Analysis of Factors Influencing the Performance of Fiber Reinforced Concrete

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Abstract. As a new type of building material, fiber reinforced concrete (FRC) has been widely used in the field of construction engineering. Further analysis of the mechanism of discontinuous fiber improving concrete performance is the key to the preparation and rational application of high performance FRC. The mechanisms of crack resistance, tensile strength and bending resistance of discontinuous fiber reinforced concrete were analysed. The influence factors of fiber reinforced concrete performance were discussed. The results show that fiber length, fiber section shape, fiber volume fraction, fiber orientation and fiber length diameter ratio have significant effects on the performance of concrete. The existence of the fiber group effect leads to the increase of the critical volume fraction of the fiber. The improvement of the tensile strength of the composite was slow down, and it increased nonlinearly with the change of the volume fraction of the fiber. The utilization rate of the fiber decreased greatly. The fiber hybrid effect was the important factor affecting the improvement of concrete performance by fibers. The effective way of discontinuous fiber improving concrete performance is to reduce fiber group effect and use the positive fiber hybrid effect.

Keywords. Fiber reinforced concrete, enhanced mechanism to improve, fiber group effect, fiber hybrid effect.

1. Introduction
Fiber reinforced concrete (FRC) is a kind of composite concrete material mixed with a certain amount of fiber. The research shows that the effective enhancement of the mechanical behaviour of concrete can be achieved through the incorporation of fibers. And the fatigue resistance and durability significantly of concrete structures has also been enhanced. At present, the research on FRC mainly focuses on the experimental study of mechanical properties of concrete with single or hybrid fiber and the mechanism of fiber reinforced crack resistance. The extensive experiments show that the mechanical and tensile properties of concrete can be improved by adding SF, CF, GF or BF, el at [1]. Synthetic fiber reinforced concrete has excellent impermeability, frost resistance, wear resistance and corrosion resistance [2-3]. However, it is difficult for the synthetic fiber to disperse evenly in the matrix concrete, which results in the decrease of the performance improvement of the matrix concrete. Hybrid fiber concrete (HFRC) are formed by mixing different kinds of fibers or fibers with different characteristics in a certain proportion in the concrete matrix. Due to the advantages of different fibers, the performance of concrete matrix is improved in multi-phase, multi structure and multi-level [4]. For HFRC, it is still in the exploratory research stage, and there are few practical engineering applications. There is no reasonable mechanism analysis theory at home and abroad, especially the “1+1>2”
phenomenon of hybrid fiber improving matrix properties. A large number of experimental studies have proved that “fiber positive hybrid effect” exists, and hybrid fiber has a significant effect on improving the comprehensive performance of concrete. It can be seen that the analysis of the intrinsic mechanism of fiber hybrid effect is the key to the study of HFRC.

The research on the mechanism of fiber improving concrete performance mainly includes the mechanical properties of fiber matrix interface, the tensile constitutive model of composite and the effect of fiber bridging on crack resistance. At present, the widely accepted mechanisms of fiber improving concrete mechanical properties are “fiber spacing theory” and “composite material theory”. There are many defects in these two theories. For example, the fiber spacing theory is based on the linear elastic fracture mechanics theory. It is considered that fiber plays a certain constraint on the initiation and expansion of the crack of the matrix concrete, which can slow down the stress concentration at the crack tip of the matrix, and points out that the fiber spacing directly affects the strength and toughness of the concrete [5]. In practice, the fiber content, fiber diameter, fiber and matrix bonding properties also have a significant impact on the strengthening and toughening effect of concrete matrix. Therefore, some scholars pointed out that the mechanical properties of fiber matrix interface and the influence of fiber bridging factors should be considered. Based on the mixing principle, the composite theory regards the concrete matrix as the basic phase and the fiber as a kind of reinforcement phase. It is assumed that the reinforced phase material and the basic phase material are well bonded, and the mechanical properties of the composite are the superposition of the internal phase separation properties. The influence of fiber length and bonding properties is ignored, which leads to great difference between predicted strength and actual strength. Therefore, it is necessary to conduct in-depth analysis on the influencing factors of fiber reinforced concrete performance, so as to provide a reliable basis for further improving the current theoretical system. This paper intends to analyse the influencing factors of fiber reinforced concrete performance, and provide reference for the application and development of FRC in civil engineering.

2. Effect of Geometric Fiber Characteristics on Reinforcement

The properties of fiber include mechanical properties and geometric characteristics. Mechanical properties refer to the tensile strength, elastic modulus and ultimate elongation of the fiber. And the mechanical properties of the fiber itself are important indexes affecting the tensile properties of the composite. Fiber geometric characteristics generally include fiber length, cross section shape, surface roughness, aspect ratio and so on. Fiber geometry is the main factor affecting the bond performance between fiber and matrix concrete.

2.1. Fiber Length

The mechanical behaviour of the interaction between single fiber and matrix is analysed. The model is shown in figure 1. When the matrix is cracked, the fiber bears all the tensile stress. It is assumed that the position where the crack intersects with the fiber has the same probability. There is a critical value of fiber length \( l_{(crit)} \). If the fiber length \( l_f \) is less than the critical value \( l_{(crit)} \), the fiber will be pulled out; if the fiber length \( l_f \) is greater than the critical value \( l_{(crit)} \), the fiber will be broken. The influence of \( l_f \) on the tensile mechanical behaviour was characterized by the effective fiber length coefficient \( \eta_l \), which was deduced and calculated.

When \( l_f < l_{(crit)} \), the fiber stress distribution is shown in figure 1(a). The fiber reinforcement efficiency can be expressed as follows when take half of the fiber length for analysis:

\[
\frac{\sigma_f}{\eta_l \sigma_{f,\text{max}}} = \frac{2x}{l_f}
\]  

(1)

Therefore, the effective coefficient of fiber length is:
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\[ \eta = \frac{l_f}{l_f} \frac{2x}{2} \frac{2}{l_f} dx = \frac{1}{2} \]  

(2)

Figure 1. The stress of fiber in the concrete matrix.

When \( l_f \leq l_{fcrit} \), the fiber stress distribution is shown in figure 1(b). In this case, the probability of any position where the fiber and the crack intersect is \( 2dx/l_f \), the effective coefficient of fiber length is:

\[ \eta = \int_0^{l_{fcrit}} \frac{4x}{l_f} \frac{2}{l_f} dx + \int_{l_{fcrit}}^{l_f} \frac{2}{l_f} dx = 1 - 0.5 \frac{l_{fcrit}}{l_f} \]  

(3)

2.2. Fiber Section Shape and Surface Roughness

The elastic modulus of fiber and matrix concrete are different. Considering the influence of the bonding degree between the fiber and the matrix, the shear stress is generated around the fiber axis when the composite is under tension. The stress transfer model of fiber and matrix is shown in figure 2.

\[ \tau = \frac{\pi r^2 \sigma_f}{l/2} \]

(4)

\[ \sigma_f = \frac{2\pi}{r_f} \int_0^x \tau_f dx \]

(5)

Where \( r_f \) is the fiber radius; \( \sigma_f \) is the tensile stress of the fiber at \( x_0 \); \( \tau_f \) is the shear stress at \( x_0 \); that is, the interfacial bonding force. \( \eta_b \) is the interfacial adhesion coefficient, that is, the ratio of the maximum tensile stress to the ultimate tensile strength of the fiber.

\[ \eta_b = \frac{\sigma_f}{\sigma_{fu}} \]  

(6)
It is assumed that the fiber length meets the minimum required shear zone length equal to half of the fiber length when the directional discontinuous fiber is damaged under tension. Therefore, the critical bond length of fiber can be calculated as follows:

\[ l_{fbu} = \frac{\sigma_{fu} d_f}{2\tau} \]  

(7)

The fiber can reach its maximum tensile stress after matrix cracking when \( l_f < l_{fbu} \). At this time, the substrate is destroyed and the fiber has not reached its yield strength, and the failure mode of fiber is mostly pulled out.

\[ \sigma_f = 2\tau \frac{l_f}{d_f} \]  

(8)

The fiber can reach its maximum tensile stress after matrix cracking when \( l_f \geq l_{fbu} \):

\[ \sigma_f = 2\tau \frac{l_{fbu}}{d_f} \]  

(9)

At this time, the substrate is destroyed and the fiber reaches its yield strength. The failure mode of the fiber is mostly broken. It can be seen that different fiber section shape and surface roughness have significant influence on the bond performance between fiber and concrete matrix. The bond coefficient \( \eta_b \) is used to characterize the influence of the bond between fiber and concrete on the tensile properties of FRC [6].

\[ \eta_b = 2\tau \frac{l_f}{d_f\sigma_f}, \quad (l_f < l_{fbu}) \]  

(10)

\[ \eta_b = 1, \quad (l_f \geq l_{fbu}) \]  

(11)

here \( d_f \) is the diameter of the fiber and \( \tau \) is the bond strength between the fiber and the matrix.

2.3. Aspect Ratio
The aspect ratio refers to the ratio of fiber length to diameter, which is a dimensionless parameter to characterize the size effect of fiber. The results show that the aspect ratio has a significant effect on the mechanical properties of concrete. Liang carried out an experimental study on the early crack resistance of PPFRC [7]. The results show that the early crack resistance effect of the composite is relatively good when the ratio of length to diameter is small with the same content. Su believe that when the length diameter ratio is large, the matrix will enhance the fiber occluding effect. However, when the length diameter ratio is too large, the fiber distribution is uneven and it is easy to produce agglomerations, thus weakening the fiber reinforcement effect [8].

3. Effect of Fiber Orientation on Reinforcement Effect
Fiber orientation is one of the factors that directly affect the fiber reinforcement effect [9]. Mu prepared unidirectional SFRC by using the method of magnetic force, and carried out experimental research on its mechanical properties [10]. The results show that the splitting tensile strength and bending tensile strength of SFRC increase with the increase of fiber orientation coefficient. The orientation of fibers in the matrix is usually characterized by “fiber orientation coefficient \( \eta_\theta \)”. Soroushian considered that the probability of the angle value between fiber and spatial Cartesian coordinate axis in matrix concrete is equal [11]. Its model is shown in figure 3.
Based on this, the orientation coefficient of disorderly distributed fibers is derived.

$$\eta_0 = \frac{\int_0^{\pi/2} \int_0^{\pi/2} \cos \theta \cos \phi d\theta d\phi}{\pi/2} = \frac{4}{\pi^2} = 0.405$$  \hspace{1cm} (12)

DuPont assumed that the fiber distribution in the matrix concrete along any direction has the same probability density [12], and its model is shown in figure 4. When the angle between the projection of fiber on X0Y plane and Y axis is $\phi$, and the angle between fiber and Z axis is $\theta$, the probability can be expressed by the ratio of $dA$ area and hemispherical area.

$$\frac{r^2 \sin \theta d\theta d\phi}{2\pi r^2} = \frac{1}{2\pi} \sin \theta d\theta d\phi$$ \hspace{1cm} (13)

Therefore, the fiber orientation coefficient is:

$$\eta_0 = 2\int_0^{\pi/2} \int_0^\pi \frac{1}{2\pi} \sin \theta \cos \theta d\theta d\phi = \frac{1}{2}$$ \hspace{1cm} (14)

In practice, the fiber orientation is affected by its own geometric characteristics, matrix concrete mix proportion, molding process and other factors, which makes the actual fiber orientation coefficient difficult to obtain accurately, and there is a certain gap between the orientation coefficient predicted by equal angle theory and equal density theory based on statistical principle. Therefore, how to accurately
characterize the fiber orientation in the matrix and its effect on the mechanical properties of the composite is one of the key issues in the mechanism analysis of fiber reinforced concrete.

4. Effect of Fiber Volume Fraction on Reinforcement Effect

According to the fiber center spacing theory, the larger the fiber volume fraction, the smaller the fiber spacing, and the greater the effect of fiber on matrix crack resistance. According to the composite material theory, the tensile strength and elastic modulus of the composite increase with the increase of the tensile strength and elastic modulus of the fiber. When the fiber volume fraction is small, the tensile properties of the matrix concrete are almost not affected. It is assumed that the matrix concrete will crack after yielding under tension, and the load will be transferred to the fiber and the fiber will be broken. Considering the influence of discontinuous fiber length, orientation and bond, the tensile strength of fiber reinforced concrete is expressed as follows:

\[ \sigma^*_f = \eta_f \sigma^*_f V_f = \eta_f \eta_f \sigma^*_f V_f \]  

(15)

\( \eta_f \) is the effective coefficient of fiber, \( \sigma^*_f \) is the tensile strength of fiber reinforced concrete, and \( \sigma^*_f \) is the tensile strength of fiber. It can be seen that the tensile yield strength of the composite must be greater than its initial cracking strength when the fiber plays a reinforcing role, and there is a critical value of the fiber volume addition rate \( (V_f^\text{crit}) \):

\[ \eta_f \sigma^*_f V_f^\text{crit} = \eta_f \sigma^*_f^\text{crit} + \sigma^*_m (1-V_f^\text{crit}) = \eta_f E_f \varepsilon^*_m V_f^\text{crit} + \sigma^*_m (1-V_f^\text{crit}) \]  

(16)

\[ V_f^\text{crit} = \frac{\sigma^*_m}{\eta_f (\sigma^*_f - E_f \varepsilon^*_m) + \sigma^*_m} \]  

(17)

When the fiber volume addition rate is greater than the critical volume addition rate, the fiber can enhance the matrix concrete, which has been confirmed by a large number of research conclusions. However, in practice, when the fiber volume ratio is too large, the tensile properties of matrix concrete will be reduced. For example, Zhao research shows that when the volume addition rate of aramid fiber is too large, the phenomenon of fiber intersection and agglomeration occurs, which leads to the decrease of mechanical properties of cement mortar [13]. Chu obtained the model equation of fiber reinforced concrete through experiments, and considered that the matrix strength and fiber volume addition rate are the key factors affecting the fiber reinforcement effect [14].

5. Effect of “Fiber Group Effect” and “Fiber Hybrid Effect”

Due to the different mixing process of matrix concrete, the fiber is difficult to disperse evenly in the matrix concrete, and the phenomenon of fiber group occurs. The uneven dispersion of fibers in the bond interface with cement paste produced a certain weak surface, which increased the initial defects in the concrete and reduced its mechanical properties. In this regard, reference [15] takes basalt fiber composite epoxy resin as the research object, analyzes the influence of fiber group effect on the tensile properties of the composite, and establishes an arbitrary K-shaped fiber group model. By analyzing the geometric characteristics of the model, the fiber average coefficient \( \eta_0 \) is introduced to represent the fiber group effect, such as:

\[ \eta_0 = 1.13 \frac{d^2}{S} \times (\frac{c}{2d_f} + \frac{\mu \sigma_e c}{2 \tau d_f} + \frac{\mu \sigma_e}{\tau} + 1) \]  

(18)

According to the composite material theory, considering the effect of fiber group effect, the tensile strength of the composite and the critical volume addition rate of fiber are:

\[ \sigma^*_f = \eta_f \eta_f \sigma^*_f V_f (1-w) + \eta_f \eta_f \sigma^*_f V_f w \]  

(19)
Therefore, the critical volume blending rate of fiber increases to some extent due to the fiber group effect. The improvement of the tensile strength of the composite was slowed down, and the nonlinear growth was observed with the change of fiber volume fraction, and the utilization rate of fiber decreased significantly. At present, many scholars have found that the fiber beating effect is the key factor affecting the mechanical properties of the composite. At present, many scholars have found that the fiber group effect is the key factor affecting the mechanical properties of the composite. For example, Zhou introduced the fiber distribution coefficient to quantify the fiber dispersion, and analyzed the relationship between the fiber dispersion and the tensile properties of the composite [16]. The results showed that the greater the fiber dispersion, the better the tensile properties of the composite. Therefore, in the design and preparation of fiber reinforced concrete, we should try to increase the fiber dispersion, avoid the phenomenon of fiber agglomeration, and improve the utilization rate of fiber.

Fiber hybrid effect refers to the mixing of fibers with different properties into matrix concrete. Due to the complementary effect of different geometric shape fiber and multi-level aggregate inside the matrix concrete, the cracks in each layer of the matrix can be restrained, which is beneficial to the mutual supplement and promotion of the mechanical properties of concrete, resulting in positive hybrid effect. Under the same conditions, the improvement of matrix comprehensive properties of hybrid fiber is better than that of single doped fiber [17]. However, some studies have shown that with the increase of the volume ratio of hybrid fiber, negative hybrid effect will be produced on the comprehensive performance of concrete. At present, the mechanism of fiber hybrid effect is relatively less, there is no mature theoretical mechanism of positive hybrid effect caused by different characteristics of fiber, and the internal mechanism of negative hybrid effect leading to the decline of concrete performance needs further analysis.

6. Conclusion

The geometric characteristics of fiber, volume ratio, orientation, fiber group effect and hybrid effect are the main factors affecting the improvement of concrete performance by fiber. It is an effective way to improve the performance of concrete by reducing the fiber group effect and using the positive hybrid effect of fiber.

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