Mechanical properties and environmental protection analysis of non-metallic fibers

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Abstract. Non-metallic fiber concrete is an emerging composite material that capitalizes on the exceptional strength, toughness, and durability of non-metallic fibers to enhance the mechanical properties and longevity of concrete. This article examines and explores the pertinent literature on non-metallic fiber concrete, considering various types and dosages. It also analyzes the impact and mechanisms of non-metallic fibers on concrete's compressive strength, tensile strength, flexural strength, and durability performance. The findings indicate that non-metallic fiber concrete exhibits superior mechanical properties and durability. This article presents a theoretical foundation for the design and utilization of non-metallic fiber concrete.

Keywords: Non-metallic fiber; Concrete; Mechanical properties

1 Introduction

In recent years, carbon emissions have been steadily increasing, as shown in Figures 1 and 2. Consequently, energy conservation and emission reduction have become crucial research topics in the field of building materials. Non-metallic fiber concrete is an innovative material that enhances the properties of concrete through the incorporation of non-metallic fibers. The addition of fibers to concrete has been proven to increase its strength and durability by enhancing fiber content. This helps prevent cracking and structural failure.

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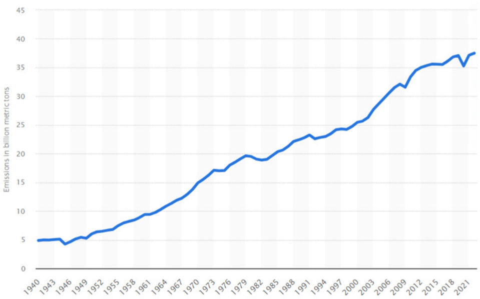

Fig. 1. Growth trend of CO_2 emissions

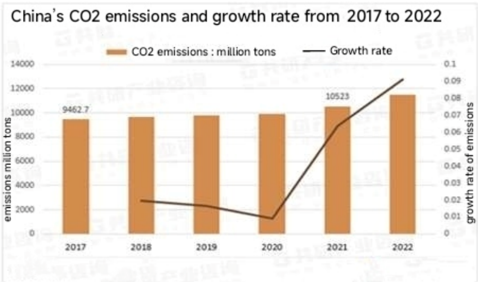

Fig. 2. CO2 emissions in the past five years from 2017 to 2022

Non-metallic fiber concrete is gaining increasing attention and research as an emerging building material due to the growing demand for high-performance and environmentally sustainable construction materials. Traditional reinforced concrete has drawbacks such as high energy consumption and significant environmental pollution. It also struggles to meet the material performance requirements of certain special projects. Non-metallic fiber concrete improves upon the weaknesses of traditional concrete by incorporating various types of non-metallic fibers. It offers advantages such as crack resistance, increased toughness, and enhanced load-bearing capacity. As a result, it has emerged as an excellent material that combines environmental sustainability with economic performance.

Non-metallic fiber concrete will provide a scientific basis and guidance for its practical application in engineering, promoting innovation and development in building material technology. This paper will review the itinerary and development of non-metallic fiber concrete, with special attention to glass fiber concrete, polypropylene fiber concrete, reed fiber concrete, straw fiber concrete, coconut shell concrete, sisal fiber concrete, nanofiber concrete and carbon fiber concrete. We will begin by analyzing the mechanical properties of the matrix, evaluating any existing issues, in order to gain a comprehensive understanding of the characteristics and potential applications of non-metallic fiber concrete.

2 Literature research on non-metallic fiber concrete

Non-metallic fiber concrete is an advanced material that improves the properties of concrete by incorporating various types of non-metallic fibers. In recent decades, various non-metallic fibers have been extensively utilized in concrete research.

Non-metallic fiber concrete utilizes various types of fibers, each serving different purposes. We conducted a comprehensive literature review to examine the impact of adding fibers to concrete. According to scholar Xu Kun's research, these fibers are typically added to concrete at a volume doping rate of 0.5%-2%. The optimal dosage is usually determined by the modification curve, which typically has a peak point. The addition of fibers can effectively enhance the toughness of concrete.[1]. According to scholar Iskender, glass fiber has excellent tensile strength and rigidity. Adding glass fiber to concrete improves its tensile strength and toughness, reduces structural loss in fire accidents, controls the expansion of microcracks under increased tensile strain, and significantly enhances the flexural strength of concrete.[2]. Scholar Yuan Z's research indicates that incorporating polypropylene fiber into concrete can enhance its tensile strength, flexural strength, toughness, and impact strength, while also improving its failure mode.[3]. Sisal fiber is a new material that can enhance the compressive strength and ductility of concrete. Scholar Thomas proposed enhancing the strength and durability of concrete by incorporating sisal fiber, which also decreases its fluidity.[3]. Nanofiber is a high surface area and high strength fiber that exhibits superior shrinkage resistance, frost resistance, and carbonization resistance compared to ordinary concrete. Additionally, it has lower permeability than ordinary concrete.[5], can enhance the bending strength and impact resistance of concrete. Carbon fiber is a high-performance fiber known for its exceptional strength and stiffness. It enhances the adhesion of mortar to old mortar, resulting in an 89% increase in shear bond strength[6], can effectively enhance the bearing capacity and seismic performance of concrete. Xiao Jianzhuang, Li Xiao.The CO2 emissions of fiber-reclaimed concrete are analyzed by calculating a carbon emission quantification model, which is calculated as $C_{1a} = \sum_i \left(\sum_j a_{ij} K_j\right) m_j + g_1 m_1$, According to their calculation conclusions, the carbon emissions of the life cycle of fiber concrete through 1m3 C30 are gradually reduced, and when the fiber replacement rate is 3%, 5% and 10%, the carbon emissions are 314.2; 310.9, 307.6 kg, respectively; therefore, the fiber replacement rate can be effectively reducedCO2 emissions[7].

Non-metallic fiber concrete is a promising advanced material with wide-ranging applications. By incorporating a precise amount of this additive into concrete, its strength can be greatly improved, making it suitable for various working conditions. This addresses the limitations of traditional concrete, including low tensile strength, limited ultimate elongation, and brittleness. It also enhances tensile strength, ultimate extension, and alkali resistance. Additionally, using renewable materials as replacements reduces the need for natural resources, promoting green construction and sustainable development. This approach can lead to greater environmental and economic benefits in construction projects.

Table 1. Non-metallic fiber physical parameters[9]

Fiber type	Diameter (μm)	Density (g/cm3).	Tensile strength (cn/dtex)	Modulus of elasticity (Gpa)
Fiberglass	3-20	2.5-2.7	21.98-32.97	80
Polypropylene fiber	3-20	0.9-0.92	2.2-3.3	3.5
Reed fibers	4.23±0.54	1.4-1.5	0.21	4.46
Straw fiber	8	1.5	0.35-0.44	6.81
Coir	100-450	1.12-1.46	1.04-1.42	2.2-6
Sisal fiber	8-200	1.33-1.5	3.98-7.69	9-38
Nanofibers	0.001-0.1	1.38	31.86-37.36	300-350
Carbon fiber	0.006	1.5-1.8	879	150

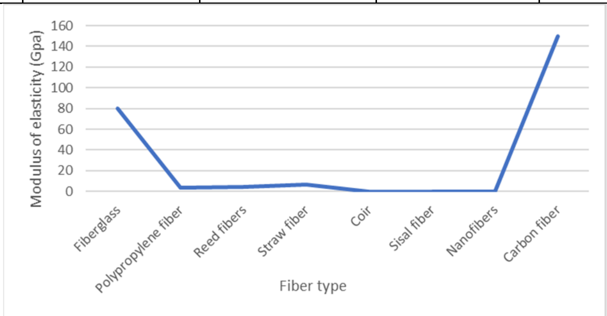

Fig. 3. Fiber strength data analysis chart

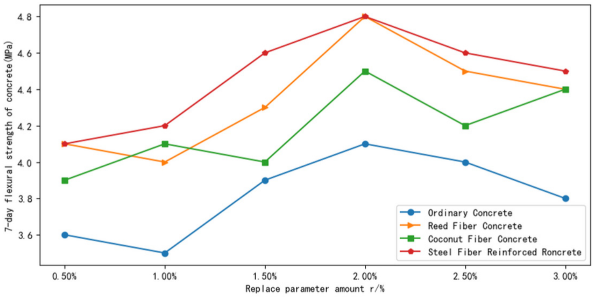

Fig. 4. Concrete seven-day strength[14]

2.1 Itinerary and development of fiberglass concrete

Glass fiber is primarily composed of silicate, with a small amount of metal oxides. The strength of glass fiber decreases and its water resistance worsens as the alkali content increases. The glass fiber molding process involves the elongation of the surface by approximately 3%. The surface of the fiber is smooth and cylindrical, with a nearly circular cross-section. During the process, the glass molecules are aligned in a specific direction due to the traction of the wire drawing machine. This alignment enhances the strength of the glass fiber. [8.]

Glass fiber concrete, which emerged in the 1950s, is prepared by combining glass fiber with a concrete matrix and improving its tensile properties through prestressing or post-tensioning. Fiberglass concrete offers several advantages over traditional reinforced concrete. It is lighter, thinner, and more flexible, allowing for greater design freedom and easier construction.

2.2 Stroke and development of polypropylene fiber concrete

The chemical composition of polypropylene fiber is mainly propylene monomer, but also contains a small amount of ethylene, vinyl alcohol and other polar monomers, which is the lightest among all chemical fibers, with good wear resistance and resilience. Polypropylene fiber also has excellent sound absorption, sound insulation, high temperature resistance, acid and alkali corrosion resistance and insulation properties.

PFRC research began in the 1970s, initially focusing on various types, proportions, and lengths of polypropylene fibers under laboratory conditions. Compared to other fibers, polypropylene has a smaller density and lower weight.

PFRC can effectively improve the durability and crack resistance of structures by adding polypropylene fibers to different types of concrete structures, such as floors, pavements, bridges, etc. Case studies and practices show that PFRC has significant effects in reducing concrete cracks, resisting impact and wear.

2.3 Itinerary and development of reed fiber concrete

The chemical composition of reed fiber is mainly cellulose, hemicellulose, lignin and ash. The length is typically around 0.9.~1.1 mm, the fineness is between 11~13 dtex, the gloss is low, the moisture absorption is high, the thermal stability is poor, and the resistivity is high.

The study of reed fiber concrete originated in the early 21st century. At this stage, the focus is on the extraction technology, fiber length and content of reed fibers on the properties of concrete.

Through practical application, the advantages of reed fiber concrete in crack resistance, leakage resistance and impact resistance are verified. The researchers improved the overall performance of reed fiber concrete by improving the extraction technology, optimizing the properties and fiber dispersion of reed fibers. At the same time, the research is also committed to solving the problems of adhesion strength of the interface between reed fiber and concrete, and improving the dispersion of fiber[13].

2.4 Itinerary and development of straw fiber concrete

The main component of straw fiber is cellulose, which accounts for about 40-50%, also contains lignin, hemicellulose, pectin and other companion organisms, the length uniformity is poor, and the discreteness is large 12. The fineness of straw fibers is coarse, the average fineness is about 30-40 dtex, and the longitudinal fineness uniformity of the fibers is poor. The surface of straw fiber is not smooth, has a large number of grooves, and has a large specific surface area, which is conducive to moisture absorption performance, and the porosity is about 80%[9].

In the 70s and early 80s of the 20th centuries, scholars began to study adding straw fibers to concrete to improve its performance. Early research primarily focused on the crack resistance and durability of concrete. Researchers are studying the application, performance, durability, and sustainability of straw fiber concrete in actual construction projects as the focus on sustainable building materials and green buildings grows. Straw fiber concrete is currently widely used and recognized as a viable building material option in building standards and codes in certain countries.

2.5 Itinerary and development of coir concrete

The length of coir fiber is generally between 10-25 cm, the average length is about 17.5 cm, the length uniformity is poor, and the discreteness is large. The coir fiber has a coarse texture, with an average fineness of approximately 275 microns, and the longitudinal fineness uniformity of the fiber is low. The bulk density of coir is about 0.3 g/cm^3 and the porosity is about 80%. The main component is cellulose, accounting for about 46-63%, and also contains lignin, hemicellulose, pectin and other associated organisms.

The research and development of coir concrete can be traced back to the 70s of the 20th centuries, when scholars began to pay attention to the potential of using plant fibers to enhance concrete. After years of research and experimentation, coir fiber has been found to be effective in improving the toughness, crack resistance and durability of concrete.Researchers found that coir can effectively improve the compressive, flexural and impact strength of concrete. In addition, coir also has good penetration resistance and carbonization resistance.

2.6 Itinerary and development of sisal fiber concrete

Sisal fiber is composed of cellulose, hemicellulose, lignin, pectin, and other components. The average length of the fiber is 78cm, with a weight-weighted average length of 91cm. The average fineness of the processed fiber is 169 dtex. Sisal fiber is a strong and durable fiber with low elongation. It has an average breaking strength ratio of 5.72.~7.33cN/dtex, and it has an average elongation at break of 3.02%.~4.50%.

The research and development of sisal fiber concrete dates back to the 1970s. After extensive research and experimentation, it has been discovered that sisal fiber is effective in enhancing the tensile strength, crack resistance, and durability of concrete. Research on sisal fiber concrete, similar to the CFRC, has been conducted since the 1990s. Researchers have discovered that sisal fiber can significantly enhance the tensile, flexural, and impact strength of concrete. Sisal fibers also exhibit excellent resistance to penetration and carbonization.

2.7 Itinerary and development of nanofiber concrete

Nanofibers are composed of a variety of materials including cellulose, carbon, metals, oxides, sulfides, and other substances. These fibers have an incredibly small diameter, usually ranging from tens to hundreds of nanometers. In certain instances, they can even be as small as a single atom.

Nanofiber concrete has strong properties that can enhance the load-bearing capacity of buildings, reduce structure thickness, conserve resources, and decrease costs. The development of nanofiber concrete began in the early 21st century, with initial research focused primarily on the laboratory phase. In the context of sustainable development, NFC shows great potential as it can be derived from waste materials. This practice promotes resource recycling and effectively addresses environmental pollution. Currently, there are numerous global research initiatives focused on nanofiber concrete. One notable example is the research conducted by Purdue University in the United States, which aims to address the issue of concrete durability through the incorporation of nanofibers.

2.8 Stroke and development of carbon fiber concrete

The length of carbon fiber can range from a few microns to a few centimeters, and it is typically very fine, measuring in the tens to hundreds of nanometers. The primary benefit of CFRC is its ability to greatly enhance the tensile strength of concrete, enabling it to withstand higher levels of stress without fracturing. Additionally, incorporating carbon fiber into concrete can enhance its impact resistance and wear resistance, thereby extending its lifespan. In the 1970s and 1980s, scientists started exploring the potential of using carbon fiber as a reinforcement material in concrete. Early studies primarily focused on testing and evaluating the performance of materials on a laboratory scale.

3 Analysis of mechanical matrix properties of non-metallic fiber concrete

Table 2. Mechanical property parameters of fibers[11]

Fiber type	Tensile resistance (Mpa).	Bending resistance (Mpa).	Flexural resistance (Mpa).	Stress resistance (Mpa).
Fiberglass	3400	2000-5000	20	350-550
Polypropylene fiber	21-39	520	22	3.5
Reed fibers	19.5	23.1		3.4-6.6
Straw fiber	10-100	10		2.2-5.5
Coir	95-230			2.2-6
Sisal fiber	400-800			9-38
Nanofibers	500-200000	10-1300	50-80	5000
Carbon fiber	80000	500-1000	110	5000

The flexural and tensile strength of glass fiber is considerably higher than that of conventional materials, rendering it an optimal reinforcement material for enhancing the overall structural strength of composite materials. The addition of glass fiber to concrete enhances its strength and hardness, even in high temperature conditions, thereby preventing softening and melting. Simultaneously, it exhibits robust resistance to a wide range of chemicals and is highly resistant to erosion. According to the research conducted by Chandramouli et al., the incorporation of glass fiber into concrete has been found to enhance its compressive strength and mitigate crack formation. [12].

Polypropylene fibers possess high tensile strength and elongation, enabling them to retain their shape and resist deformation when exposed to external forces. Its exceptional tear and wear resistance makes it valuable in various applications. Polypropylene fiber has lower heat resistance compared to certain other synthetic fibers. However, it exhibits excellent resistance to aging and maintains its performance even when subjected to changes in environmental or physical conditions. Additionally, being one of the lightest fiber materials gives it an advantage in the production of lightweight products. According to research, adding polypropylene fiber to concrete can decrease cracking width, reduce brittleness, and enhance durability, thereby extending the service life of concrete[2]. Polypropylene fiber has excellent mechanical properties and overall good performance. It effectively controls concrete shrinkage cracks, reduces brittleness, and is widely used in bridge engineering for applications such as bridge deck paving, slip film processing, and other areas that require strict crack control.

According to the data in the table, reed fiber exhibits good bending and compressive strength, making it suitable for producing lightweight structures in areas that require higher strength, such as construction. However, scholar Wang argues that the addition of reed fiber does not have a positive effect on strength.14The reed fiber is known for its toughness and ability to withstand external forces, making it resistant to impact and deformation. It also has high hardness and excellent wear resistance, making it suitable for various applications in fields that require wear resistance. It has good moisture absorption and air permeability, as well as low density, which makes it excellent for heat and sound insulation in buildings14.Therefore, we believe that adding reed fiber does not enhance the strength of concrete. However, due to its excellent mechanical properties and durability, reed fiber can be utilized for road paving and enhancing road load-bearing capacity.

According to the table data, straw fiber has good compressive strength and a light density, making it suitable for producing lightweight building panels. The strength of straw fibers is high, allowing them to absorb impact and prevent damage from external forces. Straw fiber is known for its high hardness and wear resistance compared to other natural fibers. According to scholar Liao Zhaoyin's research, the addition of straw fiber can enhance the impact strength and resistance of cement-based materials.[15].

The coir fiber has a strong adhesion force and high tensile strength, as shown in Figure 4. It can withstand pressure without collapsing or rupturing, and its bending strength is also favorable. Therefore, coir fiber is a viable material for lightweight structures.

The coir fiber has a high flexural modulus and an absorption capacity for impact force, making it tough. This measure is implemented to reduce the effects of shock, vibration, and other factors on the building structure. Coir is a strong and durable building material due to its good hardness and wear resistance.[17]. Therefore, we believe that coconut shell concrete, as the base layer of the road, can fully utilize its excellent mechanical properties to enhance the road's bearing capacity and durability, while also preventing road cracking and potholes.

When conducting tensile strength tests, sisal fibers exhibit significantly higher tensile strength compared to many traditional building materials. Additionally, the elastic modulus of sisal fibers ranges from 13-22 Gpa, indicating excellent compliance and toughness. Sisal fiber is known for its high impact strength and ability to absorb impact force, making it a popular choice for building structures.

Nanofiber materials typically exhibit high compressive and tensile strength, which varies depending on the type and combination of fibers. Additionally, nanofibers are generally lighter, sometimes weighing only 1/6th of steel. Adding this material to concrete can effectively reduce porosity and this lightweight construction offers advantages in situations such as earthquakes or any other scenario where lightweight materials are necessary[5].

The compressive strength of carbon fiber composites is significantly higher than that of other common building materials like steel and concrete. Carbon fiber also has a tensile strength several times greater than these materials, making it an ideal choice for protective and supporting structures. Additionally, carbon fiber has a much lower density than steel, weighing only about 1/6 as much. This combination of strength and lightweight properties makes carbon fiber particularly advantageous for lightweight structures, such as long-span supports, or in situations where vibration and earthquakes may occur[18].We believe that using carbon fiber concrete as a load-bearing component can enhance the stability and safety of structures, while also reducing weight and engineering costs.

4 The current problems in the research of non-metallic fiber concrete

Non-metallic fiber concrete is a new composite material that exhibits superior properties in various aspects, such as compressive and tensile strength, impact resistance, tightness, and durability. However, as a developing technology, non-metallic fiber concrete still faces challenges that need to be addressed in scientific research and engineering applications..

4.1 Fiber distribution uniformity problem

The issue of fiber distribution uniformity is a significant area of research in non-metallic fiber concrete. The distribution of fibers in non-metallic fiber concrete directly impacts its mechanical properties and durability. The physical characteristics of non-metallic fibers and the viscosity and fluidity of concrete often result in uneven distribution of fibers. This can lead to inconsistent performance of concrete, and even the formation of cracks and other destructive issues. Therefore, it is crucial to study and explore effective methods for dispersing fibers, enhance the interface properties between concrete and fibers, improve the distribution of fibers within concrete, and enhance the overall performance of non-metallic fiber-reinforced concrete. Polypropylene fiber, with its three-dimensional distribution, low density, and small monofilament diameter, can thicken concrete. However, this can hinder the compactness of the concrete, leading to cracking.

4.2 The problem of adhesion between concrete and non-metallic fibers

According to Yamakawa's research, the adhesion between concrete and non-metallic fibers is a crucial factor that affects the study of non-metallic fiber concrete. This adhesion directly impacts the compressive and tensile strength of the concrete. The strength and durability of concrete can be compromised due to inadequate adhesion between non-metallic fibers and cement slurry. This requires optimizing material selection and concrete ratio to enhance the adhesion between concrete and fiber, thereby improving the mechanical properties of non-metallic fiber concrete.

4.3 Durability issues

The addition of non-metallic fibers can improve the durability of concrete due to their inherent durability. However, further research is needed to understand the impact of fiber performance on the durability of concrete in different environmental conditions, including salt erosion, freeze-thaw, and alkali-aggregate reaction[19]. Only through thorough study and understanding of concrete durability can we effectively utilize non-metallic fiber concrete to maximize its value in engineering construction. For instance, regular glass fiber concrete lacks alkali resistance and cannot be utilized as a reinforcement material for cement concrete. When glass fiber is exposed to the atmosphere for an extended period, its strength and toughness significantly decrease. Polypropylene fibers are distributed in three dimensions, with a small density and monofilament diameter. This thickening effect is not conducive to the vibration and compactness of concrete, leading to concrete cracking.

5 Conclusions and recommendations

5.1 Conclusion

Ramezanianpour's research identified two main aspects in which fibers have an impact on concrete. In terms of mechanical properties, it can enhance the compressive strength, splitting tensile strength, flexural strength, crack resistance, fatigue resistance, and impact resistance of concrete. Additionally, it improves the durability of concrete, specifically its frost resistance and impermeability[20]. Therefore, in practical engineering, it can not only reduce the thickness of the structural layer and the self-weight of the structure, but also improve the connection between the concrete at the joints, enhance the integrity of the structure, and prolong its service life.

Based on our research and discussions, non-metallic fiber reinforced concrete improves crack resistance, prevents or reduces cracks caused by shrinkage, temperature changes, and load effects. It also extends the service life of concrete, reduces maintenance costs, and enhances structural safety. Additionally, it improves concrete durability, impermeability, freeze-thaw resistance, chemical erosion resistance, and wear resistance. Non-metallic fibers reduce porosity and capillary porosity, increase compactness and uniformity, and decrease water and gas permeability, ensuring stability and reliability in harsh environments. Furthermore, non-metallic fibers have a lower density and higher specific strength than traditional reinforcement materials like steel bars, resulting in reduced self-weight of concrete and savings in materials and construction costs. By ensuring or improving structural performance, they can also reduce weight and material usage, resulting in lower costs and easier construction.

5.2 Recommendations

The interface condition between the fiber and cement matrix is a critical factor that impacts the performance of non-metallic fiber concrete. However, limited research has been conducted on the microscopic effects and influencing factors of security management due to constraints in research methods. It is essential to enhance theoretical research and microscopic analysis by utilizing modern science and technology， conduct comprehensive research on the microstructure and interface properties of non-metallic fiber concrete using modern scientific and technological methods.Establishing the mechanism of action and identifying influencing factors, developing mathematical models and calculation methods, and creating appropriate test methods and evaluation standards.

Furthermore,the mixing, transportation, pouring, and curing of non-metallic fiber concrete must adhere to relevant specifications and technical requirements. Pay close attention to controlling the water-cement ratio, admixture dosage, mixing time, vibration density, and other parameters to ensure the consistency of the concrete. and quality. Various construction methods have varying impacts on fiber dispersion and arrangement. We believe it is necessary to optimize the construction method and mix ratio. Select suitable non-metallic fibers based on project requirements and conditions to ensure uniform dispersion and dense filling of non-metallic fiber concrete. Conduct tests and evaluations at specified intervals and quantities. Testing is essential for achieving optimal performance and economic benefits.

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