A review of rheological properties of steel fiber reinforced concrete

ABSTRACT: The rheological properties of steel fiber reinforced concrete have a significant impact on engineering quality, and experimental characterization of the rheological properties of steel fiber reinforced concrete has significant engineering significance and scientific research value. By reviewing relevant literature both domestically and internationally, the article compares and analyzes the construction characteristics and applicable scope of commonly used concrete rheometers, and analyzes the influence of factors such as water cement ratio, mineral admixtures, aggregate properties, steel fiber properties, and additives on the rheological performance test results. The results show that there are significant differences in the test results using different rheometers, and the degree of influence of different factors on the rheological properties of steel fiber reinforced concrete is also different. This can provide reference for the selection of rheological performance testing methods and parameter control of steel fiber reinforced concrete.
***Keywords**: steel fiber reinforced concrete; rheological properties; rheometer; rheological model; factors affecting rheological properties*

1. INTRODUCTION

Steel fiber reinforced concrete has been extensively studied for its superior mechanical and deformation properties, and has been widely used in construction, water conservancy, road and bridge engineering fields, such as steel steel fiber reinforced concrete composite beams, steel fiber lightweight aggregate concrete composite beams, steel fiber reinforced concrete lining for weak surrounding rock tunnels, steel fiber reinforced concrete face rockfill dams, etc. Its workability has also been widely concerned in the field of engineering construction [1].

Due to the addition of mineral admixtures, additives, etc., traditional slump cone tests alone are far from sufficient to characterize the workability of concrete. After conducting extensive experimental research, it has been found that in order to fully and accurately grasp the complex workability of freshly mixed concrete, it is necessary to start with the rheological mechanism and model of concrete. Only in this way can the interaction between various components in concrete and the mechanism of the workability of fresh concrete be better revealed, thus establishing the relationship curve or formula between the rheological properties of concrete mixtures and the workability parameters in practical engineering applications, achieving on-site construction control and application, and even numerical simulation of concrete and establishing virtual laboratories. At present, there have been many studies on the rheological properties of concrete. In order to improve the strength of concrete, most scholars choose to add an appropriate amount of steel fibers, which has also made great progress. However, there is not much research on the rheological properties of steel fiber reinforced concrete. The addition of steel fibers will have an impact on the rheological properties of concrete, and the specific degree of impact needs to be further explored.

The rheological properties of steel fiber reinforced concrete mixtures are related to their transportation, pumping, pouring, forming, and workability [2], and good workability is a prerequisite for achieving their quality objectives [3]. Therefore, studying the rheological properties of steel fiber reinforced concrete is of great significance. This article summarizes the rheometers and rheological models applicable to concrete, and discusses in detail the influence of different factors on the rheological properties of steel fiber reinforced concrete.

2. METHODOLOGY

2.1 Selection of rheometer

Rheology is a science about the flow and deformation of matter, and the principles of rheology are applied to cement-based materials, providing an important means for accurately characterizing rheological properties. The rheological properties of concrete are one of the most important indicators of early workability, and excellent rheological properties ensure the performance of concrete mixtures during pouring, forming, and transportation under complex conditions [4]. Rheometer is a device used to test the relationship between torque and rotational speed of materials under shear conditions, and has gradually become the mainstream tool for characterizing the rheological properties of concrete. The geometric dimensions, testing components, and testing procedures of a rheometer can lead to differences in rheological parameters, which are related to the material composition. The test results of different concrete rheometers show the same pattern, but there are significant differences in the absolute values of the test results, indicating that the geometric structure of the rheometer has a direct impact on the measurement data, which in turn affects the establishment of the rheological model. Common concrete rheometers include coaxial cylindrical rheometers, blade rheometers, parallel plate rheometers, and so on [5]. This article analyzes the selection of rheometers by comparing their applicability.

At present, most rheometers used for studying the rheology of cement-based materials are coaxial cylindrical. The instrument consists of two coaxial cylinders, one inside and one outside. During measurement, the annular space between the two cylinders is filled with concrete, and one cylinder is kept stationary while the other cylinder rotates. The torque value is measured by changing the rotational speed. Coaxial cylinder rheometers can be divided into two types: one is the Couette type rheometer, which measures the outer cylinder rotation speed and the torque acting on the inner cylinder, and the other is the Searle type rheometer, which measures the inner cylinder rotation speed and torque at the same time [5].

The more common blade rheometer is the ICAR rheometer developed by the International Aggregate Research Center at the University of Texas. This rheometer is more portable and its larger blade size can be used to test the rheological properties of self compacting concrete containing large coarse aggregates. It is mainly composed of an electric motor, a bracket, a rotor, a computer, and a concrete cylinder. The rotor is a cross shaped propeller with ribs on the inner wall of the cylinder, which can prevent relative sliding between the concrete inside the cylinder and the inner wall [6]. The geometric structure of the rheometer, especially the distance between the rotor and the outer cylinder, the shape of the rotor, and other factors, have a significant impact on the measurement results.

The BTRHEOM rheometer is a typical representative of parallel plate rheometer. Between two horizontal plates, the circular concrete is subjected to shear around the central axis. The upper plate can rotate, and both the upper and lower plates have ribs, which can avoid relative sliding between the concrete and the instrument and affect the determination of rheological results. At the same time, vibration can also be applied to the concrete through the container that supports it at the bottom [7].

2.2 Rheological model

The rheological properties of freshly mixed concrete can be characterized by rheological models, including the Bingham model, Herschel Bulkley model, and Modified Bingham model [8]. The Bingham model can effectively meet the requirements for measuring the rheological parameters of concrete in engineering. The rheological parameters can be calculated using a rheometer, and the method is relatively simple. Within a certain range, the shear stress increases linearly with the increase of shear rate. Its mathematical expression is:

$$\tau=\tau_0+\eta\gamma \quad (3\text{-}1)$$

In the formula, τ is the shear stress (Pa); τ_0 is the yield stress (Pa); η is the plastic viscosity (Pa • s); γ is the shear rate (s^{-1}).

The advantage of the Herschel Bulkley model is that it can better describe the nonlinearity of the relationship between shear stress and shear rate of materials and avoid the occurrence of negative yield stress based on the Bingham model. Its expression is:

$$\tau=\tau_0+k\gamma^{n} \quad (3\text{-}2)$$

In the formula, k is the consistency factor (Pa • s^n); n is the power-law exponent (n<1 indicates shear thinning, n>1 indicates shear thickening, n=1 indicates the standard Bingham linear model).

For the shortcomings of the Herschel Bulkley model, the Modified Bingham model can be used to characterize the rheological properties of cement-based materials [9]. Self compacting concrete often exhibits rheological properties of shear thickening, which can be characterized by the Modified Bingham model. Its expression is:

$$\tau=\tau_0+\eta\gamma+c\gamma^2 \quad (3\text{-}3)$$

In the formula, c is the correction factor (c>0 indicates shear thickening, c<0 indicates shear thinning, and c=0 indicates Bingham model).

3. RESULTS AND DISCUSSION

Rheometers can be used to measure rheological parameters such as yield stress and plastic viscosity of freshly mixed concrete, where yield stress is the parameter that starts or stops the flow of concrete during pouring, and plastic viscosity reflects the rheological properties of concrete during the process of overcoming yield stress flow [7]. Various factors such as water cement ratio, mineral admixtures, aggregate properties, steel fiber properties, and additives can all affect the rheological properties of steel fiber reinforced concrete.

3.1 Water cement ratio

The rheological properties of cement-based materials are largely related to the water cement ratio. Lee et al. [10] studied the effect of different water cement ratios (0.38, 0.41, and 0.44) on the rheological parameters of synthetic fiber-reinforced self compacting cement-based composites. The results showed that the yield stress and plastic viscosity both decreased with increasing water cement ratio. Sadrmomtazi et al. [11] conducted a study on the influence of different water cement ratios (0.18, 0.20, and 0.22) on the rheological properties of ultra-high performance concrete (UHPC), and concluded that the yield stress decreases with increasing water cement ratio. Madandoust et al. [12] found through studying self compacting concrete (SCC) containing metakaolin with different water cement ratios (0.32, 0.38, and 0.45) that a metakaolin rotary cone distillation tower with appropriate stability can be produced without the use of viscosity modifiers at different water cement ratios.

3.2 Mineral admixture

Guo et al. [13] conducted experimental research on the influence of different fly ash contents on the rheological and workability properties of lightweight aggregate concrete. The results showed that the addition of fly ash can reduce the yield stress and plastic viscosity of lightweight aggregate concrete, and effectively improve its workability. Güneyisi et al. [14] prepared glass fiber reinforced self compacting concrete by mixing nano silica (NS) and fly ash. When the NS content increased from 0% to 4% and the glass fiber volume fraction increased from 0% to 1.5%, it resulted in an increase in the slump expansion and V-funnel time of the concrete mixture. Wu et al. [15] studied the effect of varying the content of silica fume (0, 5%, 10%, 15%, 20%, 25%) on the rheological properties of UHPC. They found that the mechanical interlocking between steel fibers and surrounding particles increased the flow resistance, so high content silica fume could increase the yield stress and plastic viscosity of UHPC. However, when 10% and 15% silica fume were added, there was a tendency to reduce the plastic viscosity. Keke et al. [16] studied the effect of bentonite content on the rheological properties of UHPC and found that when the bentonite content increased from 0% to 15%, due to its strong water swelling and PCE adsorption properties, the flowability of UHPC mixtures decreased by 55.71%, while the static yield stress, dynamic yield stress, plastic viscosity, and thixotropy increased by 17.05 times, 5.57 times, 1.16 times, and 0.04 times, respectively.

3.3 Aggregate characteristics

The characteristics of aggregates also have a significant impact on the rheological properties of concrete. Guo et al. [17] studied the influence of fine aggregate morphology on the rheological parameters of C30 concrete. The results showed that as the angularity and two-dimensional shape index of the composite fine aggregate increased, the yield stress and viscosity coefficient of the concrete mixture also increased. Zhang [18] studied the effects of different aggregate particle sizes (5-10 mm, 5-16 mm, 5-20 mm, and 5-25 mm) on the rheological and workability properties of SCC. The results showed that as the aggregate particle size increased, the yield stress and plastic viscosity of SCC showed a trend of first decreasing and then increasing, the slump expansion first increased and then slightly decreased, and T500 first decreased and then increased. Jiao et al. [19] investigated the effect of aggregate coating thickness on the rheological properties of concrete. The results showed that the yield stress and plastic viscosity of fresh concrete generally decreased with the increase of aggregate coating thickness, and the slump gradually increased, improving the fluidity of concrete. Jiao et al. [20] conducted experimental research on the influence of coarse aggregate gradation on the rheological parameters of concrete. The results showed that the yield stress decreased with the increase of large particle size aggregate content, while the plastic viscosity was mainly related to the content of small and intermediate particle size aggregates. With the increase of small particle size aggregate content, the plastic viscosity first decreased and then increased. Santos et al. [21] found through their research that the influence of aggregate gradation on plastic viscosity in SCC is much greater than its effect on yield stress.

3.4 Steel fiber characteristics

The type, aspect ratio, and dosage of steel fibers fundamentally affect the rheological properties of steel fiber reinforced concrete. Zeyad [22] studied the effect of steel fiber types on the rheological properties of steel fiber self compacting concrete (SFRCC). The results showed that end hooked steel fibers were more affected by the end shape and could lower the rheological properties of SFRCC than low-carbon steel fibers and bent steel fibers. Alrawashden et al. [23] studied the effects of aspect ratios (60, 80) and volume fractions (0.35%, 0.45%, and 0.55%) of end hooked steel fibers on the rheological properties of SFRSC. The results showed that the rheological properties of SFRSC decreased with increasing aspect ratios and volume fractions of steel fibers. Ding et al. [24] showed that the characteristics of freshly mixed SCC are more affected by the length of steel fibers than their volume fraction.

3.5 Admixture

Common additives include water reducing agents, viscosity modifiers, air entraining agents, etc. [25], all of which can affect the rheological properties of cement-based materials. Water reducing agents are mainly organic water-soluble polymers, commonly used to improve the workability of concrete and significantly reduce its rheological parameters [26, 27]. The main types of water reducing agents include sulfonated naphthaldehyde (SNF), polycarboxylate ether (PCE), lignin sulfate (LS), hydroxycarboxylic acid, carbohydrates, etc [28]. Among them, PCE and SNF high-efficiency water reducing agents have been widely used. Qian et al. [29] studied the different effects of PCE and SNF high-efficiency water reducers on the dynamic yield stress of cement slurry. They observed that both PCE and SNF high-efficiency water reducers reduced the dynamic yield stress of the slurry, but compared with SNF high-efficiency water reducer, PCE high-efficiency water reducer was more effective in reducing the dynamic yield stress of the slurry. Yu et al. [30] found through studying the effect of high-efficiency water reducing agent (SP) on the rheological parameters of fresh UHPC that the yield stress and plastic viscosity showed a trend of first decreasing and then increasing with the increase of SP dosage. When the SP dosage was 3.5%, UHPC with a dense microstructure could be obtained. Wang et al. [31] studied the effect of changing the dosage of SP on the rheological parameters of a new type of UHPC mortar. The results showed that as the dosage of SP increased, the yield stress significantly decreased, but the effect on plastic viscosity was not significant.

Meng et al. [32] found that adding a high molecular weight ethylene oxide viscosity modifier can increase the yield stress and plastic viscosity of UHPC under a fixed water cement ratio. Geng et al. [33] used UWB II flocculant as a viscosity modifier (VMA) to prepare underwater non dispersible concrete (UNC). The study found that the expansion time increased exponentially with the decrease of slump expansion. When the slump, slump expansion, and T_{500} were 280 mm, 830 mm, and 0.9 s, respectively, the best workability of freshly mixed UNC could be obtained. Tang et al. [34] systematically studied the effects of polycarboxylate SP and VMA on the rheological properties of ECC mortar. The results showed that increasing the amount of SP without VMA resulted in a rapid decrease in yield stress and a steady decrease in plastic viscosity; After adding an appropriate amount of VMA, increasing the amount of SP still effectively reduces the yield stress value while maintaining a plastic viscosity higher than 1.1 Pa·s. Yuan et al. [35] used two types of VMA and two types of SP, namely hydroxypropyl methyl cellulose (HPMC), Weilun gum and polycarboxylate (PCA), and polynaphthalene sulfonate (PNS), to study the coupling effect of additives on the rheological properties of cement slurry. The results showed that the interaction between PNS and HPMC was stronger. Yun et al. [36] found through studying the effect of air entraining agents on the rheological properties of high-performance wet mix shotcrete (HPWMS) that the use of air entraining agents aims to reduce flow resistance and torque viscosity, which can effectively improve the pumping performance of HPWMS. The rate of decrease in torque viscosity decreases with the increase of air content. Kim et al. [37] investigated the relevant characteristics of lightweight aggregate porous concrete (LACC) with a large amount of air entrainment, and the results showed that LACC containing sufficient air entraining agent had higher workability.

However, the testing of rheological parameters of concrete and steel fiber reinforced concrete not only requires high instrument requirements, but is also expensive and usually not suitable for construction sites. Therefore, establishing the relationship between rheological properties and workability can open up a new way to solve this problem, and further research is needed [38].

4. CONCLUSION

For decades, the workability of concrete has been a significant concern in the field of civil engineering. The pumpability, placing, self-compatibility, and shaping of concrete are closely related to its rheological properties. Moreover, the rheological behavior of concrete also influences its strength and durability after hardening. The incorporation of steel fibers into concrete can modify its workability and rheological performance to a certain extent. Therefore, enhancing the workability of steel fiber-reinforced concrete remains a topic that requires further research, and the current body of knowledge on the rheological properties of steel fiber-reinforced concrete still needs to be expanded. In addition, establishing the correlation between rheological properties and workability is a new approach for optimizing the design of steel fiber reinforced concrete.

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