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Research Status of Durability of Fiber-Reinforced Concrete

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Abstract

As a new type of composite material, fiber-reinforced concrete significantly improves the inherent defects of traditional concrete such as low tensile strength and high brittleness by incorporating various types of fibers into the concrete matrix. Meanwhile, its durability has attracted extensive attention and research. This paper systematically reviews the effects of different types of fibers on the durability of concrete, analyzes the key influencing factors including fiber parameters, matrix properties and environmental conditions, summarizes the main testing methods and evaluation indicators of the durability of fiber-reinforced concrete currently available, and points out the deficiencies of existing research and future development directions. It provides a reference for the engineering application and subsequent research of fiber-reinforced concrete in complex service environments.

Keywords

Fiber-reinforced concrete; Durability; Synthetic fibers; Natural fibers; Hybrid fibers.

1. Introduction

Concrete, as the most widely used building material in the field of civil engineering, has promoted the rapid development of global infrastructure construction by virtue of its advantages such as high strength, low cost and easy formability. It is extensively applied in projects such as high-rise buildings, bridges and tunnels, water conservancy hubs, and transportation networks. However, the inherent defects of traditional concrete, such as low tensile strength, significant brittleness and poor crack resistance, make it prone to cracking due to external loads, temperature changes, dry-wet cycles and other factors during service. These cracks will reduce the bearing capacity of concrete structures and become channels for harmful substances such as chloride ions, sulfate ions and acidic media to invade, accelerating the deterioration processes such as steel corrosion, cement stone carbonation and alkali-aggregate reaction. Eventually, it leads to the decrease of structural durability, the shortening of service life, and even the occurrence of safety accidents[1].

To solve the durability defects of traditional concrete, scholars have carried out a lot of research, and fiber reinforcement technology has been widely recognized for its efficiency and economy. By uniformly dispersing short-cut fibers in the concrete matrix, fiber-reinforced concrete utilizes the bridging effect, crack resistance and energy absorption capacity of fibers to inhibit the initiation and propagation of microcracks, reduce internal pores and connected channels, thereby delaying the penetration rate of harmful substances and improving the durability properties of concrete such as corrosion resistance, freeze-thaw resistance and aging resistance[2]. Since fiber-reinforced concrete gradually entered engineering application in the 1980s, its durability research has become a hot direction in the fields of materials science and civil engineering. The research scope covers the performance evolution laws under different fiber types, different environmental media and different engineering scenarios. In marine environments, fiber-reinforced concrete can delay chloride ion erosion by inhibiting crack propagation; in cold regions, its freeze-thaw cycle resistance is significantly better than that of

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traditional concrete; in industrial corrosive environments, the addition of fibers can enhance the integrity of the matrix and improve acid resistance and sulfate erosion resistance.

With the global infrastructure developing towards high durability, long service life and green environmental protection, the application scenarios of fiber-reinforced concrete are constantly expanding. Currently, the types of fibers have expanded from early steel fibers and glass fibers to polypropylene fibers, basalt fibers, natural plant fibers and hybrid fiber systems, and the service environment has also transformed from a single corrosive medium to multiple environmental coupling. However, the physical and mechanical properties of different types of fibers are significantly different, and their improvement mechanisms and applicable scenarios for concrete durability still need to be systematically sorted out; the coupling mechanism of fiber parameters, matrix properties and environmental conditions has not been fully clarified; the durability evaluation methods and prediction models under multiple environmental coupling still need to be improved.

Based on this, this paper takes the durability of fiber-reinforced concrete as the core, systematically sorts out relevant research results, first classifies and elaborates the influence laws of synthetic fibers, natural fibers and hybrid fibers on the durability of concrete, and then analyzes the key influencing factors such as fiber parameters, matrix properties and environmental conditions.

2. Effects of Different Types of Fibers on the Durability of Concrete

There are various types of fibers, which can be divided into synthetic fibers, natural fibers and hybrid fibers according to their materials. The physical and mechanical properties of different types of fibers are significantly different, and their improvement effects on the durability of concrete also vary.

2.1. Synthetic Fibers

Synthetic fibers have the advantages of high strength, corrosion resistance and good stability, and are currently the most widely used fiber type in fiber-reinforced concrete. Common ones include steel fibers, polypropylene fibers (PPF), glass fibers (GF) and so on. Steel fibers can effectively improve the crack resistance and durability of concrete by virtue of their high tensile strength and good interface bonding performance. Talaeitaba et al.[3] studied the durability of steel fibers on self-compacting lightweight concrete (SCLC) in sulfate, sulfuric acid and chloride ion environments. The results showed that after adding 0.6% volume fraction of steel fibers, the compressive strength loss rate of concrete immersed in 10% magnesium sulfate environment for 750 days was only 20.8%, which was much lower than 33.2% of the fiber-free control group; after immersing in sulfuric acid environment for 65 days, the compressive strength loss rate was 15.30%, which was lower than 19.92% of the control group. However, steel fibers have high density and are prone to corrosion in corrosive environments such as chloride ions and sulfate ions, which may cause expansion stress inside the concrete and affect long-term durability. Polypropylene fibers (PPF) have good chemical stability and corrosion resistance, and can effectively inhibit early plastic cracks of concrete. Studies have found that adding PPF can significantly improve the freeze-thaw resistance and sulfate erosion resistance of concrete. In addition, the dispersibility of short-length PPF is better than that of long-length PPF, and the improvement effect on durability is more significant. Glass fibers (GF) have certain tensile strength and crack resistance, but poor alkali resistance, and are prone to erosion in the alkaline environment of concrete, affecting their long-term durability. Saljoughian A et al.[6] studies have shown that the freeze-thaw resistance and sulfate erosion resistance of GF-reinforced concrete are better than those of the fiber-free control group. ECC containing a large amount of GGBFS and PP fibers is superior to ECC containing PVA fibers in terms of tensile

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strain capacity and compressive strength. The ratio of water to binder and the ratio of silica fume to cement are important parameters affecting the performance of enhanced ECC.

2.2. Natural Fibers

Natural fibers (such as sisal, jute and hemp fibers) have the advantages of renewability, environmental friendliness and low cost, and have gradually become a research hotspot in the field of fiber-reinforced concrete in recent years. However, the surface of natural fibers contains impurities such as lignin and wax, resulting in poor interface bonding performance with the concrete matrix. Moreover, they are prone to water absorption and decay. Direct incorporation will affect the durability of concrete, so chemical treatment (such as NaOH treatment) is needed to improve their performance. Scholars have studied the effects of sisal, jute and hemp fibers treated with different chemicals on the durability of concrete. The results show that chemical treatment is the most critical factor affecting the durability of natural fiber-reinforced concrete. Silane-treated sisal fibers have the best effect. After adding 10% mass fraction and 5mm length of silane-treated sisal fibers, the water absorption rate of concrete is only 5.1%, which is much lower than 9.3% of untreated jute fiber concrete. NaOH treatment can remove impurities on the surface of natural fibers, increase surface roughness and improve interface bonding performance; silane treatment can form a chemical bonding layer on the fiber surface, further improve the bonding strength between fibers and the matrix, and reduce the penetration of water and harmful substances. However, the long-term durability of natural fiber-reinforced concrete still faces challenges. It is prone to biodegradation in humid environments, leading to the degradation of fiber performance and thus affecting the overall performance of concrete. At present, the research on the long-term durability of natural fiber-reinforced concrete is relatively scarce, and further experiments need to be carried out.

2.3. Hybrid Fibers

Hybrid fiber-reinforced concrete refers to the concrete matrix mixed with two or more types of fibers of different scales at the same time. It utilizes the synergistic effect of various fibers to control cracks of different scales in concrete, thereby more comprehensively improving its durability. Vadivel et al.[7] studied the effect of mixing steel fibers, glass fibers and polypropylene fibers on the durability of concrete. The results showed that the optimized hybrid fiber system can effectively densify the concrete matrix, enhance the performance of the interface transition zone (ITZ), and significantly inhibit the initiation and propagation of microcracks and macro cracks; compared with single fiber concrete, the chloride ion penetration resistance and freeze-thaw resistance of hybrid fiber concrete are improved, its compressive strength is increased by 20%~25%, and the splitting tensile strength is increased by about 30%. The synergistic effect of hybrid fibers is mainly reflected in: low modulus fibers (such as polypropylene fibers) control the initiation of early microcracks, and high modulus fibers (such as steel fibers and glass fibers) inhibit the propagation of macro cracks, thereby reducing the invasion channels of harmful substances. Other studies have confirmed that the mixed incorporation of steel fibers and polypropylene fibers can significantly improve the toughness and crack resistance of concrete, and its freeze-thaw cycle resistance and sulfate erosion resistance are better than those of single fiber reinforced systems. However, the ratio, length, volume fraction and other parameters of hybrid fibers have a significant impact on their synergistic effect. At present, there is no unified optimal design standard, and targeted research needs to be carried out in combination with specific engineering scenarios.

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3. Influencing Factors of the Durability of Fiber-Reinforced Concrete

The durability of fiber-reinforced concrete is affected by many factors, mainly including fiber parameters, matrix properties and environmental conditions. These factors interact to jointly determine the long-term service performance of concrete.

3.1. Fiber Parameters

Fiber parameters such as type, length, volume fraction and surface treatment method directly affect their dispersibility, interface bonding performance and crack resistance in the concrete matrix, thereby affecting durability.

The ratio of fiber length to diameter is an important parameter affecting its crack resistance. If the aspect ratio is too large, it is easy to cause fiber agglomeration, reducing the workability and compactness of concrete; if the aspect ratio is too small, it cannot effectively play the bridging role.

There is an optimal value for the influence of fiber volume fraction on durability. If it is too low, an effective fiber network cannot be formed, and the crack resistance effect is not good; if it is too high, it will affect the workability of concrete, leading to insufficient vibration compaction and increasing internal defects. Studies have shown that the optimal volume fraction of polypropylene fibers is about 0.1%~0.3%. The surface treatment method of fibers is crucial to the interface bonding performance. After natural fibers are treated with NaOH and silane, the interface bonding strength is significantly improved, which can effectively block the invasion of harmful substances. The density of plant fibers is lower than that of synthetic fibers, making them relatively superior in specific mechanical and physical properties[5]; after steel fibers are treated with copper plating, their corrosion resistance and interface bonding performance can be improved.

3.2. Matrix Properties

The compactness, pore structure, hydration degree and other properties of the concrete matrix are the basis for affecting durability, and the enhancement effect of fibers depends on good matrix properties. The higher the compactness of the matrix and the lower the porosity, the fewer the penetration channels of harmful substances and the better the durability. The water-binder ratio is too large, which is easy to increase the porosity of the matrix and reduce the durability; if the water-binder ratio is too small, it will affect the workability, leading to insufficient vibration compaction. Adding an appropriate amount of high-efficiency water reducer can ensure workability while reducing the water-binder ratio, improve the compactness of the matrix and enhance durability.

3.3. Environmental Conditions

The service environment of fiber-reinforced concrete directly determines its durability degradation mechanism. The erosion mechanism is different under different environments, and the improvement effect of fibers also varies. In a sulfate environment, sulfate ions react with cement hydration products to form expansive substances (such as ettringite), leading to concrete cracking and spalling. Fibers inhibit the propagation of cracks caused by expansion stress through crack resistance, thereby improving sulfate erosion resistance[4]. In a chloride ion environment, chloride ions are easy to invade the interior of concrete and cause steel corrosion. Fibers can reduce the crack width and delay the penetration rate of chloride ions, but steel fibers themselves are prone to corrosion in a chloride ion environment, which will affect long-term durability. In an acidic environment, hydrogen ions react with cement hydration products to cause a decrease in concrete strength and surface spalling. Fibers can enhance the integrity of the matrix, reduce the invasion of acidic media and improve acid corrosion resistance. In a freeze-thaw cycle environment, the freeze-thaw expansion of pore

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water inside concrete will generate internal stress, leading to the initiation and propagation of cracks. Fibers inhibit crack propagation through bridging effect and improve the freeze-thaw resistance of concrete. In a high-temperature environment, the concrete matrix is prone to dehydration and cracking. The type of fiber has a significant impact on high-temperature resistance. The high-temperature resistance of basalt fibers and steel fibers is better than that of polypropylene fibers.

4. Conclusions and Prospects

The durability of fiber-reinforced concrete is affected by many factors such as fiber type, fiber parameters, matrix properties and environmental conditions. Synthetic fibers can significantly improve the sulfate erosion resistance, chloride ion penetration resistance, freeze-thaw resistance and other properties of concrete; after appropriate chemical treatment, natural fibers can also improve the durability of concrete, but their long-term performance still needs attention; hybrid fibers can more comprehensively improve the durability of concrete by utilizing the synergistic effect.

Future research on the durability of fiber-reinforced concrete should focus on carrying out long-term aging tests of natural fibers, revealing their biodegradation and chemical corrosion mechanisms, developing efficient surface modification technologies to improve long-term durability; further studying the synergistic mechanism of hybrid fibers and establishing a multi-objective optimization-based hybrid fiber ratio design method; strengthening the research on the durability of fiber-reinforced concrete under multiple environmental coupling, and establishing a durability prediction model in line with actual service conditions; carrying out life cycle assessment of fiber-reinforced concrete to achieve the synergistic optimization of durability, economy and environmental protection.

Compared with ordinary strength concrete, the advantage of iron tailings concrete lies in the compactness of its microstructure. However, good compactness greatly reduces fire resistance. When a fire occurs, the concrete structure is subjected to high temperatures of 1000 °C or higher in a short time, leading to explosive spalling of its protective layer, or even local damage and collapse, which seriously reduces the bearing capacity and fire resistance of the concrete structure. Therefore, studying the fire resistance of iron tailings, especially the blasting performance after high-temperature exposure, is of great significance.

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