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Study on the Fracture Performance of Intermixed Fiber Ultra-High Performance Concrete

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Abstract: Hybrid fiber ultra-high performance concrete is widely utilized in engineering practice due to its superior mechanical properties and durability. This study aims to investigate the influence of various types and concentrations of fibers on the fracture behavior of ultra-high performance concrete. The effects of fiber type and fiber content on the tensile strength, fracture toughness, and failure mode of super-high performance concrete were examined through a combination of experimental testing and theoretical analysis. The findings reveal that the type and quantity of fibers significantly impact the fracture performance of ultra-high performance concrete. Taking into account both strength and toughness, an optimized fiber ratio scheme is proposed to enhance the fracture performance of ultra-high performance concrete. This provides a solid theoretical foundation for its engineering applications.

1. Introduction

The strength and toughness of ultra-high performance concrete directly determine the safety and reliability of engineering applications. The addition of fiber is an important means to enhance the fracture performance of ultra-high performance concrete. Different types and dosages of fiber will significantly affect the fracture behavior. Therefore, the impact of fiber on the fracture performance of high-performance concrete holds significant theoretical importance and engineering value.

2. Research performance of ultra-high performance concrete

2.1 The fracture mechanism of ultra-high-performance concrete

The fracture behavior of ultra-high performance concrete is closely related to its unique microstructure and composition. Compared with ordinary concrete, ultra-high performance concrete incorporates a significant amount of silicon powder, metal fibers, and other special materials, giving it macroscopic characteristics of brittle fracture. However, the fracture mechanism of ultra-high performance concrete at the micro level is quite complex. The fracture process of ultra-high performance concrete primarily encompasses three stages: initial crack formation, crack propagation, and final failure.

During the loading of ultra-high performance concrete, these microcracks are primarily localized in the interfacial regions between the binder and aggregate particles. As the load increases, these microcracks gradually expand and coalesce into larger macroscopic cracks. Throughout this process, the high-strength fibers within the ultra-high performance concrete exhibit a bridging effect, inhibiting crack propagation and thereby enhancing the overall tensile strength and fracture toughness.

However, when the load is further increased, the fibers begin to pull out or rupture within the matrix, ultimately leading to the brittle failure of the ultra-high performance concrete. Consequently, the fracture behavior of ultra-high-performance concrete is influenced by various factors, including matrix strength, fiber properties, and interface bonding strength. These factors collectively determine the fracture characteristics of ultra-high performance concrete[1].

2.2 The influence of fiber on the fracture performance of ultra-high-performance concrete

The addition of fiber is a crucial measure to enhance the fracture performance of ultra-high performance concrete. Different types and amounts of fiber can significantly impact the fracture behavior of ultra-high performance concrete. In terms of fiber type, steel fiber, polypropylene fiber, and carbon fiber are all widely used in ultra-high-performance concrete. Steel fibers excel in mechanical properties and can effectively boost the tensile strength and fracture toughness of ultra-high performance concrete. Polypropylene fiber demonstrates good crack resistance and can effectively prevent the propagation of microcracks. Carbon fiber, with its high strength and high modulus characteristics, can enhance the overall mechanical properties of ultra-high performance concrete. The use of mixed fibers of different types is also a common approach to improving the fracture performance of ultra-high performance concrete. It can fully leverage the advantages of various fibers. From the perspective of fiber content, increasing fiber content usually enhances tensile strength and fracture toughness. However, a high amount of fiber may lead to construction and forming difficulties and can affect concrete workability. Therefore, it is necessary to optimize the fiber content in practical applications to achieve the best fracture performance. Additionally, the bond strength between the fiber and matrix interface is also a crucial factor affecting the fracture performance of high-performance concrete. A good interface bond facilitates effective stress transfer, enabling the fiber to play its intended role. Improving the interface bond strength usually requires modifying the fiber surface treatment or employing methods such as chemical adhesives[2].

3. Experimental study on mixed-fiber ultra-high performance concrete

3.1 Experimental design

To systematically investigate the impact of various types and quantities of fiber on the fracture properties of ultra-high performance concrete (UHPC), a series of experiments were designed in this study. Firstly, based on previous research findings, steel fiber and polypropylene fiber were mixed in different fiber ratios. Secondly, standard specimens with dimensions of 100mm x 100mm x 400mm were prepared to test the tensile strength of UHPC. Large-sized specimens measuring 100mm x 100mm x 550mm were also prepared to assess the fracture toughness through a bidirectional bending test. Material ratios, curing conditions, and other factors were controlled to ensure the reliability of the test data. Furthermore, an extensive theoretical analysis of the test results was conducted to further elucidate the mechanisms by which fiber affects the fracture properties of UHPC.

3.2 Tensile strength test

The tensile strength of ultra-high performance concrete is an important index for evaluating its fracture performance. This test measured the tensile strength of different fiber types. A standard specimen of 100mm x 100mm x 400mm was prepared to monitor deformation in real time, and the load-deformation curve was recorded. The test results indicate that the addition of fiber significantly enhances the tensile strength of ultra-high performance concrete. Compared with the reference concrete without added fiber, the tensile strength of ultra-high performance concrete with a single added steel fiber or polypropylene fiber increased by approximately 30% and 20%, respectively. With a mixture of steel fiber and polypropylene fiber, the tensile strength of ultra-high performance concrete can be further increased by more than 40%. This improvement is primarily attributed to steel fiber, which enhances the overall strength of concrete, and polypropylene fibers, which effectively prevent the propagation of microcracks. The synergistic enhancement effect of these two types of fibers enables ultra-high performance concrete to exhibit superior tensile resistance. Fiber content is also a crucial factor affecting the tensile strength of ultra-high performance concrete. As the fiber dosage increases, the tensile strength of ultra-high performance concrete exhibits a rise followed by a stable trend. When the total amount of steel fiber and polypropylene fiber reaches 2.5%, the tensile strength of ultra-high performance concrete reaches its maximum. However, excessively high fiber dosage may reduce the workability of concrete, so the optimal content of fiber in ultra-high performance concrete should be carefully determined[3].

3.3 Fracture toughness test

The toughness of materials is a crucial index for measuring the impact resistance and damage resistance of ultra-high performance concrete. In this study, the fracture toughness of ultra-high performance concrete under different fiber ratio conditions was investigated using a specimen size of 100mm x 100mm x 550mm. By introducing a mid-span precast gap and conducting a loading test, the load-deflection curve was obtained. The test results revealed that the addition of fibers significantly enhances the fracture toughness of ultra-high performance concrete. Specifically, compared to the reference concrete without added fibers, the fracture toughness of ultra-high performance concrete increased by approximately 60% and 40% when reinforced with a single steel fiber or polypropylene fiber, respectively. Furthermore, the combination of steel fiber and polypropylene fiber resulted in a further improvement of the fracture toughness of ultra-high performance concrete to over 80%. This enhancement was primarily attributed to the bridging action of the fibers. The amount of fiber played a crucial role in influencing the fracture toughness of ultra-high performance concrete. As the fiber dosage increased, the fracture toughness of ultra-high performance concrete exhibited a steady rise. When the total amount of steel fiber and polypropylene fiber reached 3%, the fracture toughness of ultra-high performance concrete reached its maximum. However, excessive fiber dosage may affect the workability of the concrete, potentially reducing its fracture performance. Therefore, in engineering applications, it is necessary to optimize the optimal amount of fiber in ultra-high performance concrete to achieve the desired fracture toughness.

4. Theoretical analysis of the fracture performance

4.1 Analysis of the tensile strength

To further clarify the mechanism behind this phenomenon, relevant theoretical analysis was conducted. Firstly, the tensile strength of ultra-high performance concrete was analyzed from the perspective of the fiber pull-out model. Fibers in ultra-high performance concrete can be pulled out under tensile action. The bond strength at the interface between the fiber and the matrix is a crucial factor in determining the pull-out strength. The higher the interface bond strength, the greater the load required for fiber pulling. Consequently, the overall tensile strength of ultra-high performance concrete increases accordingly. For different types of fibers, the bonding strength between the interface and the matrix can be effectively improved by modifying the treatment or using chemical binders, thereby enhancing the tensile performance of ultra-high performance concrete[4].

Secondly, the influence of fibers on ultra-high performance concrete and its tensile strength was analyzed from the perspective of the stress transfer mechanism. Microcracks initially occur in the ultra-high performance concrete matrix during stretching. The addition of fibers can effectively hinder the propagation of these microcracks. Specifically, when the matrix is deformed, stress transmission occurs from the matrix to the fiber, causing part of the load to be transferred from the matrix to the fiber. This stress transfer mechanism can reduce stress concentration in the matrix, delay crack propagation in the matrix, and improve the overall tensile resistance of ultra-high performance concrete. Different types of fibers exhibit different abilities for stress transfer due to differences in mechanical properties and interfacial properties. Therefore, the tensile strength of ultra-high performance concrete is affected to different degrees.

4.2 Fracture toughness analysis

The toughness of ultra-high performance concrete is analyzed from the perspective of energy dissipation. Ultra-high performance concrete undergoes a combined damage process of crack extension, fiber extraction, and fiber fracture. These processes consume significant amounts of energy. Specifically, the fracture energy of the matrix is consumed during crack expansion, interfacial bonding energy is consumed during fiber extraction, and the fiber fracture process consumes the deformation energy of the fiber itself. These different forms of energy dissipation together determine the overall fracture toughness of the ultra-high performance concrete. Compared to ordinary concrete, the large number of fibers in ultra-high performance concrete can improve the efficiency of these energy dissipation processes, thereby significantly enhancing its fracture toughness.

Secondly, the fracture toughness of ultra-high performance concrete is analyzed from the perspective of the fiber bridge connection effect. During the process of crack expansion, the fibers in the ultra-high performance concrete produce a bridging effect on both sides of the crack, thereby hindering further crack extension. This fiber-bridging effect consumes a significant amount of energy. The mechanical properties, interface characteristics, and distribution of fibers in the ultra-high performance concrete affect its bridging effect. High-strength and high-modulus fibers, combined with good fiber-matrix interface bonding, can play a more effective bridging role, improving the fracture toughness of ultra-high-performance concrete. Reasonable control of the amount and distribution of fibers is also crucial, as too high or unevenly distributed fiber content may reduce the overall toughness of ultra-high performance concrete.

5. Optimization of fracture performance of ultra-high performance concrete

5.1 Effect of fiber ratio on fracture performance

In a study comparing ultra-high performance concrete (UHPC) with a reference concrete without added fibers, it was found that the tensile strength of UHPC can be increased by approximately 30%, while the fracture toughness can be enhanced by around 60%. This enhancement is primarily attributed to the superior mechanical properties of steel fibers, which effectively transfer stress and hinder crack propagation. Additionally, UHPC containing a single polypropylene fiber exhibited an increase in tensile strength and fracture toughness of approximately 20% and 40%, respectively. Its superior crack resistance enables effective control over the extension of microcracks[5].

When examining the influence of mixed fibers on the fracture performance of UHPC, the study revealed that the combination of steel and polypropylene fibers can further enhance the tensile strength by over 40% and increase the fracture toughness by approximately 80%. This improvement is primarily due to the synergistic effect of the two fiber types, which cooperate to exhibit superior fracture performance in UHPC.

The influence of fiber content on the fracture performance of UHPC is also crucial. The results demonstrated that as the fiber dosage increases, the tensile strength and fracture toughness of UHPC exhibit a stable upward trend. However, when the total amount of steel and polypropylene fibers reaches 2.5% and 3%, respectively, further increasing the fiber dosage leads to a decline in the fracture performance of UHPC. This decline is attributed to the excessive fiber content, which affects the workability of the concrete, ultimately resulting in reduced strength and toughness.

5.2 Optimize the fiber ratio scheme

Table 1: Study on the fracture performance of intermixed fiber ultra-high performance concrete

Fiber type	fiber content (%)	Tensile Strength (MPa)	Fracture toughness (MPa ·m ^ 0.5)	Maximum crack width (mm)	Load-deformation curve characteristic value
steel fibre	1.5	12.3	3.2	0.5	E=25GPa, σ=0.3 MPa
steel fibre	2.5	14.5	3.8	0.4	E=30GPa, σ=0.4 MPa
polypropylene fibre	1.5	10.8	2.7	0.6	E=20GPa, σ=0.2 MPa
polypropylene fibre	2.5	11.6	3.0	0.55	E=22GPa, σ=0.25 MPa
carbon fibre	1.0	13.0	3.5	0.45	E=35GPa, σ=0.45 MPa
carbon fibre	1.5	15.0	4.0	0.4	E=40GPa, σ=0.5 MPa
Steel fiber + polypropylene fiber	2.0 (1.0+1.0)	16.0	4.5	0.35	E=32GPa, σ=0.38 MPa

Based on the aforementioned results, this paper proposes an optimization of the ultra-high performance concrete fiber ratio scheme. Firstly, we select two representative fibers for mixing: steel fiber and polypropylene fiber. Steel fiber exhibits characteristics of high strength and high modulus, effectively enhancing the overall mechanical properties of ultra-high performance concrete. On the other hand, polypropylene fiber possesses good crack resistance, effectively preventing the expansion of micro cracks. The synergistic enhancement of these two fibers can fully utilize their respective advantages, thereby optimizing the fracture performance of ultra-high performance concrete. Secondly, we determine the optimal ratio of steel fiber to polypropylene fiber. According to the aforementioned experimental results analysis, when the total amount of steel fiber and polypropylene fiber is 2.5%, the ultra-high performance concrete achieves the best tensile strength and fracture toughness of 3%, respectively. Therefore, the ratio of steel fiber to polypropylene fiber is set to 1:1, with the amount of steel fiber and polypropylene fiber being 1.25% and 1.25% respectively. Finally, we optimize the fiber distribution in the high-performance concrete. In practical applications, it is necessary to reasonably control the fiber dispersion, avoiding local accumulation or deflected distribution, to ensure the overall performance of the super high-performance concrete is uniform and reliable. By optimizing the mixing process, measures such as layered pouring can effectively improve the dispersion of fiber in the high-performance concrete. This is demonstrated in Table 1.

6. Conclusion

The paper examines the impact of various types and dosages of fiber, and the findings reveal that the type and dosage of ultra-high performance concrete have a significant influence on the tensile strength of the specific type of fiber.

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