interfacial behavior.

(4) GFRP-FRP reinforced concrete columns and GFRP profiles with concrete composite beams exhibit excellent load-bearing capacity and seismic performance, demonstrating significant engineering application potential.

(5) The research still faces challenges such as unstable raw materials, excipient defects, lack of additives, unclear interfacial mechanisms, and structural design.

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