Review on Adhesion Properties of GFRP Reinforced Concrete Bonded with Coal Gangue-Powdered Fly Ash-Mine Slag Ternary Polymer Concrete

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Abstract

Tri-element geopolymer concrete prepared from coal gangue, fly ash, and slag composite materials represents a typical low-carbon green cementitious material. Glass fiber reinforced plastics (GFRP) tendons, due to their corrosion resistance, are widely used as alternatives to traditional steel reinforcement. The interfacial bonding performance between these components serves as the core for structural synergy. Based on existing domestic and international literature, this study systematically reviews current research progress from three perspectives: preparation of tri-element geopolymer matrices, interfacial bonding mechanisms between GFRP tendons and matrices, and influencing factors of bonding performance. It summarizes research subjects, experimental methods, key conclusions, and academic viewpoints from various scholars. The review indicates that coal gangue requires thermal and mechanical activation to enhance reactivity, demonstrating significant synergistic reinforcement effects among tri-element solid wastes. The interfacial bonding between GFRP tendons and geopolymer concrete primarily relies on mechanical interlocking forces, which are significantly influenced by matrix strength, tendon surface morphology, protective coatings, stirrups, and high-temperature conditions. Although current research has established a relatively comprehensive understanding of interfacial stress mechanisms, long-term durability and performance evolution under composite environments still require further refinement.

Keywords

GFRP Fiber; Coal Gangue; Fly Ash; Slag; Bonding Performance.

1. Introduction

China faces massive stockpiles of bulk industrial solid waste, making the resource utilization of coal gangue, fly ash, and slag a key research focus in the building materials sector [1]. Alkali-activated geopolymer, derived from solid waste, exhibits significantly lower carbon emissions than Portland cement while offering advantages like high strength and corrosion resistance. The coal gangue-fly ash-mineral slag ternary system has become the mainstream research approach due to its remarkable synergistic effects [2,3]. Glass Fiber Reinforced Plastic (GFRP) tendons, characterized by lightweight, high strength, and rust resistance, effectively address the durability limitations of reinforced concrete [4,5,6]. The interfacial bonding performance directly determines the load-bearing capacity of GFRP tendons and concrete, serving as a critical parameter in structural design.

Current research on specialized bonding between GFRP reinforcement and coal gangue-fly ash-mineral slag ternary polymer concrete remains fragmented and lacks systematic organization. This paper reviews relevant achievements, summarizes research progress and patterns, and clarifies future directions. Key findings include: experimental studies on GFRP-reinforced concrete bonding systems; interface properties of GFRP-reinforced concrete with single coal gangue mixtures; and preparation methods with mechanical characteristics of ternary solid waste-based polymer composites.

2. Research Progress on Ternary Geopolymer Matrix

2.1 Raw Material Activation and Triad Synergistic Effect

Ma Yue [1] conducted experimental studies on the effects of mineral admixtures on cement-based materials, highlighting that slag possesses inherent hydraulic properties, fly ash primarily exhibits volcanic ash activity, and coal gangue has extremely low natural activity requiring activation for utilization. Gu Xuetian [7] investigated coal gangue concrete and proposed that calcination of coal gangue at 600–950°C effectively removes crystallization water, disrupts kaolinite lattice structure, and significantly enhances activity.

Wang Haigang et al. [8] investigated the reinforcement behavior of coal gangue, fly ash, and slag in cement mortar, revealing synergistic effects among the three components: slag enhances early strength, fly ash improves fluidity and shrinkage, while activated coal gangue optimizes pore structure. The composite performance exceeded that of individual components. Guo Lingzhi [2] and Liao Yue [3] conducted separate studies on ternary geopolymers for grouting materials, demonstrating that slag provides early strength, fly ash stabilizes late-stage performance, and coal gangue improves solid waste utilization rates. Their research established optimal proportion ranges to guide matrix design.

2.2 Characteristics of Hydration/Polymerization Reactions

Ma Yue [1] and Jiang Qingqing [9] determined the hydration degree of cementitious materials using chemical binding water analysis and thermal analysis methods, demonstrating that fly ash and slag undergo secondary hydration, consuming $Ca(OH)_2$ and forming C-S-H gels. Guo Lingzhi [2] proposed that ternary geopolymers exhibit a core reaction of alkali-induced depolymerization followed by repolymerization, resulting in amorphous silicoaluminate gels with significantly lower $Ca(OH)_2$ content than cement-based systems and more compact interfacial transition zones.

2.3 Mechanical Properties and Porosity Structure

Jiang Qingqing [9] investigated the strength and pore structure of three-component blended cement, demonstrating that mineral admixtures can refine pore size, reduce harmful porosity, and enhance matrix density. Wang Haigang et al. [8] confirmed that ternary solid waste composites improve matrix volume stability and minimize drying shrinkage. Guo Lingzhi [2] and Liao Yue [3] measured that ternary geopolymers concrete achieved 28-day compressive strength ranging from 25 to 50 MPa, meeting structural load requirements and providing a stable matrix for bonding tests.

3. Study on Material Properties and Interface Adhesion Mechanism of 3GFRP Composite Materials

3.1 Study on Material Properties of GFRP Reinforced Concrete

Gao Danying et al. [5] conducted central pull-out tests, measuring the elastic modulus of GFRP tendons to be 45–60 Gpa-approximately one-fourth to one-third that of steel tendons-with greater stress slip observed. Hu Binbin [4] employed beam-end tests, categorizing GFRP tendons into four surface types: smooth, ribbed, shallow ribbed sand-coated, and fiber-wrapped, demonstrating that surface morphology directly determines bonding performance. Zhang Wangxi et al. [6] and Ye Jiaqi et al. [10] summarized FRP tendon research progress, concluding that ribbed and fiber-wrapped tendons are more suitable for engineering applications.

3.2 Composition of Interface Adhesion Force

Hu Binbin [4] and Gao Danying et al. [5] proposed that the bond strength between GFRP fibers and concrete consists of three components: chemical bonding force, mechanical interlocking force, and frictional force. Specifically: chemical bonding force only plays a role during the initial stage of slip, accounting for less than 10% [4,10]; mechanical interlocking force, provided by shear interlocking between ribs and concrete, accounts for 60%–75% and determines peak strength [4,5]; frictional force becomes dominant after slip initiation, determining residual strength [4,11].

Gu Xueting [7] demonstrated in the study on GFRP fibers and coal gangue concrete that the interfacial bonding behavior between the geopolymer matrix and GFRP fibers follows the same principles as conventional concrete. However, due to the denser matrix structure, the contribution of chemical bonding is slightly enhanced.

4. Research Progress on Factors Affecting Interface Adhesion Performance

4.1 Matrix Factors

Hu Binbin [4] and Gao Danying et al. [5] demonstrated through extensive experiments that bonding strength is proportional to the 0.75 power of concrete compressive strength. When strength is elevated from C20 to C40, bonding strength improves by 40%–50%. Wang Haigang et al. [8] and Guo Lingzhi [2] noted that increasing slag content in ternary geopolymer systems enhances interfacial bonding, while excessive fly ash incorporation reduces early-stage bonding performance, with optimal coal gangue dosage around 15%. Ma Yue [1] and Jiang Qingqing [9] emphasized that increased matrix drying shrinkage weakens interfacial cohesion, and standard curing conditions (20±1°C, RH>90%) ensure optimal bonding performance.

4.2 Fiber Parameters

Hu Binbin [4] and Gu Xuetian [7] conducted comparative studies on GFRP tendons with different surface treatments, determining the bonding strength ranking as follows: fiber-wrapped type> shallow ribbed sand-coated type> ribbed type> smooth type, with the wrapped type exhibiting 1.8–2.2 times higher bonding strength than the smooth type. Li Wei et al. [11] identified key influencing factors, revealing that bonding strength decreases with increasing tendon diameter—specifically, a 20%–30% reduction occurs when diameter increases from 10 mm to 18 mm. Zhang Wangxi et al. [6] proposed that enhancing the elastic modulus of GFRP tendons could reduce slip and improve interfacial efficiency.

4.3 Structure and Constraints

Hu Binbin [4] demonstrated through beam end tests that the relative thickness of the protective layer c/d is a critical parameter: cracks tend to occur when c/d <2.0, while bonding strength stabilizes when c/d> 2.5. Li Wei et al. [11] similarly confirmed that the protective layer exerts control over failure morphology and strength.

Hu Binbin [4] and Gao Danying et al. [5] found that stirrups can constrain splitting cracks, resulting in a 15%–45% increase in peak strength and approximately 60% improvement in residual strength, while converting brittle failure into ductile pull-out.

4.4 Environment and Loading Factors

Yang Jiaxing [12] investigated repeated loading effects, demonstrating that load cycling induces interfacial micro-damage leading to progressive degradation of bonding strength. Xu Yifan [13] conducted high-temperature experiments revealing that bonding strength remains essentially stable below 200°C, while resin degradation occurs above 400°C, resulting in a sharp decline in interfacial strength with retention rates below 21%.

Hu Binbin [4] found that when two GFRP tendons were successively loaded on the same specimen, the strength of the later-loaded tendon was approximately 0.68 times that of the first-loaded tendon due to matrix micro-damage, but this had minimal impact on slip displacement.

5. Conclusion

Activation treatment and ternary ratio synergy are key to enhancing matrix performance. The complementary advantages of slag, fly ash, and activated coal gangue enable the production of an optimal matrix suitable for bonding with GFRP.

The bonding mechanism between GFRP fibers and ternary geopolymer concrete interfaces is well understood, characterized by mechanical interlocking as the dominant factor, frictional assistance, and initial cementation, allowing for unified analytical and predictive approaches.

Adhesion performance is influenced by multiple factors including material properties, structural configuration, and environmental conditions. Optimal bonding results can be achieved through proportion optimization, selection of wound/sand-reinforced bars, ensuring adequate cover layer thickness, and proper stirrup placement.

Current studies predominantly focus on ambient temperature and static conditions, while the interface evolution and life prediction under long-term erosion, fatigue, freeze-thaw cycles, and high-temperature coupling require further investigation.

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