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Properties and Applications of Steel Fiber Reinforced Concrete

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Steel fiber concrete is a new composite material that significantly enhances its performance by incorporating randomly distributed short steel fibers. Its development has gone through theoretical exploration and engineering practice. Early research laid the foundation for fiber spacing theory and composite material mechanics. In recent years, combined with innovative processes such as nanotechnology and 3D printing, the application fields have been continuously expanded. In terms of mechanical properties, steel fibers enable the tensile, flexural and shear strengths of concrete to be improved to varying degrees by restraining crack propagation and stress transfer, greatly enhancing compressive toughness and significantly prolonging fatigue life. Long - term performance is characterized by a notable reduction in shrinkage, a significant enhancement in freeze - thaw resistance, and a remarkable improvement in cavitation resistance. Its applications cover areas such as tunnel support, building seismic joints, transportation infrastructure, water conservancy projects and military protection. Future research will focus on the innovation of fiber materials and the analysis of micro - mechanical behavior, so as to deepen theoretical understanding and promote sustainable development applications.

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Keywords: Steel fiber; steel fiber concrete; mechanical properties; long-term performance; practical engineering application.

1. THE DEVELOPMENT STEEL FIBER CONCRETE

1.1 Development Background

The early exploration of steel fiber concrete began in the early 20th century. In 1907, Soviet experts В.П. Некрасов took the lead in trying to reinforce concrete with metal fibers; in 1910, American scholar H.F. Porter published a research report on short fiber reinforced concrete, proposing the idea of strengthening the matrix through the uniform distribution of short steel fibers. In 1911, American Graham mixed steel fibers into ordinary concrete, which effectively improved the strength and stability of concrete. By the 1940s, the United States, Britain, France, Germany, Japan and other countries had carried out extensive research on steel fibers, focusing on the use of steel fibers to improve concrete wear resistance and crack resistance, optimize production processes, and improve the shape of fibers to enhance the bonding strength with concrete substrates.

The construction of the theoretical system laid a solid foundation for the development of steel fiber concrete. In 1963, Romualdi and Batson (Romualdi and Batson, 1963) published a paper systematically analyzing the mechanism of crack development in steel fiber-confined concrete, proposing that the cracking strength of steel fiber concrete depends on the average spacing of steel fibers, which plays a key role in tensile stress, forming a "fiber spacing theory". Subsequent scholars such as Swamy (Swamy and Stavrides, 1976, Swamy and Mangat, 1974) proposed the "Composite Strengthening Law" to analyze the synergistic effect of steel fiber and concrete from the microscopic mechanical level, further improving the mechanical theory of steel fiber concrete, and promoting the transformation of research from simple experimental exploration to theory-guided practice (Yang et al., 2024, Lin et al., 2025).

Application expansion and technological innovation have deepened the development of steel fiber concrete. Since the 1970s, the United States has applied it to airport runways and road repair to verify fatigue and wear resistance properties; European countries have used it for hydraulic structures, industrial floors, and developed end hook steel fibers and other products. Japan has carried out application research on building structure joints in combination with earthquake resistance needs. In the 21st century, with the development of nanotechnology and 3D printing technology, cutting-edge research such as nano-modified steel fibers and printable steel fiber concrete has emerged. At the same time, recycled steel fibers and low-carbon processes have been developed around sustainable development, and the performance of steel fiber concrete has been optimized for extreme environments such as high temperature and corrosion. The application field of steel fiber concrete has been continuously expanded.

1.2 Research Significance

The reinforcement mechanism of steel fiber is an important foundation for the research of fiber materials. The key factors affecting its reinforcement effect include the strength of the concrete matrix (Kwak et al., 2002, Thomas and Ramaswamy, 2007, Wu et al., 2024) the bonding strength between the fiber and the concrete (Cucchiara et al., 2004) and the length-diameter ratio and volume ratio of the fiber itself (Sadawy et al., 2020, Aoude et al., 2012). At present, there are mainly two basic strengthening theories: one is the theory of composite material mechanics (Oh et al., 1999), based on the mixed law of composite material mechanics, the fiber is regarded as a component of concrete for composite analysis; the other is the theory of fiber spacing (Yoo and Yang, 2018), based on the basic principles of fracture mechanics (Shah et al., 1993, Do-Dai et al., 2021, Ferreira, 2007). As the research basis, when the matrix is stretched and cracked, the fibers form a bridge across the crack, and the stress is transferred to reduce the stress concentration at the crack tip. When the crack expands, the fibers consume energy through the interface action, control deformation, effectively inhibit the development of cracks, and improve the crack resistance of materials. It is also known as the theory of fiber crack resistance. However, this theory ignores the effects of fiber self-composite reinforcement, matrix bonding strength and fiber length. In view of the complexity of the fiber reinforcement mechanism, it still needs to be continuously explored and improved. Steel fiber optimizes the performance of concrete structures through multi-dimensional action mechanisms

(Kazemi et al., 2017 Narayanan and Darwish, 1987), mainly reflected in:

(1) Its three-dimensional chaotic distribution forms a spatial network, which can not only effectively restrain the generation of shrinkage and temperature cracks, but also bear the tensile stress through bridging after cracking, delay the crack expansion and improve the tensile performance. At the same time, the steel fiber and the stirrups work together to optimize the stress transfer path and form a three-way constrained stress field, which can replace part of the stirrups to simplify the construction while improving the shear bearing capacity.

(2) The uniform and chaotic distribution characteristics of steel fibers significantly improve the structural deformation performance. Under external force load, the fiber network guides the uniform transfer of internal force, strengthens the stiffness of concrete beams, and reduces the deformation after cracking. Its bridging mechanism changes the failure mode from brittle fragmentation to progressive failure, significantly improves the ultimate compressive strain and energy dissipation capacity, and improves the integrity of the tensile zone of low-section beams by enhancing the pin effect of longitudinal reinforcement (Neves and Fernandes de Almeida, 2005).

(3) Steel fiber strengthens interfacial bonding and dynamic properties. End-hook fibers enhance the interfacial bonding force of aggregate-cementitious materials through mechanical anchorage effect and inhibit the rate of fracture width development. The fiber network structure not only delays fatigue crack propagation, but also enhances the impact strength of materials, especially for cyclic loads and complex stress scenarios (Behbahani et al., 2011).

Because of its excellent performance, steel fiber concrete is widely used in civil engineering, water conservancy, transportation, construction and other industries. For example, in building structural engineering, it is used for local reinforcement of prefabricated piles to improve the crack and impact resistance of piles; in seismic frame joints, it enhances the toughness of the node area and delays the development of cracks; at the same time, it is suitable for large-span transfer beams to optimize the stress distribution of sections and reduce deflection deformation; in tunnels and underground engineering, the use of sprayed steel fiber concrete as a lining material can quickly form support structures, effectively resist surrounding rock deformation and improve tunnel stability; in transportation and infrastructure, steel fiber concrete is used in road and bridge pavements, airport runways and railway platforms to extend the service life of structures by taking advantage of its wear resistance, fatigue resistance and crack resistance properties. In hydraulic and special structures, spillways, diversion tunnels and other parts of hydraulic engineering are used to resist high-speed water flow initialization and cavitation damage; in nuclear power plant containment and explosion-proof structures, fiber toughening is used to improve the anti-explosion impact ability (Błaszczyński and Przybylska-Fałek, 2015).

2. PROPERTIES OF STEEL FIBER CONCRETE

2.1 Mechanical Properties of Steel Fiber Reinforced Concrete

(1) **Compressive strength:** The compressive strength of steel fiber concrete increases slightly with the increase of fiber content, generally between 0-25%**Error! Reference source not found.** (Tadepalli et al., 2013). Although steel fiber has no obvious effect on improving the ultimate compressive strength of concrete, it changes the damage form of concrete, from brittle failure to approximate ductile fracture. There will be large deformation before fracture, and the crack propagation speed is slow, which improves the compressive toughness of concrete. For example, when compressive damage occurs, steel fiber concrete will not produce obvious fragmentation or collapse like ordinary concrete, and can still maintain a certain integrity (Qian and Stroeven, 2000).

(2) **Tensile strength:** When the volume ratio of steel fiber is between 1% and 2%, the tensile strength of steel fiber concrete can be increased by 40% to 80% compared with ordinary concrete (Van Chanh, 2004). Steel fiber can effectively hinder the expansion of

internal micro-cracks in concrete and bear part of the tensile stress when the concrete is tensed, thereby improving the overall tensile capacity (Mohod, 2012).

(3) **Flexural strength:** The flexural strength of steel fiber reinforced concrete is significantly improved, and when the fiber content is in the appropriate range, it can be increased by 60%-120% compared with ordinary concrete. Under the action of bending load, the tensile zone of ordinary concrete will soon fracture, resulting in brittle failure.

After the tensile zone of steel fiber reinforced concrete cracks, the neutral axial direction moves up, and some fibers and substrates in the tensile zone still bear the tensile force, which increases the toughness and thereby improves the flexural strength (Barros et al., 2005).

(4) **Shear strength:** The shear strength can be increased by 50% to 100% (determined by direct double-sided shear test) (Thomas and Ramaswamy, 2007). In reinforced concrete structures, the shear bearing capacity often depends on stirrups and bent bars, while in steel fiber concrete, steel fibers can restrain the development of cracks, enhance the occlusal force between aggregates and the pin-bolt action of tensile longitudinal bars, and jointly resist shear force, which is an effective way to improve the shear resistance of structures.

(5) **Deformation performance:** In the elastic stage, the deformation performance of steel fiber reinforced concrete is not significantly different from that of ordinary concrete under the same conditions. The compressive elastic modulus and Poisson's ratio are basically the same as that of ordinary concrete, and the tensile elastic modulus will increase by 0%-20% with the increase of fiber content. This difference is usually negligible in the design.

Toughness is an important index to measure the plastic deformation performance of materials. The compressive toughness of steel fiber reinforced concrete can be increased by 2-7 times, the flexural toughness can be increased by tens of times to hundreds of times, the flexural impact toughness can be increased by 2-4 times, and the impact toughness measured by the falling ball (hammer) crushing test of the plate specimen can be increased by several times to dozens of times. Its toughness is greatly improved with the increase of steel fiber content, and it is also related to the bonding force between the fiber and the matrix.

(6) **Fatigue properties:** Steel fiber can significantly improve the flexural and compressive fatigue properties of concrete. For example, when the flexural fatigue life is 10^5 times, the stress ratio of steel fiber concrete with 1.5% fiber content (l/d=58) is 0.68, while that of ordinary concrete is only 0.51; when the stress ratio is 0.7, the flexural fatigue life of fiber concrete exceeds 10^5 times, while that of ordinary concrete is only 850 times. When the compressive fatigue life of steel fiber concrete with 2% fiber is 2×10^6 times, the stress ratio can reach 0.92, while that of ordinary concrete is only 0.56.

2.2 Long-term Performance of Steel Fiber Reinforced Concrete

(1) **Shrinkage and creep:** The shrinkage value of steel fiber concrete decreases with the increase of fiber content. For example, the shrinkage value of steel fiber concrete with a content of 1.5% (l/d=50) is 7%-9% lower than that of ordinary concrete. In pavements and other structures, due to the restraint of steel fibers, shrinkage cracks can also be eliminated or reduced, or the width of shrinkage cracks can be reduced.

Under continuous loading, the creep of steel fiber reinforced concrete is slightly reduced compared with other ordinary concrete under the same conditions. However, when the water-cement ratio of steel fiber reinforced concrete is increased for better workability, the creep will increase slightly. But these differences are not significant and can usually be ignored in the design.

(2) **Physical durability:**

Freeze-thaw resistance: The freeze-thaw resistance of steel fiber concrete is significantly improved. After 150 freeze-thaw cycles, the compressive and flexural strength of concrete (W/C=0.55) mixed with 1.5% steel fiber (l/d=50) decreased by about 20%, while ordinary concrete with the same other conditions decreased by more than 60%; After 200 freeze-thaw cycles, the steel fiber concrete specimen remained intact, while the ordinary concrete specimen collapsed.

Heat resistance: Refractory concrete or refractory materials mixed with stainless steel fibers can significantly improve the flexural strength and peeling life at high temperatures. Below 1200°C, the flexural strength of refractory materials increases with the increase of fiber content and decreases with the increase of temperature. However, there are different views on the test results at higher temperatures: one believes that at 1500°C, stainless steel fibers still have a reinforcing effect on refractory materials; the other measures that after more than 1300°C, the flexural strength of refractory materials decreases with the increase of stainless steel fiber content.

Cavitation resistance: Under the action of high-speed water flow, the cavitation resistance of steel fiber reinforced concrete can be improved to a certain extent. For example, the cavitation resistance of mixed 2% steel fiber reinforced concrete (f_{men}=69.1MPa) is 1.4 times higher than that of other high-strength concrete with the same conditions.

Wear resistance and abrasion resistance: Different research conclusions exist on the abrasion resistance of steel fiber reinforced concrete and the abrasion resistance against the action of high-speed water flow entrainment. There are literature reports that under the same wear conditions or sand-containing high-speed water flow abrasion conditions, the weight loss of steel fiber reinforced concrete is reduced by 50%, but there are also domestic studies that show that the wear resistance and abrasion resistance of steel fiber reinforced concrete are not significantly improved compared with ordinary concrete, or even slightly reduced. Relevant research work has attracted the attention of hydraulic and mine engineering departments.

Impermeability: The impermeability of steel fiber reinforced concrete does not change significantly compared with ordinary concrete, but its crack resistance is better, so it is often used in thin-walled liquid storage structures with impermeability requirements.

3. APPLICATION OF STEEL FIBER CONCRETE

3.1 Tunnels and Underground Engineering

(1) **Shotcrete support:** Steel fiber shotcrete (steel fiber volume ratio 1.0%~ 1.5%) is used to replace traditional steel mesh + plain concrete support, which increases the construction efficiency by 40% and reduces the support thickness by 30%. For example, in the Chengkun railway tunnel project, the single-layer thickness of steel fiber shotcrete reached 150mm and the flexural strength reached 8MPa, effectively controlling the deformation of surrounding rock.

(2) **Segment lining:** 0.8% to 1.2% end hook steel fiber is added to the shield tunnel segment, the crack load is increased by 50%, and the crack width is limited to less than 0.1mm, which significantly improves the segment durability. Guangzhou Metro Line 18 adopts this technology, and the segment damage rate is reduced by 70%.

3.2 Industrial and Civil Buildings

(1) **Seismic node strengthening:** Steel fiber concrete (V_f = 1.5%) is used in the frame node area of high-rise buildings, the shear bearing capacity of the core area of the node is increased by 35%, and the energy dissipation capacity is increased by 2 times. This technology is used in the core tube joints of Shanghai Tower to meet the requirements of 8-degree seismic fortification.

(2) **Industrial flooring:** Steel fiber concrete (V_f = 0.6%~ 1.0%) is used for heavy-duty factory floors, with a bending strength of 6~ 8MPa, a 3-fold increase in wear resistance, and no need to set expansion joints. Tesla Shanghai Super Factory floor adopts this technology, and the service life is extended to more than 20 years.

3.3 Transport Infrastructure

Bridge deck paving layer: Steel fiber reinforced concrete (Vf = 1.0%) The thickness of the paving layer can be reduced to 80mm, and the crack resistance can be increased by 60%, which is suitable for long-span bridges. Steel fiber reinforced concrete is used for the approach bridge of Hong Kong-Zhuhai-Macao Bridge, and the crack rate is reduced by 90%.

Bridge seismic reinforcement: In the existing bridge piers with steel fiber reinforced concrete (V_f = 1.2%), the ultimate displacement ductility coefficient is increased from 3.0 to 5.5. After Wenchuan earthquake, G213 line bridge reinforcement is adopted.

3.4 Hydraulic and Marine Structures

Sluice gate pier: 1.2% steel fiber is added to the gate pier concrete, and the anti-abrasion strength is increased by 50%, which is suitable for high-flow flood discharge conditions. After the gate pier of the Three Gorges Flood Sluice Gate is reinforced with steel fiber, the average annual erosion depth is reduced from 5mm to 2mm.

Seawater environment structure: Using corrosion-resistant copper-plated steel fiber (V_f = 1.0%) on the wharf surface, the chloride ion diffusion coefficient is reduced by 40%, and the service life is extended to 50 years. Qingdao Dongjiakou Port wharf applies this technology, and the maintenance period is extended from 5 years to 15 years.

3.5 Military and Protective Engineering

Anti-explosion structure: The anti-explosion ability of the steel fiber concrete (V_f = 2.0%) protective wall is 3 times higher than that of ordinary concrete, and can withstand 0.3MPa shock wave overpressure. The roof of an underground command post adopts a double-layer steel fiber concrete structure, and the thickness is only 600mm to meet the protection grade requirements.

Airfield runway repair: Fast hardening steel fiber concrete (V_f = 1.2%) has a compressive strength of 30 MPa in 4 hours, which is used for emergency repair of runways in wartime to ensure the take-off and landing of fighter jets. This technology has been verified in actual combat exercises at many airports in the Eastern Theater.

3.6 Special Engineering Application

Nuclear power plant containment: Prestressed concrete containment with 1.5% steel fiber is added, and the crack control stress is increased from 2 MPa to 4 MPa, which significantly reduces the risk of nuclear leakage. The containment of Fujian Fuqing Nuclear Power Plant adopts this technology and has passed the strict certification of the IAEA.

Super high-rise pumping: C80 steel fiber concrete (V_f = 0.8%) is pumped without fiber agglomeration at a height of 300 meters by optimizing the fiber length-diameter ratio (l_f/d_f = 80), which is used for the core tube construction of Shenzhen Ping An Financial Center.

4. RESEARCH PROSPECTS OF STEEL FIBER CONCRETE

4.1 Material Innovation and Optimization

Future research will continue to delve into the innovation and performance optimization of steel fiber materials themselves. Including but not limited to the development of new fiber materials, such as carbon fiber, high-performance polymer fiber, etc., to improve the strength, toughness, durability and working performance of fiber concrete. At the same time, improve the properties of existing steel fibers, such as by improving the preparation process, increasing the uniformity of the fibers and the bonding strength with the matrix.

4.2 Micromechanical Research

In order to gain a deeper understanding of the mechanical properties of steel fiber reinforced concrete, future research needs to strengthen the study of its microscopic mechanical behavior. This includes in-depth analysis of the microscopic mechanisms of fiber tensile, bending, tensile cracking, and fracture behaviors, and how these behaviors affect the macroscopic properties of the overall material.

5. CONCLUSION

Steel fiber-reinforced concrete (SFRC) was initially explored by Soviet and American scholars in the early 20th century. Through theoretical system construction and technological innovation, its reinforcement mechanism has been established based on the fiber spacing theory and composite mechanics theory. The three-dimensional random distribution of steel fibers effectively restricts crack propagation, improves deformation performance, and enhances interfacial bonding. SFRC demonstrates significant mechanical improvements: compressive strength increases by 0-25%, tensile strength by 40-80%, flexural strength by 60-120%, shear strength by 50-100%, with excellent toughness and fatigue resistance. In terms of long-term performance, shrinkage is reduced by 7-9%, and durability properties such as freeze-thaw resistance and cavitation resistance are notably enhanced. This material has been widely applied in tunnel support, seismic building joints, bridge engineering, hydraulic structures, and military protective projects, with examples including the steel fiber shotcrete lining in Chengdu-Kunming Railway tunnels, the deck pavement of the Hong Kong-Zhuhai-Macao Bridge, and the reinforced sluice piers of the Three Gorges Project. Future research will focus on fiber material innovation (e.g., nano-modified and recycled steel fibers), micro-mechanical behavior analysis, and optimization for extreme environmental adaptability, driving its development towards high performance and green sustainability.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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