Journal of Computing and Electronic Information Management
ISSN: 2413-1660 | Vol. 14, No. 3, 2024

Review of Performance and Applications of Common Fiber-Reinforced Concrete

Chunjie Li, Lin Gao and Sukang Wang

School of North China University of Science and Technology, College of Civil and Architectural Engineering, Hebei 063000, China

Abstract: Since the advent of concrete materials, it has been widely used in building structures due to its advantages such as good compressive performance, durability, and ease of sourcing. In the 1970s, to further enhance the performance of concrete, fiber materials were proposed for incorporation into concrete to address its shortcomings of poor ductility and insufficient tensile strength. This paper reviews the recent research status, advantages, and mechanical performance of fiber-reinforced concrete, and explores the future development trends of its application in building structures.

Keywords: Fiber-reinforced concrete; Steel fiber; Glass fiber; Polypropylene fiber.

1. Introduction

With the rapid pace of urbanization, concrete has maintained its status as an indispensable and irreplaceable material in the construction industry, evolving in tandem with advancements in modern engineering. Its versatility and adaptability have made it the backbone of infrastructure development worldwide. However, despite its widespread use, ordinary concrete has inherent limitations that hinder its performance in demanding applications. Specifically, its low tensile strength, significant brittleness, vulnerability to cracking, and poor dynamic mechanical properties make it less suitable for projects requiring high durability and resilience.

To address these shortcomings, researchers and engineers, both domestically and internationally, have been committed to enhancing the mechanical properties of concrete. Efforts have focused on improving its tensile strength, reducing its brittleness, and increasing its resistance to cracking and dynamic loads. These endeavors have led to the development of various high-performance concrete formulations, such as fiber-reinforced concrete, which integrates different types of fibers to improve the structural integrity and longevity of concrete in avariety of challenging environments. The continued research in this field not only aims to extend the lifespan of concrete structures but also seeks to align construction practices with sustainable development goals by reducing maintenance costs, minimizing resource consumption, and enhancing safety in built environments.

The use of fiber materials in concrete was first introduced in the 1970s as a way to address the inherent weaknesses of traditional concrete, particularly its brittleness and tendency to crack under stress. By integrating fibers into the concrete matrix, the material's toughness, ductility, and crack resistance were significantly enhanced. This innovation led to the development of high-performance fiber-reinforced concrete (HPFRC), which has since gained widespread acceptance and application in various construction projects around the world. HPFRC has proven to be especially effective in environments where durability, strength, and longevity are crucial, such as infrastructure projects, high-rise buildings, and industrial structures. Over the past few decades, fiber-reinforced concrete has experienced remarkable progress. The incorporation of different types of fibers, such as steel, glass, and synthetic fibers, has allowed for tailored improvements in concrete performance based on the specific needs of each project. The presence of fibers in the concrete mix helps to prevent or significantly reduce early shrinkage cracks that can form during the curing process. Moreover, fibers play a crucial role in minimizing cracks caused by external loads, thereby improving the overall structural integrity. By limiting crack propagation and maintaining cracks within acceptable limits, fiber-reinforced concrete offers enhanced toughness and ductility, making it more resilient to environmental stressors and mechanical impacts. This development has revolutionized the construction industry, allowing engineers to design more durable and long-lasting structures that require less maintenance and exhibit improved safety standards.

2. Common Types and Properties of Fiber Reinforced Concrete

With the continuous research and development of high-performance fiber-reinforced concrete (HPFRC) materials, there are many types of fibers available. Table 1 lists the commonly used fibers for reinforcing concrete and their basic parameters.

Table 1. Fiber types and basic parameters

FIber type	Tensile strength (MPa)	E_0(GPa)	Diameter (μm)
Steel fiber	400~2100	154~200	300~800
Basalt fiber	3000~5000	80~110	10~15
Glass fiber	14~2800	70~90	8
Carbon fiber	2450~3150	205	7~8
Polypropylene fiber	400~650	5~8	43
Nylon fiber	900~960	4~6	30
Polyethylene fiber	2850	73.9	35

Fibers can generally be divided into two categories based on their elastic modulus: the first type has an elastic modulus higher than the concrete matrix, such as steel fibers, carbon fibers, and glass fibers. These are primarily used to enhance the tensile, compressive, flexural, impact strength, and toughness of concrete. The second type has an elastic modulus lower than the concrete matrix, such as nylon fibers, polyethylene fibers, and polyester fibers. While these do not improve the tensile or compressive strength of concrete, they have a significant impact on the early structural formation of concrete, inhibiting the growth of early cracks and significantly improving its impact strength and toughness. [3] Additionally, with the increasing focus on environmental issues, many researchers are paying more attention to the use and development of eco-friendly fibers, such as sisal fiber, jute fiber, and banana fiber.

Currently, the most commonly used fibers in concrete materials in engineering are steel fibers, glass fibers, and polypropylene fibers.

3. Steel fiber

Steel fiber-reinforced concrete (SFRC) is an advanced multiphase composite material created by introducing short steel fibers, randomly distributed throughout the concrete matrix, into conventional concrete. This innovative combination results in a material that significantly enhances the mechanical properties of ordinary concrete. The addition of steel fibers changes the brittle nature of concrete into a more ductile form, which is beneficial for structures subjected to tension, bending, or shear forces.

Steel fibers typically range from 0.3 mm to 1.0 mm in diameter and vary in length from 10 mm to 60 mm. These fibers, when mixed into the concrete, act as a bridging mechanism across cracks, preventing them from propagating and thus improving the concrete's overall toughness and durability. The randomly distributed fibers create a more uniform resistance to loads in all directions, unlike ordinary reinforced concrete, which relies on strategically placed rebar for tensile strength.

According to statistical research, steel fibers are the most commonly studied reinforcement material in ultra-high-performance concrete (UHPC). About 73.5% of the papers on the impact of fibers on UHPC focus primarily on steel fibers, highlighting their importance in both academic and practical contexts. [2] In many experimental studies, steel fibers are used as a control material, indicating their baseline effectiveness in enhancing concrete performance. Their widespread use reflects their reliability in improving the mechanical properties of concrete.

When compared to traditional concrete, steel fiber-reinforced concrete shows marked improvements in key areas. The tensile strength is significantly increased, allowing the material to better resist stretching or pulling forces, which is critical for structures like bridges, tunnels, and high-rise buildings that face dynamic loads. Flexural strength, or the concrete’s ability to resist bending, is also enhanced, making SFRC ideal for floors, pavements, and industrial structures that endure constant wear and heavy loads. Additionally, the shear strength is notably improved, providing greater resistance to failure in regions where concrete beams or slabs experience diagonal stresses, such as in earthquake-prone areas.

Furthermore, steel fiber-reinforced concrete offers increased resistance to impact, fatigue, and crack formation, extending the lifespan of concrete structures. These characteristics make SFRC particularly valuable in applications such as airport runways, industrial floors, precast concrete elements, and even high-performance military structures. Its ability to perform under extreme conditions of load and environmental stress makes it a preferred material for projects demanding high durability and safety standards.

In conclusion, steel fiber-reinforced concrete is a critical development in modern construction materials. Its enhanced mechanical properties—especially in tensile, flexural, and shear strength—make it a superior alternative to ordinary concrete in demanding structural applications. Given its widespread use and continued research focus, SFRC is poised to play an even more significant role in the future of infrastructure and engineering projects worldwide.

As early as the 1840s, French gardener Joseph Monier tried to strengthen cement flower pots by incorporating wire mesh. In the 1970s, steel fibers began to be added to concrete, forming a relatively uniform and multidirectional reinforced concrete by incorporating small amounts of low-carbon steel, stainless steel, or fiberglass fibers. This type of concrete is known as Steel Fiber Reinforced Concrete (SFRC). Since concrete has high compressive strength and steel fibers have high tensile strength, SFRC has several advantages, including good tensile, flexural, impact, fatigue, and wear resistance, as well as high toughness.

In 1963, J. P. Romualdi studied the mechanism of crack control in steel fiber-reinforced concrete. In his published paper, he pointed out that if cracks develop between steel fibers, bond stress occurs at the ends of the fibers surrounding the cracks. He proposed the fiber spacing theory, which states that the crack strength of SFRC is determined by the average spacing of the steel fibers that effectively resist tensile stress, thus initiating the practical development of this new composite material. [3] In 1973, steel fiber shotcrete was applied for the first time in Idaho, USA, and was soon used in tunnel linings, slope stabilization, culverts, and other projects. [1]

In 1982, the U.S. Idnlard Materials Laboratory began developing steel fiber-reinforced cementitious materials (SIFC) with a steel fiber volume content of 12% to 23%. The technical indicators included: a compressive strength of 103 MPa to 207 MPa, a limit compressive strain of 0.1, axial tensile strength of 13.88 MPa, flexural strength of 27 MPa to 69 MPa, and shear strength of 27.6 MPa. When the temperature did not exceed 800°C, the strength of the concrete significantly decreased within 5 hours. Additionally, its impact and wear resistance showed significant improvements.[3] In 1984, domestic scholars Cheng Tiesheng, Zhang Wengang, and others reported that when the fiber content was 1% to 2%, the tensile strength of SFRC could increase by 25% to 50%, its compressive strength by 0% to 25%, and its flexural strength by 30% to 80%.[4] Through experiments, P. S. Mangata and M. M. found that SFRC with a fiber content of 1.5% and an aspect ratio of 50 reduced shrinkage by about 7% to 9% compared to ordinary concrete, indicating that increasing the fiber content reduces concrete shrinkage.[5].

4. Glass fiber

Glass fiber is an inorganic, non-metallic material produced by drawing molten glass into fine filaments. It is well-known for its combination of lightweight properties, cost-effectiveness, and high tensile strength, making it a popular choice in the production of fiber-reinforced concrete (FRC). Glass fibers serve a critical role in enhancing the performance of concrete by filling in microcracks and voids within the concrete matrix, which increases its overall density. This densification process directly improves the compressive strength of the concrete, allowing it to better withstand heavy loads.

In addition to improving compressive strength, glass fibers also play a vital role in limiting the development of cracks in the concrete. As concrete is inherently brittle and prone to cracking under tensile forces, the inclusion of glass fibers helps distribute these tensile stresses more evenly throughout the material. [6]

This process not only increases the tensile strength of the concrete but also enhances its crack resistance, ensuring that small cracks do not rapidly propagate and lead to structural failure. As a result, glass fiber-reinforced concrete (GFRC) is regarded as a material with excellent toughness and durability, particularly in applications where tensile and flexural strengths are critical, such as facades, wall panels, and other architectural elements.

However, despite its initial mechanical advantages, GFRC can face challenges over the long term, particularly when exposed to harsh environmental conditions. One of the main drawbacks of glass fiber-reinforced concrete is its tendency to become brittle over time due to weathering. Prolonged exposure to moisture, temperature fluctuations, and other environmental stressors can cause glass fibers to deteriorate, leading to a loss in mechanical properties such as tensile and flexural strength. This process, known as fiber embrittlement, can significantly affect the long-term durability of the concrete, especially in climates with extreme weather conditions.

To mitigate the effects of weathering and improve the long-term performance of GFRC, the use of alkali-resistant (AR) glass fibers is highly recommended. Conventional glass fibers can degrade in the high-alkaline environment of concrete, leading to a reduction in their reinforcing properties. AR glass fibers, on the other hand, are specifically engineered to withstand the alkaline conditions present in concrete, thus preventing degradation and maintaining the mechanical integrity of the material over time. Alkali-resistant glass fibers are produced by incorporating zirconium into the glass composition, which provides a protective barrier against the alkalinity of the cementitious matrix. By choosing AR glass fibers, the durability, crack resistance, and long-term stability of GFRC can be significantly enhanced.

In conclusion, glass fiber is a valuable reinforcement material for concrete, offering benefits such as increased density, compressive strength, and improved crack resistance. While the long-term performance of GFRC can be affected by environmental factors, the use of alkali-resistant glass fibers provides a practical solution to extend the lifespan of the material. With the proper selection of glass fibers, GFRC can continue to serve as a high-performance, cost-effective solution in a wide range of construction applications, from architectural facades to industrial flooring and beyond.

In 2017, Liu Yafei and others [7] conducted experiments and found that, when considering both concrete strength and elastic modulus, the optimal amount of glass fiber to incorporate is 2%. In 2019, Meng Yunfang and others [8] conducted orthogonal experiments and, in combination with auxiliary cementitious materials such as silica fume and fly ash, determined that the optimal glass fiber content for reliability and safety is 1%, with the best mix ratio being a water-binder ratio of 0.31, fly ash content of 10%, and silica fume content of 1%. Incorporating alkali-resistant fibers and optimizing the mix ratio can also improve the concrete’s heat resistance. In 2021, Bai Qingsong, Wang Ling, and others [9] conducted six compressive strength tests, demonstrating that increasing the length and content of glass fibers can improve the compressive strength of concrete to a certain extent, but this reduces the concrete's fluidity.

5. Polypropylene fiber

Polypropylene fiber is a synthetic material derived from polypropylene, known for its simple production process and versatility in application. Compared to other fiber materials such as steel or glass fibers, polypropylene is lighter, more cost-effective, and often more efficient in specific uses. One of its key advantages is its hydrophobic nature, which helps to prevent fiber clumping during the mixing process, ensuring an even distribution of fibers throughout the concrete matrix.

Polypropylene fiber-reinforced concrete offers multiple benefits over ordinary concrete. In addition to its superior tensile and compressive strength, it demonstrates improved toughness and enhanced resistance to corrosion, making it more durable in harsh environments. One significant advantage is its improved strain rate sensitivity under dynamic loading conditions, which makes it particularly suitable for structures subjected to vibrations or impact forces, such as roads, bridges, and industrial flooring.

Moreover, polypropylene fibers reduce shrinkage cracks in the early stages of concrete curing and enhance the concrete’s resistance to cracking over time. This results in longer-lasting concrete structures with reduced maintenance needs. Due to these advantages, polypropylene fiber-reinforced concrete is widely used in a variety of engineering applications, including pavements, bridges, tunnels, and industrial floors. It is especially valuable in projects requiring high resistance to impact, abrasion, and dynamic loads, such as airport runways, parking decks, and highways, where durability and longevity are crucial.

The combination of its cost-effectiveness, ease of production, and performance-enhancing properties makes polypropylene fiber an attractive choice in modern construction, contributing to improved concrete performance and supporting more sustainable and durable infrastructure.

In 2001, Lu Anqi and others [10] conducted experiments showing that polypropylene fiber can effectively reduce plastic shrinkage and cracking in concrete, lowering the plastic cracking index by about 56%. It also significantly improves the ductility, flexural toughness, and ultimate tensile capacity of concrete. In 2010, Zhang Huili[11] used the simply supported beam bending method to study the effect of polypropylene fiber and finely ground granulated blast furnace slag on the flexural performance of hydraulic concrete. It was found that incorporating 0.1% or 0.6% polypropylene fiber and less than 55% slag can effectively improve the flexural strength and ductility of concrete. In 2019, Huang Xin and others [12] used orthogonal experiments to show that when the length of polypropylene fibers is between 10 mm and 19 mm, the tensile, compressive, and flexural strength of concrete increases with fiber length, making this the optimal range for fiber length.

6. Applications of Fiber Reinforced Concrete

Fiber-reinforced concrete, as a high-performance concrete material, has been extensively applied in numerous large-scale civil engineering projects both domestically and internationally. High modulus fibers and steel fibers, due to their significant advantages in enhancing the bending, tensile, shear strength, and durability of concrete matrices, have gradually become widely adopted in fields such as transportation engineering, water conservancy projects, port and marine engineering, civil engineering, and national defense construction.

Steel fiber-reinforced concrete, known for its excellent load-bearing capacity, impermeability, and fatigue resistance, is widely used in metro shield tunnel segments, industrial buildings, bridges, and port projects. Examples include the use of steel fiber-reinforced concrete segments in the Trasvases Manabi water transfer tunnel in Ecuador and the second phase of the Channel Tunnel Rail Link (CTRL) in the UK. [13] In the field of highway bridges, the application of steel fiber concrete presents distinct advantages. When used for bridge deck paving, steel fiber concrete can reduce the thickness of the pavement layer while increasing the spacing between expansion joints, thereby extending the service life of bridges. For instance, steel fiber-reinforced concrete was applied in the reinforcement of the Tongling Yangtze River Bridge and the Second Wuhan Yangtze River Bridge. The surface layer of the elevated lanes at Shanghai Hongqiao Airport is also paved with steel fiber-reinforced concrete. [14]

However, the drawbacks of steel fiber-reinforced concrete, such as its high usage volume, high cost, and poor performance in fire conditions, have posed limitations to its broader application.

Glass fiber-reinforced concrete, due to its excellent bending and impact resistance, is suitable for road, bridge, and slope engineering, aligning with the requirements of sustainable development. Currently, glass fiber-reinforced concrete is commonly used both domestically and internationally for canal seepage prevention, building reinforcement, slope and embankment support for hydraulic structures, underground engineering, and transportation projects related to water conservancy and hydropower. Application examples include the top box of the overpass at Tianji Power Plant and tunnel slope protection with sprayed concrete. [15]

Polypropylene fiber-reinforced concrete is also widely used in fields such as bridges, pavements, and tunnels, with examples including a bridge project in Jiangxi Province and the Gansu Province Dispatch and Communication Building project.

Additionally, other types of fibers like carbon fiber, nylon fiber, and polyethylene fiber have played important roles in various engineering projects. Carbon fiber-reinforced concrete, known for its high strength and lightweight properties, is widely applied in bridge reinforcement, high-rise buildings, and seismic structures. For example, carbon fiber composites have been extensively used in the reinforcement of buildings in earthquake-prone areas. Nylon fiber-reinforced concrete, with its excellent toughness and impact resistance, is often used in airport runways, industrial floors, and parking lots where high abrasion resistance is required. Polyethylene fiber-reinforced concrete, with its superior durability and crack resistance, is suitable for waterproofing projects, underground structures, and large-scale hydraulic engineering.

By selecting the appropriate type of fiber and optimizing fiber content, fiber-reinforced concrete demonstrates outstanding performance across various engineering projects, meeting diverse demands and driving the continuous innovation and development of building materials.

7. Conclusion

Through systematic research on the mechanical properties of fiber-reinforced concrete, it is evident that the addition of fibers significantly enhances the overall performance of concrete, especially in terms of tensile strength, flexural strength, and impact resistance. Steel fibers, glass fibers, and polypropylene fibers exhibit unique characteristics and distinct advantages in various engineering applications. For instance, steel fibers are particularly effective in improving the load-bearing capacity and durability of structures, while glass fibers contribute to increased tensile strength and resistance to cracking. Polypropylene fibers, being lightweight and cost-effective, offer improved toughness and resilience under dynamic loads.

As research advances, the application potential of fiber-reinforced concrete continues to expand across diverse engineering projects, from infrastructure to high-performance structures. Future studies should focus on optimizing the interaction between fiber materials and the concrete matrix, exploring new fiber types, and refining manufacturing processes to enhance both performance and cost-efficiency. In particular, understanding the long-term durability of different fibers, such as the weathering effects on glass fibers, will be crucial for broader adoption.

In conclusion, fiber-reinforced concrete, as a high-performance construction material, is poised to play a crucial role in the development of innovative construction technologies. It aligns well with goals for sustainable development by enhancing structural resilience, reducing material waste, and contributing to longer-lasting infrastructure.

References

[1] Zhang Cong, Cao Mingli, Xu Ling. Research Progress on Multiscale Characteristics of Concrete and Multiscale Fiber Reinforcement Theory [C/OL] // Proceedings of the 9th National Academic, Standards, and Technical Information Exchange Conference on Fiber Cement Products and the First Session of the 3rd Committee of the Fiber Cement Products Professional Committee of the Concrete and Cement Products Branch of the Chinese Silicate Society, and the First Session of the 3rd Committee of the Building Structures and Lightweight Panels Professional Committee of the Housing Building Materials Branch of the Chinese Silicate Society. Chinese Silicate Society Concrete and Cement Products Branch, Chinese Silicate Society Housing Building Materials Branch, 2014: 5 [2024-05-12].

[2] YANG J, CHEN B, SU J, et al. (Significant) Research Progress on the Effects of Fibers on the Mechanical Properties of UHPC [J/OL]. Journal of Traffic and Transportation Engineering (English Edition), 2022, 9(3): 363-387.

[3] Qi Zhi, Song Hongwei. Application and Prospects of Steel Fiber-Reinforced Concrete in Underground Engineering [J]. Concrete, 2003(11): 48-50.

[4] Zhang Wengang, Cheng Tiesheng, Zhang Rubian. Main Mechanical Properties and Process Characteristics of Steel Fiber-Reinforced Concrete [J]. Concrete and Reinforced Concrete, 1984(4): 1-9.

[5] A theory for the creep of steel fiber-reinforced cement matrices under compression: Mangat, P.S. and Motamedi Azari, M. Journal of Materials Science, Vol 20 (March 85), p. 1119 [J/OL]. Composites, 1985, 16(4): 335.

[6] Tang Haoling, Li Xiaoping. Discussion on the Performance and Application of Common Fiber-Reinforced Concrete [J]. *Sichuan Cement*, 2023(4): 20-22.

[7] Liu Yafei, Wu Chongfu. Experimental Study on the Elastic Modulus of Glass Fiber-Reinforced Concrete [J]. Concrete, 2017(6): 64-66+79.

[8] Meng Yunfang, Wang Ting, Ma Xiaoping, et al. Experimental Study on Crack Resistance and High-Temperature Resistance of Glass Fiber-Reinforced Concrete [J]. Ningxia Engineering Technology, 2019, 18(3): 239-243.

[9] Bai Qingsong, Wang Ling, Dong Yeshun. The Effect of Glass Fiber Length and Content on the Mechanical Properties of Ordinary Concrete [J]. Henan Science and Technology, 2021, 40(22): 78-80. .

[10] Lu Anqi, Zhu Yeran, Li Keliang, et al. Experimental Study on Polypropylene Fiber-Reinforced Concrete [J/OL]. Journal of Waterway and Harbor Engineering, 2002(4): 14-19.

[11] Zhang Huili, Tian Kanliang. Study on Flexural Performance of Hydraulic Concrete with Slag and Polypropylene Fiber [J/OL]. Yangtze River, 2010, 41(19): 82-87.

[12] Huang Xin, Pang Jianyong, Huang Jinkun, et al. Orthogonal Experimental Study on the Strength of Polypropylene Fiber-Reinforced Concrete [J/OL]. Bulletin of the Chinese Ceramic Society, 2019, 38(4): 1183-1190.

[13] eel plate shear walls with central perforation[J]. Journal of Constructional Steel Research, 2013, 89(5): 9-20.

[14] Bao Zhengfu, Liu Gang. Research Status and Application of Steel Fiber Reinforced Concrete [J]. Building Materials and Decoration, 2017(2): 276.

[15] Xu Yihua, Wang Heng. Research Progress and Application of Fiber Reinforced Concrete [J]. Sichuan Building Materials, 2022, 48(4): 17-18.