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Performance Characteristics of Steel Fiber Reinforced Concrete and Its Application in Different Fields

Junfeng Ren

School of Civil Engineering, Zhongkai University of Agriculture and Engineering, Guangzhou, China
1831148730@qq.com

Abstract: With the vigorous development of the construction industry, the demand for high-performance concrete materials is growing rapidly. As a cutting-edge composite material, steel fiber-reinforced concrete (SFRC) has attracted much attention in the industry. This study anchored steel fiber reinforced concrete in an in-depth analysis of its performance characteristics and practical application in multiple fields. Based on the comprehensive use of the experimental research method, case analysis method, and data statistics and analysis method, through rigorous exploration, it is found that steel fiber reinforced concrete performs excellently in the dimensions of strength, crack resistance, and impact resistance, with tensile strength increased by 25%-50% and crack formation reduced by up to 75%. In the engineering fields of coal mine shaft lining, pavement repair, shaft cover, and so on, its application has achieved remarkable results: it extends pavement maintenance cycles by 30%-40%, effectively guarantees the engineering quality, and significantly improves the engineering efficiency. However, it cannot be ignored that this study has shortcomings in the expansion of research scope and the setting of experimental conditions. The research results lay a solid theoretical foundation for expanding the application boundary of steel fiber reinforced concrete, guide the direction for subsequent research, and have far-reaching significance in promoting the technological innovation of building materials.

Keywords: Steel fiber reinforced concrete, Performance characteristics, Application

1. Introduction

In the construction industry, steel fiber reinforced concrete, as a highly innovative material, plays an important role in enhancing the performance of concrete. Adding steel fiber into an ordinary concrete matrix can effectively improve its mechanical properties, which is reflected in the significant enhancement of tensile, bending, and shear strength; the significant improvement of crack resistance, impact resistance, and fatigue resistance; and the significant improvement of shrinkage performance. The optimization of these properties enables steel fiber reinforced concrete to meet the stringent demands of various complex engineering projects. The in-depth study of the performance characteristics and application fields of steel fiber reinforced concrete is of great significance to promote the progress of construction technology, help to build a more scientific and reasonable architectural structure design scheme, and effectively improve the quality and safety performance of construction projects. In many engineering scenarios, such as mine construction, road engineering, municipal facilities, steel fiber reinforced concrete demonstrates its unique

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advantages, meets diverse engineering needs, and promotes the sustainable development of the construction industry [1].

This study takes steel fiber reinforced concrete as the core research object, aims to carry out a comprehensive and in-depth analysis of its performance characteristics, and makes a detailed exploration of its practical application in many fields. Through the systematic analysis of the mechanical properties of steel fiber reinforced concrete, such as compression, tension, and crack resistance, as well as key properties like shrinkage and durability, a complete cognitive system of its performance is built.

In the application research phase, the study covers multiple domains including construction, transportation, mining, and so on, and the performance of the material under different environmental conditions and engineering requirements is discussed in depth. The innovation of this study lies in integrating research findings from multiple fields, overcoming the limitations of single-field research, conducting a horizontal comparison of the performance of steel fiber reinforced concrete in various fields, and deeply mining the underlying patterns within multidimensional data. This approach provides a solid theoretical basis for its application in a wider range of engineering scenarios and gives full play to its application value in various engineering projects [2]. Unlike previous literature, which mainly focused on single-field applications or isolated performance analysis, this study uniquely integrated the research results of multiple disciplines, established the cross-domain correlation between material properties and engineering requirements, and revealed the previously unrecognized synergy in the behavior of fiber-reinforced concrete under different conditions.

2. Development status

2.1. Research status of performance characteristics of steel fiber reinforced concrete

In the research on the performance characteristics of steel fiber reinforced concrete, many scholars have conducted in-depth investigations into its strength, crack resistance, and impact resistance. Regarding strength performance, many studies found that the addition of steel fiber alters the internal structure of concrete, promoting more uniform stress distribution and improving overall mechanical strength, in which the tensile strength increased by 25%-50%. In terms of crack resistance, the random distribution of steel fibers effectively inhibits crack propagation. When small cracks are generated in concrete under tension, steel fibers can bear part of the tensile force and inhibit crack propagation. In terms of impact resistance, due to the good toughness of steel fiber, it can absorb impact energy and enhance the ability of concrete to resist impact load [3].

In terms of influencing factors and mechanisms, scholars pointed out that the shape, size, content, and other factors of steel fiber had a significant impact on the performance of concrete. The steel fiber with an appropriate length-to-diameter ratio and appropriate dosage can play a better role in reinforcement. At the same time, the mix proportion of the concrete matrix and aggregate properties also work together with steel fiber to determine the performance of steel fiber reinforced concrete. These studies have laid a solid foundation for further exploration [4].

2.2. Application research progress in different fields

In the field of coal mine shaft lining, with the increase of mining depth, shaft lining concrete faces more stringent performance requirements. Steel fiber reinforced concrete, with its ultra-early strength, high fluidity, and excellent crack resistance, rapidly forms stable structures even under complex environmental conditions, resisting freezing pressure and other adverse factors, meeting the engineering requirements for shaft lining strength and durability, and ensuring the safety of coal mine construction. In pavement repair, urban roads endure significant stresses from vehicle loads, and ordinary concrete repair has the problem of brittleness and easy fracture. Steel fiber reinforced concrete can effectively improve pavement performance, reduce cracks, prolong pavement service life, and reduce maintenance costs due to its strong crack resistance and high bending strength [5].

In the field of manhole covers, the traditional cast-iron manhole covers are prone to loss, high noise, and low bearing capacity. After the steel fiber is added into the steel fiber concrete manhole cover, the compressive, tensile, and bending capacity is improved, which is theft-proof, green, and environmentally friendly and will not rust and affect the environment. Different bearing levels can meet the needs of municipal roads, residential areas, and other scenarios and play an important role in improving the safety and aesthetics of urban infrastructure [6].

3. Experimental parameters

3.1. Experimental research method

In the experimental study, p-o52.5 cement conforming to the national standard was selected as the cement. The water consumption for standard consistency was 26.8%, the initial setting time was 95 min, the final setting time was 165 min, the 3D compressive strength was 32.4 MPa, the 28-day compressive strength was 57.2 MPa, the 3D flexural strength was 6.8 MPa, and the 28-day flexural strength was 8.9 MPa. The fine aggregate is Dawenhe River sand in Ningyang County, with a fineness modulus of 2.8-3.2, a mud content of less than 1%, and no mud block. Coarse aggregate shall be 5-20mm crushed stone with a crushing value of less than 8% and a mud content of less than 0.5%. The steel fiber is RC-80/50-BN bonded in rows, with a length-diameter ratio of 80, a length of 50 mm, and an equivalent diameter of 0.62mm.

When designing the mix proportion, several experimental groups with different steel fiber volume ratios were set, such as 0%, 0.5%, 1.0%, 1.5%, 2.0%, etc. When the test piece is made, the concrete mixture is poured along the edge of the mold to the center of the test mold in a spiral manner, and then the mold is filled and quickly scraped with a long wooden strip. After molding, it shall be placed in a standard curing environment; the temperature shall be controlled at 20 ± 2 ℃, and the relative humidity shall be greater than 95%. The standard method is adopted for the performance test, and the pressure testing machine is used for the compressive performance test, and the load is applied at the specified loading rate until the specimen is damaged. Tensile properties were determined by direct tensile test; the crack resistance is evaluated by the plate crack resistance test according to the time, number, and width of cracks.

3.2. Data statistics and analysis

After data collection, statistical methods were employed for analysis. Experimental data were processed using a multiple linear regression model, structured as

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+\ldots+\beta_nX_n+\varepsilon$$

Where Y represents concrete performance indices (compressive/tensile strength, crack resistance), X_1, X_2…, X_n denote steel fiber parameters (length, diameter, content), and β_0, β_1, …, β_n are regression coefficients. For case data, Pearson (Pearson Correlation Coefficient) was applied to calculate the correlation between application effects and influencing factors, using the formula:

$$r=\frac{n\sum XY-\sum X\sum Y}{\sqrt{[n\sum X^2-(\sum X)^2][n\sum Y^2-(\sum Y)^2]}}$$

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Data preprocessing involved standardizing units of fiber parameters and performance metrics, followed by inputting them into the regression model for coefficient estimation and correlation matrix computation.

3.3. Experimental results of performance characteristics of steel fiber reinforced concrete

The performance test data of concrete under different steel fiber volume ratios are shown in Table 1.

Table 1: Performance test data of concrete under different steel fiber volume ratios

volume fraction of steel fiber	compressive strength /MPa	tensile strength /MPa	Crack resistance, average crack area (mm^2/m^2)
0%	45.0	3.0	80.0
0.5%	52.0	4.0	60.0
1.0%	58.0	4.8	45.0
1.5%	60.0	5.2	30.0
2.0%	55.0	5.0	20.0

It can be seen from the Table 1 that with the volume ratio of steel fiber increased from 0% to 1.5%, the compressive strength gradually increased from 45.0 MPa to 60.0 MPa, because the steel fiber is dispersed in the concrete, which enhances the bearing capacity of the internal structure. When the volume ratio reaches 2.0%, the compressive strength decreases to 55.0 MPa, which may be due to excessive steel fibers affecting the uniformity of concrete. In terms of tensile strength, it continued to rise from 3.0 MPa at 0% to 5.2 MPa at 1.5% and then decreased slightly. In terms of crack resistance, with the increase of steel fiber volume ratio, the average crack area decreases from 80.0 mm^2/m^2 to 20.0 mm^2/m^2, indicating that steel fiber effectively inhibits the generation and development of cracks.

4. Applications

In the application of coal mine shaft lining, after the use of steel fiber concrete, the monitoring data of the clay layer and sand layer of the air shaft show that the freezing pressure is in a controllable range, the axial force of the reinforcement is not beyond the limit in both horizontal and vertical directions, the concrete strain is large in the horizontal direction but small in the vertical direction, and the shaft wall does not crack, which ensures the safety of the shaft wall and proves that it can effectively deal with the complex construction environment of the coal mine. In the field of pavement repair, compared with the pavement repaired with ordinary concrete, the pavement repaired with steel fiber reinforced concrete has delayed the occurrence time of cracks and extended the maintenance period by about 30%-40% under the same traffic load, greatly improving the durability of the pavement [7-8]. In the application of manhole covers, the compressive performance of steel fiber reinforced concrete manhole covers is good. The crack load of a grade A manhole cover is 180 kN, and the damage load is 360 kN, which can meet the requirements of airports, highways, and other places. At the same time, because it uses composite materials, it has low economic value, effectively reduces the theft situation, and improves the safety of urban roads and the integrity of facilities [9].

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5. Limitations and prospects

5.1. Limitations

There are some limitations in this study, which only covers some common application fields and does not involve the application of steel fiber reinforced concrete in some special engineering scenarios. The experimental conditions are mainly based on the conventional environment, and the performance research under extreme conditions such as high temperature, high pressure, and strong corrosion is insufficient. The selection of steel fiber type and mix proportion in the experiment is not comprehensive enough. Subsequent research can focus on expanding the scope of research and exploring its performance in deep sea, space, and other special environments; carrying out special experiments for extreme environments; deeply analyzing its performance change law; designing and enriching the types of steel fiber and mix design; optimizing the construction process; and studying the impact of different mixing and vibrating methods on the performance of steel fiber concrete so as to provide more comprehensive and accurate technical support for engineering practice.

5.2. Prospects

In view of the limitations of the current research on the evolution mechanism of extreme environmental performance, the complex load response model, and the adaptability of material design, future research can carry out systematic exploration from three aspects: the deepening of material performance, the expansion of application scenarios, and the innovation of construction technology [10]. In the field of material performance optimization, researchers should focus on the time-varying law of the bonding performance between steel fiber and concrete matrix under extreme environments such as high temperature, high humidity, strong acid-base erosion, and freeze-thaw cycles. By setting up a gradient temperature humidity box, salt solution immersion tank, and other simulation devices, combined with an X-ray diffractometer and scanning electron microscope to observe the fiber corrosion products and microcrack propagation path, a strength degradation prediction model based on fiber corrosion rate is established. At the same time, special-shaped steel fibers such as end hook type and wave type and steel-polypropylene hybrid fibers were developed. The synergistic reinforcement mechanism of fiber geometric parameters (length-diameter ratio 40-120), volume content (0.5%-2.5%), and matrix mix ratio (water-binder ratio 0.25-0.45, fly ash content 10%-30%) was determined through orthogonal experimental design, forming a high-durability material mix scheme suitable for nuclear power containment and pier columns of sea-crossing bridges. In the application of special scenarios, it is necessary to carry out the dynamic response test of steel fiber reinforced concrete under multi-field coupling for deep-sea high pressure (>20 MPa), plateau strong ultraviolet (irradiation >800 W/㎡), and ultra-low temperature (<-40 ℃); test the stress-strain curve under impact load by Hopkinson pressure bar; simulate the influence of fiber distribution on the seismic performance of the structure by using finite element software ANSYS; and construct the mechanical performance design method suitable for the foundation of deep-sea oil and gas platforms and the pile foundation of polar scientific research stations. At the level of construction technology innovation, the intelligent detection system of steel fiber dispersion based on machine vision should be developed. The charge-coupled device (CCD) camera is used to collect the mixture image in real time, the threshold segmentation algorithm is used to identify the fiber agglomeration area, and the programmable logic controller (PLC) is used to automatically adjust the mixing time (3-5 min) and the feeding sequence (fiber and coarse aggregate pre-mixing) so as to achieve the accurate control of the fiber uniform distribution coefficient (>0.92). At the same time, a construction process simulation platform based on digital twin technology is developed to input fiber parameters, ambient temperature and humidity, and other data and output the optimization scheme of vibration frequency (20-50 Hz) and curing period (7-28 d) so as to solve the problems of fiber agglomeration and unstable strength development in traditional construction. The above research can not only fill the gap of measured data of material properties under extreme conditions and provide key design parameters for special fields such as the nuclear industry and marine engineering, but also break through the bottleneck of application of steel fiber reinforced concrete in complex projects through the cross-scale collaborative optimization of material properties, construction technology, and service environment; promote the development of building materials in the direction of multi-function and high reliability; and provide long-term safety guarantees for national major infrastructure construction.

6. Conclusion

In terms of strength, the tensile strength of steel fiber reinforced concrete can be increased by 25%-50%, and the compressive strength can also be enhanced with a reasonable amount of steel fiber, effectively improving the mechanical properties of concrete. Its crack resistance performance is outstanding. In the plate crack resistance test, it can significantly reduce the cracking area per unit area and reduce the occurrence and development of cracks. It has good impact resistance, can absorb impact energy, and improve structural safety. The application effect in coal mine shaft lining, pavement repair, well cover, and other fields is remarkable, which ensures the structural safety in coal mine shaft lining, prolongs the service life of pavement in pavement repair, enhances the compressive performance and anti-theft performance in the application of well cover, plays a key role in ensuring the engineering quality and improving the engineering efficiency, and provides a reliable material selection for engineering construction in various fields.

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