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Research Progress and Engineering Application Prospects of Hybrid Fiber Reinforced Steel Slag Powder Ultra-High Performance Concrete: A Review

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Abstract

Ultra-high performance concrete (UHPC) has attracted extensive attention in the field of advanced cement-based materials due to its superior mechanical properties, excellent durability, and potential for lightweight and high-performance structural applications. However, the widespread application of UHPC is still restricted by its high cement consumption, high production cost, and associated environmental impacts. The development of sustainable UHPC through the incorporation of industrial solid wastes has therefore become an important research direction. Steel slag powder, as a major by-product of the steel industry, possesses potential hydraulic activity and micro-filling effects, making it a promising supplementary cementitious material for partially replacing Portland cement in UHPC systems. Despite its excellent compressive strength, the highly dense matrix of UHPC results in inherent brittleness and limited deformation capacity. Fiber reinforcement has been widely adopted to overcome this limitation, and different types of fibers exhibit distinct strengthening mechanisms. Steel fibers mainly contribute to macro-crack bridging and post-cracking load-bearing capacity, while polymer fibers and basalt fibers provide effective control of micro-crack initiation and propagation. Hybrid fiber systems combining multiple fibers can achieve multi-scale crack control and improve the comprehensive mechanical performance of UHPC. This paper reviews recent advances in steel slag powder-based UHPC and hybrid fiber reinforced UHPC systems. The characteristics and utilization potential of steel slag powder are first discussed, followed by an analysis of hydration behavior, microstructure evolution, and its influence on UHPC properties. The reinforcement mechanisms of steel fibers, polypropylene fibers, polyvinyl alcohol fibers, and basalt fibers are summarized. Furthermore, the synergistic effects of hybrid fibers on mechanical properties, toughness, durability, and high-temperature resistance are systematically reviewed. Finally, the engineering application prospects, existing challenges, and future research directions of hybrid fiber reinforced steel slag powder UHPC are discussed. This review provides theoretical guidance for the development of sustainable, high-performance, and multifunctional cement-based materials.

Keywords

Ultra-high performance concrete, steel slag powder, hybrid fiber, steel fiber, polypropylene fiber, PVA fiber, basalt fiber, toughness, sustainable concrete.

1. Introduction

Concrete is the most widely used construction material worldwide due to its excellent availability, relatively low cost, and adaptability to various engineering applications. However, with the continuous development of modern infrastructure, conventional concrete has gradually shown limitations in terms of mechanical performance, durability, and service life under complex environmental conditions. The increasing demand for long-span bridges,

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offshore structures, high-rise buildings, and protective engineering structures has promoted the development of advanced cement-based materials with higher strength, improved durability, and enhanced crack resistance [1].

Ultra-high performance concrete (UHPC) represents one of the most advanced developments in cement-based materials. Since the concept of reactive powder concrete was proposed by Richard and Cheyrezy in the 1990s, UHPC has been widely investigated due to its extremely dense microstructure, ultra-high compressive strength, excellent durability, and superior resistance to aggressive environments [2]. The outstanding performance of UHPC is mainly attributed to its optimized particle packing system, very low water-to-binder ratio, incorporation of high-reactivity mineral admixtures, and the bridging effect provided by short fibers [3]. Compared with ordinary concrete, UHPC exhibits significantly improved compressive strength, tensile behavior, chloride resistance, and freeze–thaw durability, making it attractive for critical infrastructure applications [4].

Nevertheless, the practical application of UHPC remains limited by several challenges. The preparation of UHPC generally requires a large amount of Portland cement, silica fume, and other high-quality supplementary materials, resulting in increased material cost and significant carbon emissions during production. Cement production is recognized as one of the major contributors to global carbon dioxide emissions, accounting for approximately 7–8% of total anthropogenic CO_2 emissions worldwide [5]. Therefore, reducing cement consumption while maintaining the excellent properties of UHPC has become an important research objective in the development of sustainable construction materials.

The utilization of industrial solid wastes as supplementary cementitious materials provides an effective approach for reducing the environmental impact of UHPC. Various industrial by-products, including fly ash, ground granulated blast furnace slag, silica fume, and steel slag, have been investigated as partial replacements for Portland cement [6]. Among these materials, steel slag powder has attracted increasing attention due to its large production quantity, chemical similarity to Portland cement, and potential cementitious activity.

Steel slag is generated during steel manufacturing processes and mainly consists of calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), magnesium oxide (MgO), and iron-containing phases [7]. After appropriate aging, grinding, and activation treatments, steel slag powder can exhibit latent hydraulic activity and participate in hydration reactions. Moreover, its fine particles can improve the particle packing density of cementitious systems through micro-filling effects, reducing internal porosity and contributing to the formation of a denser matrix [8].

Previous studies have demonstrated that the incorporation of steel slag powder can modify the hydration process and microstructure development of cement-based materials. The active components in steel slag may contribute to the formation of calcium silicate hydrate (C–S–H) gel, while unreacted particles can act as micro-fillers within the matrix [9]. However, excessive replacement of cement with steel slag powder may reduce early-age mechanical properties due to its relatively slow hydration rate and lower pozzolanic activity compared with silica fume. Therefore, the optimization of steel slag powder content and the combination with other mineral admixtures are essential for achieving a balance between sustainability and mechanical performance.

Although UHPC possesses excellent compressive strength, its brittle failure behavior remains a major concern. The highly compact matrix restricts plastic deformation, and once cracks initiate, rapid crack propagation may occur without sufficient energy dissipation mechanisms. Fiber reinforcement has therefore become an essential component of UHPC design. Fibers can improve tensile strength, fracture energy, ductility, and crack resistance by transferring stress across cracks and delaying crack propagation [10].

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Steel fibers are the most commonly used reinforcement in UHPC due to their high tensile strength, high elastic modulus, and strong bridging capability. They primarily contribute to controlling macro-cracks and maintaining post-cracking load capacity. Numerous studies have shown that steel fiber reinforced UHPC exhibits significant improvements in flexural strength, tensile performance, and fracture toughness compared with plain UHPC [11]. However, steel fibers have limited effectiveness in controlling very small cracks during the early hydration stage, and their high density may negatively influence workability when excessive amounts are incorporated.

To overcome the limitations of single-fiber systems, hybrid fiber reinforcement has been proposed as an effective strategy. Hybrid fiber systems combine fibers with different sizes, mechanical properties, and functions, enabling multi-scale crack control. For example, polymer fibers such as polypropylene (PP) fibers and polyvinyl alcohol (PVA) fibers can effectively control micro-cracks due to their small diameter and large specific surface area, while steel fibers provide bridging effects after crack development [12]. Basalt fibers, characterized by high temperature resistance, chemical stability, and relatively high elastic modulus, have also been considered as potential reinforcement materials for improving the performance of cement-based composites [13].

The synergistic effect of hybrid fibers is not simply the sum of individual fiber contributions. Instead, interactions between different fibers and the cementitious matrix can significantly influence crack evolution, energy absorption, and failure mechanisms. Fine fibers can restrict the initiation and growth of micro-cracks, reducing stress concentration around defects, whereas larger and stronger fibers can effectively transfer loads after crack formation. This multi-stage reinforcement mechanism provides hybrid fiber reinforced UHPC with improved toughness and damage tolerance [14].

In recent years, the combination of steel slag powder and hybrid fiber reinforcement has emerged as a promising approach for developing sustainable UHPC. Steel slag powder contributes to environmental benefits and microstructural optimization, while hybrid fibers compensate for the brittleness associated with high-strength cementitious matrices. However, current studies mainly focus on either the effect of steel slag powder incorporation or the influence of hybrid fibers separately. A systematic understanding of the interaction between steel slag powder-based binders and hybrid fiber systems is still insufficient, particularly regarding crack control mechanisms, toughness improvement, and performance under extreme environments.

Therefore, this review aims to summarize recent progress in hybrid fiber reinforced steel slag powder UHPC. The objectives are to: (1) introduce the characteristics and utilization mechanisms of steel slag powder in UHPC; (2) summarize the reinforcement mechanisms of different fibers; (3) analyze the synergistic effects of hybrid fibers on mechanical properties, toughness, durability, and high-temperature resistance; and (4) discuss future challenges and engineering application prospects. The findings provide valuable insights into the development of sustainable UHPC with improved mechanical performance and environmental benefits.

2. Development and Characteristics of Steel Slag Powder-Based UHPC

2.1. Characteristics and utilization status of steel slag powder

Steel slag is an industrial by-product generated during the conversion of molten iron into steel through processes such as basic oxygen furnace (BOF) steelmaking and electric arc furnace (EAF) steelmaking. According to global steel production statistics, hundreds of millions of tons of steel slag are produced annually, creating significant challenges associated with storage, land occupation, and environmental management [15]. Traditionally, steel slag has been mainly used as road aggregate or disposed of in landfills. However, these approaches often result in

ISSN: 2710-0588

low resource utilization efficiency and fail to fully exploit its potential as a value-added construction material.

The chemical composition of steel slag is similar to that of Portland cement, mainly consisting of CaO, SiO_2, Fe_2O_3, Al_2O_3, and MgO. The mineral phases generally include tricalcium silicate (C_3S), dicalcium silicate (C_2S), calcium ferrite phases, RO phases, and free calcium oxide (f-CaO) [16]. Among these components, C_2S and C_3S possess hydraulic activity and can participate in hydration reactions, producing calcium silicate hydrate (C–S–H) gels that contribute to strength development. However, compared with Portland cement clinker, steel slag usually exhibits slower hydration kinetics due to its dense crystal structure and relatively low content of highly reactive phases [17].

Grinding steel slag into fine powder is considered an effective method to enhance its reactivity. The increased specific surface area promotes water contact with active mineral phases and accelerates hydration reactions. Meanwhile, fine steel slag particles can improve the packing density of cementitious systems by filling voids between larger particles. This filler effect is particularly beneficial for UHPC, which relies heavily on optimized particle packing to achieve an ultra-dense microstructure.

The utilization of steel slag powder in UHPC provides both environmental and technical benefits. From an environmental perspective, replacing a portion of Portland cement with steel slag powder reduces cement consumption and associated carbon emissions. From a technical perspective, steel slag powder can improve the particle gradation of binder systems and contribute to long-term strength development. Therefore, steel slag powder has been increasingly considered as a promising supplementary material for sustainable UHPC production.

However, several limitations still restrict the large-scale application of steel slag powder in UHPC. The relatively slow hydration rate may result in insufficient early-age strength development. In addition, excessive incorporation of steel slag powder may introduce expansion risks caused by free CaO and MgO. Therefore, appropriate pretreatment methods, replacement ratios, and combination with highly active mineral admixtures are necessary to ensure the stability and performance of steel slag powder-based UHPC.

2.2. Hydration behavior and microstructure evolution of steel slag powder-based UHPC

The excellent performance of UHPC is strongly associated with its refined pore structure and dense hydration products. The incorporation of steel slag powder modifies the hydration process by changing the composition and evolution of cementitious phases. Compared with conventional UHPC containing only Portland cement and silica fume, steel slag powder-based UHPC exhibits different hydration characteristics due to the gradual activation of steel slag minerals.

During hydration, Portland cement reacts rapidly with water to form C–S–H gel, calcium hydroxide (CH), and other hydration products. The active components in steel slag, particularly C_2S, can undergo slower hydration reactions and contribute to additional C–S–H formation at later ages [18]. This delayed hydration behavior may improve long-term mechanical properties by continuously refining the internal structure.

Furthermore, steel slag powder can influence the interfacial transition zone (ITZ) between cement paste and aggregate or fiber surfaces. In conventional concrete, the ITZ is generally considered the weakest region due to higher porosity and less compact hydration products. The fine particles of steel slag powder can fill voids within this region, reducing local defects and improving matrix continuity [19].

ISSN: 2710-0588

When combined with silica fume, steel slag powder can produce complementary effects. Silica fume contains a high proportion of amorphous SiO_2 and exhibits strong pozzolanic activity, consuming calcium hydroxide to form additional C–S–H gels. Steel slag powder provides reactive calcium-containing phases and filler effects. The combination of these materials may promote a denser hydration network and improve the mechanical performance of UHPC.

Microstructural studies using scanning electron microscopy (SEM), X-ray diffraction (XRD), and mercury intrusion porosimetry (MIP) have demonstrated that appropriate steel slag powder incorporation can reduce capillary porosity and increase the proportion of fine pores [20]. The refinement of pore structure contributes to improved compressive strength and durability. However, the benefits strongly depend on the replacement level, particle size distribution, curing conditions, and interaction with other supplementary cementitious materials.

Excessive steel slag powder content may negatively affect the microstructure due to insufficient hydration products at early ages. A higher proportion of unreacted particles may remain embedded in the matrix, leading to weak zones and reduced bonding efficiency. Therefore, optimizing the steel slag powder content is essential for achieving a balance between environmental benefits and mechanical performance.

2.3. Influence of steel slag powder on mechanical properties of UHPC

The influence of steel slag powder on UHPC mechanical properties has been extensively investigated. In general, moderate replacement of cement with steel slag powder can maintain or even improve mechanical performance, while excessive replacement may result in strength reduction.

Compressive strength is one of the most important indicators for evaluating UHPC performance. Previous studies have shown that steel slag powder can improve later-age compressive strength through continuous hydration and micro-filling effects. The fine particles of steel slag powder contribute to improved particle packing efficiency, resulting in a denser matrix structure [21]. Moreover, secondary hydration reactions gradually generate additional C–S–H gel, enhancing the mechanical integrity of the material.

However, the effect of steel slag powder on early-age strength is more complicated. Due to its lower reactivity compared with cement clinker and silica fume, replacing a large amount of cement may reduce early hydration heat and delay strength development. Therefore, steel slag powder content should be carefully controlled according to engineering requirements.

The tensile and flexural properties of steel slag powder-based UHPC are also influenced by the modification of matrix structure. Since UHPC failure is generally governed by crack initiation and propagation rather than compressive failure, improvements in matrix compactness and interface bonding are particularly important. A refined matrix can enhance the bonding between fibers and cement paste, thereby improving the efficiency of fiber bridging.

For fiber reinforced steel slag powder UHPC, the interaction between steel slag powder and fibers becomes especially important. A denser matrix may increase fiber pull-out resistance and improve energy absorption capacity. However, excessively strong fiber-matrix bonding may also lead to fiber rupture rather than pull-out, affecting ductile failure behavior. Therefore, the balance between matrix strength and fiber interface properties should be considered during material design.

In summary, steel slag powder provides a promising pathway for developing sustainable UHPC. Its contribution is not limited to cement replacement but also includes microstructure optimization and long-term performance improvement. Nevertheless, the successful application of steel slag powder-based UHPC requires comprehensive consideration of chemical activity, particle characteristics, replacement ratio, and interaction with fiber reinforcement systems.

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2.4. Future development of steel slag powder-based UHPC

Although significant progress has been achieved, several issues remain regarding steel slag powder-based UHPC. First, the variability of steel slag composition caused by different steel production processes may influence the stability of UHPC performance. Establishing standardized processing and quality evaluation methods is necessary for practical applications.

Second, current studies mainly focus on mechanical properties under laboratory conditions, while long-term durability, fatigue resistance, and environmental performance require further investigation. The influence of steel slag powder on UHPC behavior under combined environmental actions, such as high temperature, freeze–thaw cycles, and chemical corrosion, remains insufficiently understood.

Third, the combination of steel slag powder with advanced reinforcement technologies, particularly hybrid fiber systems, represents an important direction for future research. The development of multi-functional UHPC incorporating industrial wastes and optimized fiber systems may provide new solutions for sustainable infrastructure construction.

3. Fiber Reinforcement Mechanisms in UHPC

3.1. Role of steel fibers in UHPC

Fiber reinforcement is one of the most effective approaches to improving the brittle behavior of UHPC. Among various fibers, steel fibers are the most widely used due to their high tensile strength, high elastic modulus, and excellent mechanical anchorage capability. In fiber reinforced UHPC, steel fibers mainly contribute to crack bridging, stress transfer, and post-cracking load resistance.

The failure process of plain UHPC generally involves three stages: micro-crack initiation, unstable crack propagation, and brittle failure. Due to the dense cementitious matrix, once the tensile stress exceeds the tensile capacity of the matrix, cracks can rapidly propagate, resulting in sudden loss of load-bearing capacity. The incorporation of steel fibers changes this failure mechanism by introducing additional bridging forces across cracks [22].

When cracks initiate and propagate through the matrix, steel fibers crossing the crack surfaces transfer tensile stress through interfacial bonding and frictional resistance. This bridging effect delays crack widening and improves the energy dissipation capacity of the composite material. Therefore, steel fiber reinforced UHPC usually exhibits strain-hardening behavior, higher tensile strength, and significantly enhanced fracture energy compared with non-fiber UHPC.

The effectiveness of steel fibers depends on several parameters, including fiber volume fraction, length-to-diameter ratio, orientation, surface characteristics, and fiber-matrix bonding properties. Longer fibers with higher aspect ratios generally provide stronger bridging effects because of improved anchorage. However, excessive steel fiber content may negatively affect workability due to fiber agglomeration and increased mixture viscosity.

Although steel fibers provide excellent macro-crack control, their contribution to controlling early-stage micro-cracks is relatively limited. Before visible cracking occurs, the spacing between steel fibers is generally insufficient to effectively restrict micro-defects generated during hydration shrinkage and thermal stress. Therefore, relying solely on steel fibers may not achieve optimal crack control across different scales.

This limitation has encouraged researchers to develop hybrid fiber systems by combining steel fibers with smaller and more flexible fibers. The combination of fibers with different geometrical and mechanical characteristics enables multi-level reinforcement, where small fibers control micro-cracks and steel fibers maintain structural integrity after crack formation.

ISSN: 2710-0588

3.2. Role of polypropylene fibers in UHPC

Polypropylene (PP) fibers are widely used in cement-based materials due to their low density, chemical stability, corrosion resistance, and excellent deformation capability. Compared with steel fibers, PP fibers possess lower elastic modulus and tensile strength; however, their small diameter and large specific surface area allow them to effectively control early-stage micro-crack development.

During cement hydration, internal shrinkage and thermal gradients can generate microscopic defects within the matrix. PP fibers distributed throughout the cement paste can restrain local deformation and reduce stress concentration, thereby delaying crack initiation. This mechanism is particularly important for UHPC because its dense structure limits moisture migration and increases internal stress accumulation.

Another important advantage of PP fibers is their contribution to fire resistance and explosive spalling prevention. Under high-temperature exposure, PP fibers gradually melt and decompose, creating interconnected channels within the matrix. These channels facilitate the release of internal vapor pressure and reduce the risk of explosive spalling. Previous studies have demonstrated that incorporating appropriate amounts of PP fibers can significantly improve the high-temperature stability of UHPC [23].

However, PP fibers have relatively weak bonding strength with cementitious matrices due to their hydrophobic surface characteristics. Therefore, their ability to improve tensile strength and post-cracking behavior is limited when used alone. In hybrid fiber systems, PP fibers are usually combined with steel fibers to provide complementary reinforcement, where PP fibers control micro-cracks and steel fibers bridge macro-cracks.

3.3. Role of polyvinyl alcohol fibers in UHPC

Polyvinyl alcohol (PVA) fibers have attracted considerable attention in high-performance cement-based composites due to their excellent tensile properties, hydrophilic characteristics, and strong bonding with cement hydration products. Compared with PP fibers, PVA fibers exhibit higher elastic modulus and stronger interfacial adhesion, resulting in improved crack control and tensile performance.

The surface of PVA fibers contains hydroxyl groups that can form strong interactions with hydration products, enhancing the fiber-matrix bonding strength. During tensile loading, PVA fibers effectively transfer stress across cracks through interface bonding and fiber pull-out mechanisms. This behavior contributes to improved strain capacity, energy absorption, and ductile failure characteristics.

In engineered cementitious composites (ECC), PVA fibers are commonly used to achieve multiple cracking behavior and high tensile ductility. Similar mechanisms can be observed in UHPC systems, where PVA fibers can limit crack width development and improve deformation resistance.

However, the strong bonding between PVA fibers and cement matrix has both advantages and disadvantages. Moderate bonding strength promotes efficient stress transfer, while excessively strong bonding may result in fiber rupture rather than pull-out, reducing energy dissipation. Therefore, optimizing fiber content and surface characteristics is essential.

When combined with steel fibers, PVA fibers provide complementary reinforcement. Steel fibers maintain load capacity after major cracking, whereas PVA fibers control crack evolution before macro-crack formation. This combination contributes to improved tensile performance and toughness of UHPC.

ISSN: 2710-0588

3.4. Role of basalt fibers in UHPC

Basalt fibers are inorganic fibers produced by melting and drawing natural basalt rock. They have attracted increasing attention in cement-based materials due to their high tensile strength, high elastic modulus, excellent chemical stability, and good resistance to elevated temperatures.

Compared with polymer fibers, basalt fibers possess better thermal stability and can maintain structural integrity under relatively high temperatures. Their excellent durability makes them suitable for applications requiring resistance against harsh environments.

In UHPC, basalt fibers mainly contribute through crack bridging and reinforcement of the cementitious matrix. Their relatively high modulus allows them to effectively restrain deformation and improve tensile and flexural strength. Furthermore, basalt fibers can improve the integrity of the interfacial transition zone by reducing crack propagation pathways.

However, the effectiveness of basalt fibers depends strongly on their compatibility with the cementitious matrix. Due to their relatively smooth surface characteristics, insufficient bonding may limit their reinforcement efficiency. Surface modification and hybridization with other fibers have been proposed to improve their performance.

Compared with PP and PVA fibers, basalt fibers have higher temperature resistance but lack the melting-induced pressure relief mechanism of polymer fibers. Therefore, their role in high-temperature UHPC requires comprehensive evaluation, especially when explosive spalling is a major concern.

3.5. Synergistic effects of hybrid fiber systems

The concept of hybrid fiber reinforcement is based on the idea that different fibers can provide complementary functions at different stages of damage development. Instead of relying on a single fiber type, hybrid systems combine fibers with different sizes, mechanical properties, and failure mechanisms to achieve multi-scale reinforcement.

Generally, hybrid fiber systems can be classified into two categories:

(1) fibers with different lengths;

(2) fibers with different material properties.

The first type focuses on improving fiber distribution and crack control efficiency, while the second type utilizes the different mechanical and environmental characteristics of each fiber.

In steel fiber-polymer fiber hybrid systems, polymer fibers mainly control micro-cracks generated during early loading stages, while steel fibers become dominant after macro-cracks form. This sequential reinforcement mechanism improves both initial cracking resistance and post-cracking load capacity.

For steel fiber-PVA fiber systems, the strong bonding ability of PVA fibers enhances tensile ductility and crack width control, while steel fibers provide higher energy absorption after crack development. The combined effect is particularly beneficial for structural components requiring high deformation capacity.

For steel fiber-basalt fiber systems, basalt fibers contribute additional reinforcement and thermal stability. The combination may improve mechanical performance and durability under severe environmental conditions.

The effectiveness of hybrid fibers is influenced by fiber volume fraction, dispersion, orientation, and interaction with the matrix. Excessive total fiber content may reduce workability and cause fiber clustering, negatively affecting mechanical performance. Therefore, optimized hybrid fiber design requires balancing fresh-state properties and hardened-state performance.

ISSN: 2710-0588

3.6. Influence of hybrid fibers on toughness and fracture behavior

Toughness represents the ability of a material to absorb energy during deformation and fracture. For UHPC, improving toughness is essential because high compressive strength alone cannot guarantee structural safety under impact, fatigue, or extreme loading conditions.

Hybrid fibers improve toughness through several mechanisms:

First, fibers delay crack initiation by reducing stress concentration around defects.

Second, fibers bridge cracks and transfer tensile stresses after matrix cracking.

Third, fiber pull-out and frictional sliding consume fracture energy during failure.

The fracture behavior of hybrid fiber reinforced UHPC is therefore controlled by the combined effects of matrix strength, fiber bridging capacity, and interface behavior.

Experimental studies have shown that hybrid fiber reinforced UHPC generally exhibits higher fracture energy and improved post-peak behavior compared with single fiber systems [24]. This improvement is particularly significant when fibers with different functions are appropriately combined.

For steel slag powder-based UHPC, hybrid fiber reinforcement is expected to become even more important because the incorporation of industrial solid waste may alter matrix strength and interface characteristics. Optimizing fiber combinations provides an effective method to compensate for potential reductions in matrix performance while maintaining sustainable advantages.

3.7. Summary

In summary, different fibers provide distinct reinforcement functions in UHPC. Steel fibers mainly enhance macro-crack resistance and post-cracking capacity, PP fibers improve micro-crack control and fire resistance, PVA fibers enhance tensile ductility through strong interface bonding, and basalt fibers provide high modulus and thermal stability. Hybrid fiber systems integrate these advantages and achieve multi-scale crack control, making them a promising strategy for improving the mechanical performance and durability of steel slag powder-based UHPC.

4. Hybrid Fiber Reinforced Steel Slag Powder UHPC

4.1. Mechanical performance of hybrid fiber reinforced steel slag powder UHPC

The combination of steel slag powder and hybrid fiber reinforcement provides a promising strategy for developing sustainable UHPC with improved mechanical performance. Steel slag powder modifies the binder system by improving particle packing and contributing to long-term hydration, while hybrid fibers compensate for the inherent brittleness of high-strength cementitious matrices. The interaction between the modified matrix and multiple fiber types determines the final mechanical behavior of the composite.

The compressive strength of steel slag powder-based UHPC is mainly controlled by the hydration degree, pore structure, and particle packing characteristics of the cementitious system. Moderate incorporation of steel slag powder generally improves later-age strength due to secondary hydration and filler effects. However, the influence of fibers on compressive strength is relatively limited because compression failure is primarily governed by matrix behavior rather than crack bridging. Nevertheless, fibers can indirectly improve compressive strength by restraining crack propagation and enhancing internal structural integrity [25].

The influence of hybrid fibers becomes more significant in tensile and flexural performance. Unlike compression-dominated behavior, tensile failure of UHPC is highly dependent on crack initiation and propagation. Steel fibers provide strong bridging forces after cracking, while fine

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polymer fibers contribute to controlling micro-cracks before visible damage occurs. This combined mechanism results in improved tensile strength, flexural capacity, and deformation ability.

Several studies have demonstrated that hybrid fiber reinforced UHPC exhibits higher fracture energy compared with single fiber systems. The improvement is mainly attributed to the synergistic interaction between different fibers. Small fibers increase crack resistance by reducing crack spacing, whereas large fibers enhance energy dissipation through pull-out and bridging mechanisms. Therefore, the design of hybrid fiber systems should consider not only fiber content but also the compatibility between fiber properties and matrix characteristics.

For steel slag powder-based UHPC, the fiber-matrix interface plays an especially important role. The incorporation of steel slag powder can modify hydration products and pore structure around fibers, affecting bonding strength and pull-out behavior. A denser matrix may improve fiber anchorage, but excessive interface strength may reduce ductility by causing fiber rupture. Therefore, achieving an appropriate balance between matrix strength and fiber interface behavior is essential.

4.2. Toughness enhancement mechanism of hybrid fiber reinforced SSP-UHPC

Toughness is one of the most important indicators for evaluating the practical applicability of UHPC. Although UHPC possesses extremely high compressive strength, insufficient toughness may lead to sudden failure under dynamic loading or structural deformation conditions. Therefore, improving fracture resistance and energy absorption capacity is essential for expanding UHPC applications.

The toughness improvement provided by hybrid fibers can be explained through several mechanisms.

First, the distributed fine fibers reduce stress concentration and restrict the development of micro-defects. During early loading stages, polymer fibers such as PP and PVA fibers interact with the surrounding matrix and delay crack initiation.

Second, steel fibers become increasingly important after crack formation. Through mechanical anchorage and frictional resistance, steel fibers transfer tensile stresses across cracks and maintain load-bearing capacity after matrix cracking.

Third, the pull-out process of fibers consumes considerable fracture energy. During crack propagation, fiber debonding, frictional sliding, and deformation contribute to energy dissipation, resulting in a more gradual failure process.

Compared with single-fiber systems, hybrid fiber reinforced UHPC demonstrates improved post-cracking behavior and higher residual load capacity. This characteristic is particularly important for engineering structures subjected to repeated loading, impact, or extreme environmental conditions.

However, toughness evaluation methods for UHPC are still not fully unified. Common evaluation approaches include flexural toughness indices, fracture energy, load-displacement curve analysis, and tensile strain capacity. Establishing standardized evaluation methods is necessary for comparing different hybrid fiber systems and promoting engineering applications.

4.3. Durability and high-temperature performance

Durability is a key factor determining the service life of UHPC structures. Due to its low permeability and dense microstructure, UHPC generally exhibits excellent resistance against chloride penetration, freeze-thaw cycles, and chemical deterioration. The incorporation of steel slag powder and hybrid fibers may further modify durability-related properties.

Steel slag powder can refine pore structure through particle filling and secondary hydration effects, reducing the connectivity of harmful pores. Meanwhile, fibers can restrict crack

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development and prevent the formation of continuous transport channels for aggressive substances.

However, the durability performance of hybrid fiber reinforced steel slag powder UHPC under extreme conditions requires further investigation. High-temperature exposure is one of the most important concerns because UHPC has a tendency toward explosive spalling due to its dense structure and limited vapor permeability.

During heating, free water evaporation generates internal vapor pressure. If vapor migration is restricted, internal pressure may exceed tensile resistance, resulting in explosive spalling. Polymer fibers such as PP fibers can partially solve this problem because their melting creates additional channels for vapor release.

PVA fibers may also improve high-temperature performance due to their ability to control cracking before severe damage occurs. Steel fibers contribute to maintaining structural integrity after matrix deterioration. Basalt fibers exhibit excellent thermal stability, although their effectiveness in preventing explosive spalling requires further investigation.

The combined use of steel slag powder and hybrid fibers provides potential advantages for improving UHPC fire resistance. Steel slag powder may modify thermal properties and hydration structure, while hybrid fibers provide crack control and vapor pressure relief mechanisms. Nevertheless, systematic studies on thermal damage evolution, residual mechanical properties, and microscopic degradation mechanisms remain limited.

5. Engineering Application Potential and Challenges

5.1. Sustainable advantages and environmental benefits

The application of steel slag powder in UHPC provides significant environmental benefits. By replacing part of Portland cement, steel slag powder reduces cement consumption and contributes to lower carbon emissions. At the same time, utilizing industrial waste materials improves resource efficiency and reduces environmental pressure caused by steel slag accumulation.

The combination of steel slag powder and hybrid fiber reinforcement represents a promising pathway toward sustainable high-performance construction materials. Compared with traditional UHPC, this approach achieves a better balance between mechanical performance and environmental sustainability.

5.2. Engineering application prospects

Hybrid fiber reinforced steel slag powder UHPC has considerable potential for applications requiring high strength, durability, and crack resistance.

In bridge engineering, UHPC can be used for bridge deck overlays, connection joints, and strengthening components due to its excellent durability and load-bearing capacity.

In prefabricated construction, UHPC components can reduce structural thickness and improve construction efficiency.

In marine engineering, the low permeability and high durability of UHPC provide advantages in resisting chloride-induced corrosion.

Furthermore, improved toughness and high-temperature resistance make hybrid fiber reinforced SSP-UHPC attractive for protective structures and infrastructure exposed to severe environmental conditions.

5.3. Current limitations and research challenges

Despite significant progress, several challenges remain before large-scale application of hybrid fiber reinforced steel slag powder UHPC.

ISSN: 2710-0588

First, the variability of steel slag composition affects material stability. Different steel production processes generate steel slag with different mineral compositions and activity levels, making quality control necessary.

Second, the optimal design of hybrid fiber systems remains challenging. Fiber type, content, length, orientation, and interaction with the matrix must be comprehensively considered.

Third, the relationship between microstructure evolution and macroscopic performance requires further clarification. Advanced characterization techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), and computed tomography (CT), should be combined with mechanical testing to understand damage mechanisms.

Finally, more research is needed on long-term durability, life-cycle assessment, and field applications to verify the practical feasibility of steel slag powder-based UHPC.

6. Conclusions and Future Perspectives

This review summarized recent developments in hybrid fiber reinforced steel slag powder ultra-high performance concrete. The main conclusions are as follows:

(1) Steel slag powder is a promising supplementary material for sustainable UHPC production. Through particle filling effects and secondary hydration reactions, steel slag powder can improve microstructure and reduce cement consumption.

(2) Different fibers provide different reinforcement mechanisms. Steel fibers mainly improve macro-crack bridging and post-cracking capacity, while PP, PVA, and basalt fibers contribute to micro-crack control, ductility improvement, and environmental resistance.

(3) Hybrid fiber systems achieve multi-scale reinforcement by combining fibers with complementary properties. The synergistic interaction between fibers improves tensile behavior, toughness, and damage tolerance.

(4) The combination of steel slag powder and hybrid fibers provides new opportunities for developing environmentally friendly and high-performance UHPC. However, further research is needed regarding optimization methods, durability evaluation, and engineering application.

Future studies should focus on:

establishing quantitative relationships between fiber characteristics and performance enhancement;

developing intelligent mix design methods for steel slag powder UHPC;

investigating long-term durability under combined environmental actions;

evaluating life-cycle environmental benefits;

promoting large-scale engineering applications.

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