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Crack resistance study of high strength cementitious composites in modern housing construction

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Abstract In order to improve the overall fracture resistance of building structures, modern housing buildings are constructed by applying high-strength cementitious composites to the key stress positions of building beam and column nodes. In this paper, PVA-FRCC composites were prepared by using cement, quartz sand, fly ash, and PVA fibers with composite material theory, fiber spacing theory, and fiber orientation distribution as the theoretical basis. For the mechanical properties of this material, it was verified by compressive and tensile tests, and the influence of fiber orientation coefficient on mechanical properties was analyzed. In order to analyze the crack resistance of the material applied in modern housing construction, the tests were carried out from the dimensions of PVA doping and PVA length, respectively.The PVA fiber doping has a greater impact on the compressive strength of high-strength cementitious composites, and the compressive strength of 2.4% PVA fibers doped into the composite material can be up to 47.34±6.14 MPa.The tensile ultimate stresses with the increase of PVA fiber doping were all shown to be increased firstly and then decreased. The tensile ultimate stress showed an increasing and then decreasing trend with the increase of PVA fiber dosage. The length of the doped fibers is 10-18mm, which can delay the appearance of early cracks in the composites. The combination of PVA fibers and Gaucho Du cementitious composites can better prepare building materials to meet the needs of modern housing construction crack resistance, and better ensure the safety of housing construction.

Index Terms building structure, modern housing construction, composite material, PVA-FRCC material, high strength cementitious

I. Introduction

In recent years, with China's rapid economic development and large-scale construction, there has been an increasing demand for building materials and thus an increasing pressure on the environment. Therefore, the development of new building technologies and building materials to improve the utilization efficiency and service life of buildings is crucial to energy conservation and environmental protection, and to realize the national policy of sustainable development.

High-strength cementitious composite (LCHPCC) is an advanced composite material, which is mainly composed of cement, special aggregates, fiber reinforcement and necessary chemical additives. In the preparation process, the cement and special aggregate are homogeneously mixed, different types and quantities of fibers are added according to the design requirements, and certain chemical additives can also be added to improve the rheological, impermeable, or other properties of the material according to the application scenarios [1]-[3]. LCHPCC has higher toughness and durability compared to conventional cement mortar or concrete [4]. While conventional materials are prone to cracking when subjected to tension, high toughness materials can significantly improve their elongation and fracture resistance due to the incorporation of fibers, which undergo a bridging reaction between the fibers and the cementitious substrate [5], [6]. In addition, conventional materials may require more frequent maintenance and earlier replacement, whereas high-strength composites can significantly extend their service life due to their excellent durability [7], [8]. From an economic point of view, although the initial cost of high-strength composites may be higher, their long-term benefits and reduced maintenance requirements make them a more economical choice.

Literature [9] investigated the mechanical properties of cementitious composites with the addition of homemade anionic waterborne polyurethane (WPU), and experiments showed that the three-dimensional polymer network structure formed by the interpenetration of WPU and the hydration products of the cement significantly reduces the brittleness of the repair material, and makes the material more flexible and adhesive capacity. Literature [10] investigated the strengthening effect and mechanism of carbon fiber reinforced cementitious foam composites under different carbon fiber dosages, and the experimental results showed that the fracture cracks of the samples applied with this material changed in a jagged shape and the fracture surfaces became inhomogeneous, which implied that the proposed material had excellent fracture and bending resistance. Literature [11] analyzed the compressive properties and internal microstructure of fiber-reinforced coral sand cementitious composites (FRCSCC), the results of uniaxial compressive strength tests showed that the compressive strength and elasticity of FRCSCC decreased with the increase in the particle size of coral sand due to the uneven dispersion of the fibers in the increasing coral sand particle size, which led to the reduction of specimen ductility. Literature [12] shows that steel fibers have the advantage of high strength, high modulus of elasticity and can be aligned by magnetic field, while hybrid polypropylene fibers have the advantage of high number and small fiber spacing, and both are used for reinforcing cementitious composites, and their flexural properties are significantly higher than those of the composites with steel or polypropylene fibers alone. Literature [13] basalt fibers and polypropylene fibers were added into cementitious composites in a single doped and blended manner, and carried out comprehensive mechanical properties and durability tests, and found that the two types of fibers can be tightly bonded with the cement matrix, and a certain doping range of the blend is more able to enhance the densification of the composites microstructure, which significantly improves the composites' mechanical properties and durability. Literature [14] conducted impact tests on building specimens composed of two strain-hardening cementitious composites (SHCC), and found that the transverse reinforcing layer of SHCC improved the mechanical loading of the material structure, which greatly increased the load-bearing capacity of the specimens. Literature [15] used pressed mercury method and scanning electron microscope method to study the freeze-thaw damage mechanism of magnesium phosphate cementitious composites (UHDMC) under cold conditions and constructed a probability distribution function model to predict the freeze-thaw damage of UHDMCs with less than 30% of fly ash replacement, which can help to extend the service life of the building. Literature [16] analyzed the combined effect of styrene acrylate emulsion (SAE) and CaCO3 in high-strength cementitious composites, i.e., the integration of SAE and CaCO3 optimized the pores in the cement matrix, which significantly improved the composite's resistance to cracking, whereas too high a concentration of SAE would slow down the hydration process of the cement and, on the contrary, reduce the mechanical strength of the cement. Literature [17] enhanced the mechanical properties and frost resistance of cementitious composites by pretreating jute fibers, the pretreated fibers will reduce the fluidity of the composites and optimize the pore structure within the cementitious composites in order to improve their flexural strength, cracking strength as well as frost resistance. Literature [18] explored the significance of carbon nanomaterials in cementitious composites, stating that the integration of graphene into cementitious composites can improve the safety and durability of their microstructure, which in turn improves the damping and mechanical properties of the materials and contributes to the sustainable development of construction materials. Literature [19] assessed the degree of performance enhancement of wollastonite microfibers (WM) and zeolite powder (ZP) on cementitious composites, WM can significantly improve the flexural and shear properties of the material due to its unique fiber structure with skeletal support and bridging anti-cracking ability in the matrix, while ZP can refine the pore size of the material and reduce the porosity through chemical reaction, which has a more significant impact on improving the compressive strength in the later stage.

This paper proposes a method for the preparation of cementitious composites doped with polyvinyl alcohol fibers, and analyzes the basic mechanical properties and crack resistance of the material to provide new ideas for improving the crack resistance of modern housing construction.

The generation of cracks in concrete structures is inevitable, and the incorporation of a certain amount of fibers in concrete is an effective way to improve the toughness of the material and the ability to resist cracking. In this paper, PVA-FRCC composites were prepared using silicate cement, natural river sand, quartz sand, fly ash, PVA, and water reducing agent. The mechanical properties of the material were analyzed by tensile and compressive tests, and the specific effect of PVA orientation on the mechanical properties was investigated using the fiber orientation coefficient. Specimens with different PVA dosage and different PVA lengths were also produced to analyze the crack resistance of PVA-FRCC composites.

II. Research on the preparation of high-strength cementitious composites

Concrete is the most widely used construction material in modern housing construction projects, but the strong brittleness, easy to crack, low tensile strength and other shortcomings make it easy to produce different degrees of cracks in the building structure, which seriously affects the durability of the modern housing building structure in the process of use. The production of cracks in the concrete structure is inevitable, and the production of cracks for the invasion of corrosive media to provide a channel, so that the durability of the structure gradually deteriorate, reducing the service life of modern housing construction. Adding a certain amount of fibers into concrete is an effective way to improve the toughness and crack resistance of the material, which can significantly improve the energy consumption and crack control ability of the structure, and greatly improve the safety of the structure.

II. A. Mechanism of high-strength cement composites

II. A. 1) Composite material theory

Fiber Reinforced Cementitious Composites (FRCC) is called from the perception of composite material theory. Concrete material is a complex material composed of cementitious materials, sand and gravel aggregates and water multiphase materials, which can be regarded as a cementitious composite material composed of cementite formed by sufficient hydration of cementitious materials as the matrix phase and fillers such as sand and gravel as the reinforcing phase. For fiber concrete, especially fiber-reinforced cement mortar, the fiber can be regarded as the reinforcing phase, and the cementitious material as the matrix phase, thus forming a fiber-reinforced cementitious composite material. According to the theory of composite materials, the relative proportion of the matrix phase and the reinforcing phase, the distribution pattern of the reinforcing phase, and the interface situation determine the properties of the composite material, generally speaking, the addition of the reinforcing phase will make the matrix phase of certain properties can be enhanced [20].

First of all, according to the composite material theory to analyze the force state of composite material before cracking, assuming that the matrix material is homogeneous and isotropic, the reinforcing phase is uniformly dispersed in the matrix, and the matrix and the reinforcing phase are well bonded without relative slip. Then the matrix phase and reinforcing phase will share the external force action, and according to the superposition principle, there is:

$$\sigma A = P \equiv P_m + P_f = \sigma_m A_m + \sigma_f A_f \tag{1}$$

where, P is the external force applied to the composite material, σ_0 is the stress applied to the composite material, A is the cross-sectional area of the composite material; P_m is the force applied to the matrix phase, σ_m is the stress applied to the matrix phase, A_m is the cross-sectional area of the matrix phase; P_f is the force applied to the reinforced bulk phase, σ_f is the stress applied to the reinforced phase, A_f is the cross-sectional area of the reinforced phase.

Dividing both sides of the equation by A at the same time gives:

$$\sigma = \sigma_m \rho_m + \sigma_f \rho_f \tag{2}$$

where ρ_m is the reinforced phase volume rate and ρ_f is the reinforced phase volume rate.

According to the assumption that there is no relative slip between the matrix and reinforcing phases before cracking, the composite phases have the same strain as the composite when subjected to an external force, i.e., $\varepsilon = \varepsilon_m = \varepsilon_f$, while $\rho_f + \rho_m = 1$, then:

$$E = E_m \left(1 - \rho_f\right) + E_f \rho_f \tag{3}$$

In fiber-reinforced cementitious composites, the volume doping of fibers is generally not high, and the elastic modulus of most of the fibers and the cementitious matrix is roughly in the same order of magnitude, so the effect of fibers on the strength and elastic modulus of the composite is not large. However, it can be seen that when the strength of the base material and the volume rate of fibers are fixed, the enhancement effect of fibers with high modulus of elasticity and high strength on the strength and modulus of elasticity of the composites will increase.

Secondly, the force state after cracking is analyzed according to the composite material theory. After the cracking of the matrix phase, the fiber as the reinforcing phase will bridge the matrix phase at the crack and transfer the load, according to the two-force equilibrium relationship, the bond between the fiber and the matrix phase is the same, then there is:

$$\pi d_f \eta l_f \tau = \frac{1}{4} \pi d_f^2 \sigma_f \tag{4}$$

where, d_f is the diameter of the fiber, l_f is the fiber length, τ is the average bond stress between the fiber and the matrix, and η is the effective bond length factor. Simplifying this, we have:

$$\sigma_f = \eta_0 \frac{l_f}{d_f} \tau \tag{5}$$

where η_0 is the effective fiber bridging coefficient, which is related to the distribution of fibers in the matrix. Then the force behavior of fiber reinforced cementitious composites at cracking can be described as:

$$\sigma = \sigma_m \left(1-\rho_f\right) + \eta_0 \frac{l_f}{d_f} \tau \rho_f \tag{6}$$

II. A. 2) Fiber spacing theory

Fiber spacing theory is also called “fiber crack resistance theory”, which holds that there are a large number of macro and microscopic defects such as micro cracks and pores randomly distributed within the cement matrix, and that when subjected to external forces, different degrees of stress concentration will be generated at these defects, leading to the expansion of the defects, and ultimately causing damage to the matrix [21]. However, the addition of fibers within the matrix will change the stress state of cementitious composites, namely:

(1) Fibers and matrix are closely linked to jointly bear the stresses given by the outside world and improve the crack-resisting ability of the matrix.

(2) When the matrix cracks expand so that the matrix to withstand a reduction in stress, this part of the stress is transferred to the fiber, and then the fiber rely on the interfacial bond stress to inhibit the cracks to continue to expand, and through the interfacial bond stress of the fiber will be transferred to the load on both sides of the cracks, so that the cracks can continue to withstand the load in order to achieve the purpose of the crack-resistant and composite reinforcement.

Existing studies have concluded that fibers can inhibit the expansion of cracks within the cementitious matrix and change the damage history of the matrix, thus improving the strength of the matrix, and have given the equation for the relationship between the fiber dosage and the fiber spacing. Namely:

$$s = \frac{13.8 d_f}{\sqrt{V_f}} \tag{7}$$

The above equation indicates that the increase of fiber volume rate will reduce the fiber spacing, and the stronger the inhibition effect of fiber on crack extension. Some researchers further proposed a semi-empirical formula for calculating the tensile strength of cementitious composites based on a large number of test results, i.e.:

$$\sigma_{tc} = k\left(\frac{1}{\sqrt{s}} - \frac{1}{\sqrt{s_c}}\right) + \sigma_{tm} \tag{8}$$

and s_c is the maximum spacing of fibers to produce reinforcement effect.

The fiber spacing theory only explains the fiber blocking mechanism through the concept of fiber spacing, without considering the effect of fiber orientation on the matrix. Therefore, in most cases, the fiber spacing theory can only be used as a qualitative analysis of the fiber reinforcement mechanism.

II. A. 3) Fiber orientation distribution

Assuming that the fibers in the cementitious composites are in the ideal state of completely uniform distribution, the theoretical model of the three-dimensional spatial distribution map of the fibers is shown in Figure 1. Establish a spatial three-dimensional coordinate system, with one end of the fiber as the coordinate origin O, where the angle between the steel fiber and the z-axis is β, and the angle between the steel fiber in the xOy-plane projection and the y-axis is φ. The joint formula (9)-(10) can be derived as the orientation coefficients of the steel fiber in the three mutually orthogonal directions. Namely:

$$\eta_{\theta,x} = \eta_{\theta,y} = \frac{\int_0^{\frac{\pi}{2}} \int_0^{\frac{\pi}{2}} l_f \sin\beta \sin\varphi \, d\beta \, d\varphi}{\frac{\pi}{2} \cdot \frac{\pi}{2} \cdot l_f} = 0.405 \tag{9}$$

$$\eta_{\theta.z} = \frac{\int_0^{\frac{\pi}{2}} l_f \cos\beta \, d\beta}{\frac{\pi}{2} \cdot l_f} = 0.637 \tag{10}$$

$$\eta_\theta = \frac{\int_0^{\frac{\pi}{2}} \pi \frac{l_f^2}{2} \sin\theta \cos\theta \, d\theta}{2\pi \cdot \left(\frac{l_f}{2}\right)^2} = \int_0^{\frac{\pi}{2}} \sin\theta \cos\theta \, d\theta = 0.5 \tag{11}$$

$$p\left(\theta\right) = \frac{1}{A} \frac{dA}{d\theta} = \sin\theta \tag{12}$$

where $\eta_{\theta,x}$, $\eta_{\theta y}$ and $\eta_{\theta,z}$ are the fiber orientation coefficients along the x, y and z axes, respectively. Eq. (12) in $p(\theta)$ is the fiber orientation probability density function when the fibers are randomly distributed.

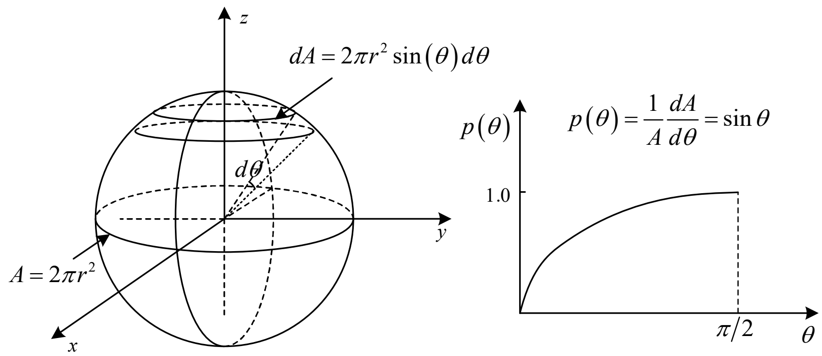


Figure 1: The fiber space random distribution diagram

Since the fibers in high-strength cementitious composites are oriented through a magnetic field resulting in fiber orientation coefficients that are much higher than the three-dimensional random distribution, it is necessary to obtain a more accurate fiber orientation probability density function [22].

The fiber orientation normal distribution curve is obtained by fitting the fiber orientation frequency histogram with a normal distribution, recording the relevant parameters of each fitted curve, and establishing the fiber orientation probability density function of HASFRCM $p(\theta)$. i.e:

$$p(\theta) = ae^{-\frac{(\theta-b)^2}{2c^2}} \tag{13}$$

Among them, a, b and c are dimensionless coefficients, which are related to the shape of the normal distribution curve.

By comparing the change of fiber orientation coefficient, as a way to verify the influence of fiber orientation coefficient on the mechanical properties of high-strength cementitious composites, and to provide support for the further enhancement of the crack resistance of modern building design.

II. B. Test raw materials and mixing ratio design

II. B. 1) Test raw materials

In this paper, the ordinary silicate cement produced by HB Taihang Cement Co., Ltd. is used for the test, and the natural river sand and quartz sand produced by HB Mancheng are used for the test, with reference to the design theory of ECC, and the river sand is sieved to obtain two kinds of graded sand with the maximum particle sizes of 0.61 mm and 0.32 mm as the test sand. According to the division of fineness modulus, the sand used in this test is medium sand. The particle size of quartz sand is 160-220 mesh, the maximum particle size is 0.08mm, the density is 2.66g/cm³, the bulk density is 1.6g/cm³, and the melting point is 1650℃. Fly ash is an active mineral mixing material, mixed into the cementitious materials to replace or partially replace cement, can save the amount of cement, improve the comprehensive performance of cementitious materials, improve the overall quality of the project, reduce costs and so on. The fineness of fly ash selected in this paper is 11.2%, and the loss on burning, water requirement ratio, and sulfur trioxide content are 4.25%, 93%, and 1.86%, respectively, which are in accordance with the “Technical Specification for Fly Ash Concrete Application”.

In this paper, the test is used in J polyvinyl alcohol (PVA) fiber, the fiber high strength and high modulus, good adhesion with the matrix, applied in cementitious materials, can effectively control the cracks due to temperature changes or plastic contraction, inhibit the cracks and development. And it can effectively improve the structure's flexural strength, impact strength, seismic performance, as well as acid and alkali resistance, durability and so on. In this paper, the polycarboxylic acid high performance water reducing agent PC-F produced by BJ Muhu Admixture Co., Ltd. was used in the test, with a density of 1.06±0.03, a water reduction rate of 25~45, and a commonly used dosage of 0.9%~1.6%. The mixing water is ordinary tap water with a density of 1.2g/cm³.

II. B. 2) Design of cementitious composites mix ratio

Concrete ratio refers to the number of proportional relationship between the constituents of concrete materials, to determine the ratio of the process known as the ratio design, the design of concrete ratio not only affects a series of concrete performance, but also affects the cost of the project, is the configuration of the concrete process is one of the most important work. Concrete mixing ratio is usually expressed in two ways, one is to use each cubic concrete in the amount of individual materials, another is to use the mass ratio between the various materials. The design task of the ratio is based on the performance of raw materials and construction conditions, to determine the amount of each component material to meet the required technical and economic indicators, the basic requirements for the design of the ratio include the following four aspects:

(1) Satisfy the concrete strength class required by the structural design.

(2) To meet the required ease of construction process

(3) Satisfy the durability of concrete required by the environment and use conditions of the project.

(4) Under the premise of meeting the above, taking into account the cost of materials, saving the amount of cement as much as possible to reduce costs, in line with the principle of economy.

In this paper, the design theory of PVA-ECC formulated with reference to existing studies, the FRCC mixes with PVA admixture are designed as shown in Table 1. In this paper, the amount of cement replaced by fly ash is 65%, and the water-cement ratio, PVA doping and sand-cement ratio are taken as the influencing factors to investigate the effects of the changes of the three on the performance of PVA-FRCC. Among them, four grades of water-cement ratio of 0.25, 0.30, 0.35 and 0.40, four grades of PVA volumetric dosing of 2.4%, 1.8%, 1.2% and 0.6%, and four grades of sand-cement ratio of 0, 0.3, 0.9 and 1.4 are taken.

Table 1: Mix proportions of PVA-FRCC (kg/m³)

No.	PVA	Cement	Fly ash	Sand	Water	Water reducer
PV1	0.00	503.4	759.6	455.3	295.4	18.9
PV2	12.7	503.4	759.6	455.3	295.4	18.9
PV3	18.5	503.4	759.6	455.3	295.4	18.9
PV4	25.3	503.4	759.6	455.3	295.4	18.9
PV5	25.3	462.8	705.7	422.1	341.5	17.4
PV6	25.3	429.5	653.8	398.5	382.6	16.5
PV7	25.3	416.3	624.3	375.6	416.5	15.6
PV8	25.3	618.5	922.5	0.000	355.3	23.2
PV9	25.3	383.6	576.3	963.5	223.1	14.3
PV10	25.3	325.2	486.5	1213.4	185.4	12.7

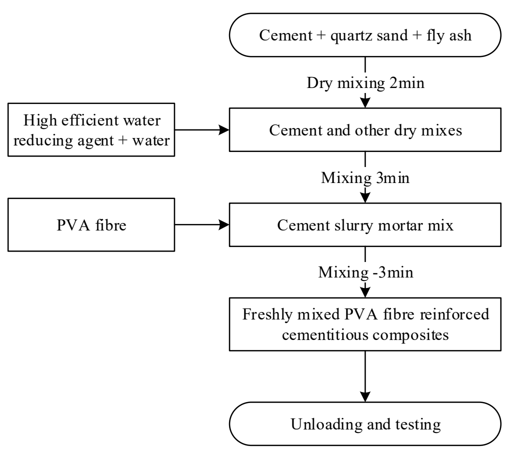


Figure 2: PVA-FRCC composite material mixing method

II. B. 3) Cementitious composite mixing methods

In order to give fuller play to the advantages of various raw materials, a scientific and reasonable preparation process is needed. The key to prepare PVA fiber reinforced cementitious composites is to ensure that PVA fiber and polycarboxylic acid water reducing agent are well dispersed in the mixed system. The polycarboxylic acid water reducing agent is mixed with water, and due to the good dispersibility of the water reducing agent, it can be uniformly dispersed in the water, and the PVA fibers are mixed in the final mixing process one by one.

The preparation process of PVA fiber reinforced cementitious composites is shown in Figure 2. Firstly, the dry raw materials quartz sand, cement and fly ash were poured into the mixer and stirred for two minutes to make the mixture mix evenly. Subsequently, the polycarboxylic acid water reducing agent was mixed with water, and the mixture of water and water reducing agent was blended into the mixture and stirred for three minutes to form cementitious mortar mix. Finally, the mixing was timed for 3 minutes, during which the PVA fibers were blended into the cementitious mortar mix in 5 batches until the PVA fibers were well blended in the mix.

III. Mechanical properties of high-strength cementitious composites

Fiber-reinforced cementitious compliant materials are cementitious composites formed by mixing reinforcing short fibers in the cementitious matrix. The reinforcing fibers can improve the toughness of the material after concrete cracking, but the mechanical properties of traditional fiber concrete are not fundamentally different from those of ordinary concrete, and the tensile stress-strain curve enters the strain-softening stage soon after the initial cracking, and the width of the cracks cannot be controlled. In this paper, a FRCC composite material doped with PVA is proposed, and this chapter mainly analyzes the basic mechanical properties of the material to lay the foundation for exploring the crack resistance of the material.

III. A. Specimen preparation, maintenance and test content

III. A. 1) Test piece preparation and maintenance

After the preparation of cementitious PVA-FRCC composites, a portion of the freshly mixed cementitious composites were loaded into the rheometer drum, consistency meter and slump cylinder for testing, and a portion of the freshly mixed cementitious composites were loaded into the water secretion rate drum, which was moved to the shaking table, vibrated for 30s, and measured the mass, and then moved the water secretion rate drum indoors to conduct the water secretion test. The remaining cementitious composites were loaded into the test mold, placed in the vibration table vibration molding, and then the specimen was moved indoors and covered with a layer of plastic film on the surface of the specimen, and the specimen was removed from the mold after 24 hours and placed in the standard curing room (temperature of 20±2°C, relative humidity ⩾95%), and the specimen was taken out for the mechanical test related to cubic compressive strength and tensile at an age of 30 d. The specimen was then placed in the standard curing room for the mechanical test.

III. A. 2) Mechanical performance test content

(1) Cubic compressive test

The compressive tests were conducted to investigate the 30d cubic compressive strength values of PVA-FRCC composites. During the test, it was found that the damage of the specimens mainly showed two damage modes. The specimen without PVA fibers was accompanied by a crisp sound at the end of the compression damage, showing the typical concrete compression damage pattern, showing the traditional pattern of damage from the edge to the center of the specimen. The specimen mixed with PVA fiber at the end of the compression damage, no obvious sound, the specimen in the upper and lower edges of the production of many fine cracks, the edge of the part of the shedding but with the main body is still adherent, and mixed with 1.2% PVA fiber specimen damage, the specimen is more intact.

The compressive strength of the specimen is determined with reference to the specification JC/T2461-2018 “Test Method for Mechanical Properties of Highly Ductile Fiber Reinforced Cementitious Composites”. Namely:

$$f_{cc} = \frac{F_{cc}}{A_{cc}} \tag{14}$$

where f_{cc} is the value of cubic compressive strength, F_{cc} is the destructive load of the specimen, and A_{cc} is the pressurized area of the specimen.

(2) Splitting tensile test

Cement is a brittle material, a small deformation in tension will lead to cracking, the axial tensile test can show the stress-strain relationship, but the method has a certain degree of difficulty in operation, and the test conditions are very demanding, so this study adopts the split tensile test to indirectly measure the axial tensile strength of cement mortar.

The compressive strength of cementitious composites is generally 10-20 times the tensile strength, and the ratio of tensile strength to compressive strength decreases as the strength grade of cementitious composites increases. The tensile strength represents the resistance to produce maximum uniform deformation and also indicates the ultimate load carrying capacity of the material under static tensile conditions. Therefore, in this paper, the splitting tensile strength is used to test the tensile strength of PVA-FRCC composites, and the experimental instrument is WA-1200C microcomputer-controlled electro-hydraulic servo universal testing machine produced by WX Instruments and Equipment Co. The specific steps are as follows:

(1) When the maintenance is up to the age, take out the specimen and dry the surface of the specimen with a towel, check the appearance, and then draw the position line of the splitting surface.

(2) Put the splitting mold on the lower pressure plate of the press, and then draw the splitting surface of the specimen and put it into the mold.

(3) After adjusting the height of the upper platen, put the upper pad strip and bedding against the position line.

(4) Turn on the press, the test is loaded with equal stress, keep it uniformly loaded at a rate of 0.06 MPa/s, and record the maximum force of damage when the specimen is damaged.

(5) Calculate the tensile strength from the destructive maximum force obtained by the press according to the formula. i.e:

$$f_t = \frac{2F_{\max}}{\pi A} = 0.637\frac{F_{\max}}{A} \tag{15}$$

where f_t is the splitting tensile strength, $F_{\max}$ is the maximum force of destruction, and A is the area of the splitting surface of the specimen.

III. B. Effect of mechanical properties of composite materials

III. B. 1) Analysis of compressive test results

The purpose of the compressive experiments is to examine the compressive performance of PVA-FRCC composites and to understand the specific effect of PVA doping on the enhancement of high-strength cementitious composites. In this paper, four different grades of PVA doping were selected for the preparation of specimens for the preparation of high strength cementitious composites. After 30 days of maintenance, the compressive strength and compressive strength ratio of each group of specimens were measured and averaged, and the test results are shown in Figure 3.

The compressive strengths of the four groups of specimens were all located above 40 MPa, and the compressive strength ratios exceeded 92%, which is in accordance with the specification requirements for synthetic fibers for cement concrete and mortar. As can be seen from the figure, the compressive strength of cementitious composites without PVA fibers is 35.73±2.78 MPa, while the compressive strength of high-strength cementitious composites with only 0.6% PVA fibers can reach 42.63±5.02 MPa, and the compressive strength of composites with 2.4% PVA fibers reaches 47.34±6.14 MPa. The compressive strength of the cementitious composites was significantly increased by 16.23% as compared to the cementitious composites without PVA fiber doping. This indicates that further doping of PVA fibers in cementitious composites is beneficial to improve their compressive properties, and the ratio of compressive strength to compressive strength increases with the increase of PVA fiber doping. And in this paper, in the preparation of PVA-FRCC composites, the first doping method is used for the preparation, so that the PVA fibers and the cementitious matrix materials are mixed uniformly and then reacted with water in contact, which can ensure that the surface of each fiber is coated with cement mortar.

In addition, the morphology of the four groups of specimens under compression damage is obviously different from that of the specimens without fibers. In general, the ordinary mortar specimens without fibers are brittle damage with intense cracks progressing near to the damage and serious surface spalling at the time of damage. The four groups of specimens with fibers were cracked one by one as the load continued to be pressurized, accompanied by a slight sound of fibers pulling off or pulling out. Due to the bridging effect of the fibers at the cracks, the lateral deformation of the bearing process is reduced. Due to the pulling effect of the fiber, only a small amount of debris falls off the surface of the specimen when it is damaged, and the whole specimen cracks but does not fall apart, basically maintaining the initial shape before the beginning of compression. With the increase of PVA fiber doping, the damage morphology also showed some differences.

In conclusion, the addition of PVA fibers in high-strength cementitious composites can significantly improve the compressive properties of the material, but also has a certain crack bridging effect, in the event of material fracture does not completely collapse, to ensure the safety of housing construction to provide reliable material support.

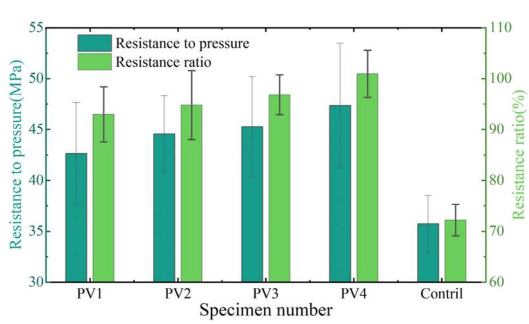


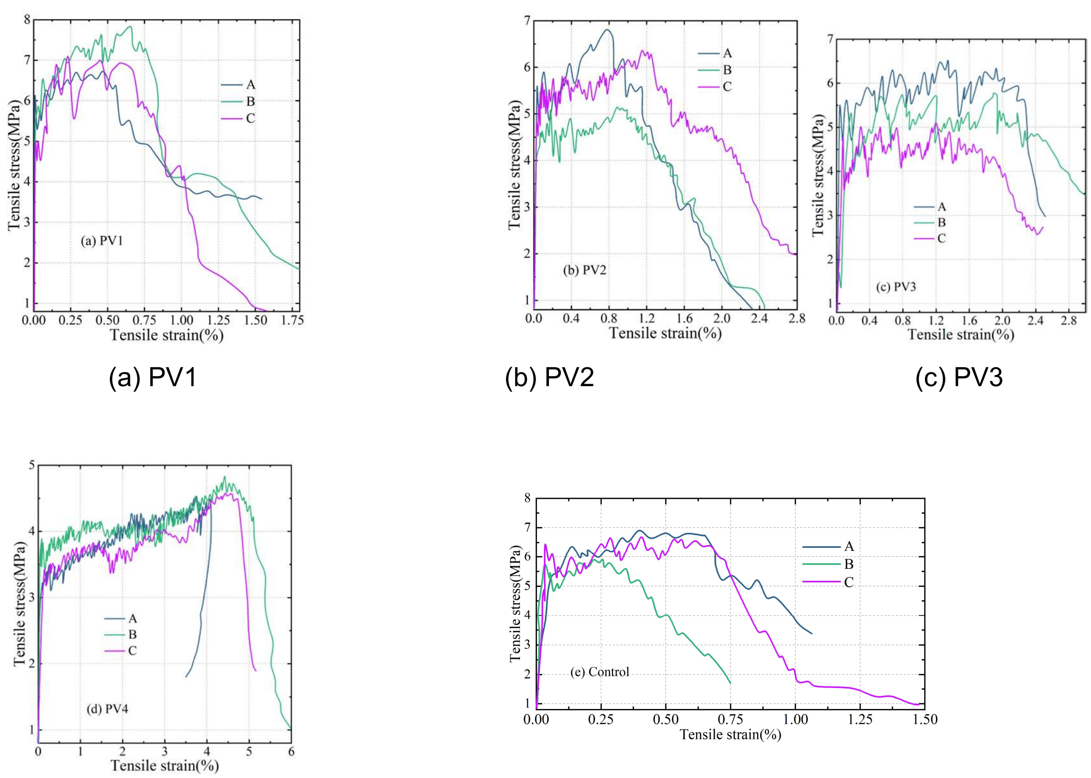
Figure 3: Compression test results of PVA-FRCC composite materials

III. B. 2) Analysis of tensile test results

The specimens PV1~PV4 with different dosage were still selected as the test objects, and the most representative three sets of data in each specimen were chosen to be shown. The typical tensile stress-strain curves of PVA-FRCC with PVA fibers incorporated for 30 days of maintenance are shown in Fig. 4, in which Figs. 4(a) to (e) show the tensile stress-strain curves of PV1~PV4 and those without PVA fibers incorporated, respectively. Table 2 shows the tensile test results of PVA-RFCC composites, where FC, TU, KS and MS are cracking stress, ultimate stress, cracking strain and ultimate strain, respectively.

From the figure, it can be seen that under the tensile load, there is a significant difference between the tensile properties of PVA fiber reinforced cementitious composites and ordinary fiber reinforced cementitious composites. Ordinary fiber reinforced cementitious composites under the action of tensile load will appear strain softening phenomenon, while mixed with PVA fiber reinforced cementitious compound appeared typical strain hardening characteristics. Zooming in on the stress-strain curve can be seen that the curve is not as smooth as the tensile stress-strain curve of metal materials, but in the process of increasing strain, the stress is constantly fluctuating up and down, but the overall trend is up. Through a large number of experimental observations, it is found that this load fluctuation phenomenon corresponds to the generation of cracks on the specimen, i.e., for every additional crack in the specimen during the loading process, the stress-strain curve fluctuates downward once. Therefore, the tensile stress-strain curve also approximates the condition of crack expansion during the test.

The tensile ultimate stresses of cementitious composites reinforced with PVA fibers showed a tendency of increasing and then decreasing with the increase of PVA fiber dosage. Compared with the control group, the ultimate tensile stress of the PV1 group increased the most, with an increase of 1.144 MPa, and the ultimate tensile stress of the PV4 group decreased the most, with a decrease of 0.988 MPa.From the point of view of the tensile strength of the materials, the tensile strength of PVA-RFCC cementitious composites was optimal when the PVA fiber doping was at 1.2%. The ultimate tensile strains of the PVA-RFCC reinforced cementitious materials all increased with the increase of PVA fiber doping, while the ultimate tensile strains of the PVA-RFCC reinforced cementitious materials increased with the increase of PVA fiber doping. The tensile strains of PVA-RFCC reinforced cementitious materials increased gradually with the increase of PVA fiber doping. The ultimate tensile strain of the specimen with 2.4% PVA fiber doping can reach 4.939%, which is nearly 23 times higher than that of the control group, and the cementitious composites with different amounts of PVA fiber doping show excellent tensile properties.



(a) PV1 (b) PV2 (c) PV3

(d) PV4 (e) Control

Figure 4: The PVA-FRCC typical tensile stress strain curve

Table 2: The PVA-FRCC typical tensile stress strain result

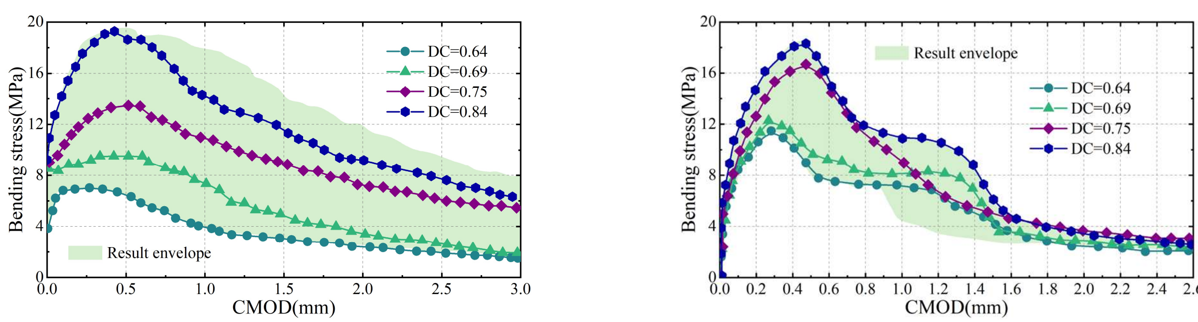
Group	FC (MPa)	TU (MPa)	KS (%)	MS (%)
Control	3.841	4.535	0.015	0.207
PV1	4.985	6.746	0.034	0.531
PV2	4.024	6.198	0.069	0.854
PV3	3.176	4.653	0.123	1.952
PV4	2.853	3.279	0.046	4.939

III. B. 3) Effect of fiber orientation distribution

After analyzing the mechanical properties of cementitious composites with different dosage of PVA fibers, this paper also addresses the effect of fiber orientation distribution on the bridging effect between cracks of composites. Based on the calculation method of fiber orientation coefficient given in the previous section, the specific effects on bending stress and shear stress of PVA-FRCC composites with different fiber orientation coefficients are compared. Figure 5 shows the effect of fiber orientation coefficient on the mechanical properties, where Figures 5(a)~(b) show the variation of bending stress and shear stress, respectively.

A large difference in the fiber orientation distribution will lead to present a smaller bridging stress in PVA-FRCC cementitious composites, which makes PVA-FRCC more susceptible to fracture in the tensile process. The specimens were cut along three different directions, namely transverse, longitudinal and at 45° to the transverse direction, and the orientation coefficients of the three were compared, which showed that the fiber orientation coefficients of the transverse direction were about 8.5 times lower than those of the longitudinal direction.

In addition, compared with the longitudinal specimens, the maximum decrease in ultimate tensile strength and ultimate flexural strength of the transverse PVA-FRCC specimens were 42.64% and 60.38%, respectively.The orientation distribution of the PVA fibers inside the cementitious composites directly affects their shear strength. The ultimate shear strength of the cast slabs was cut at 60°, 30° and 0° to the direction of slurry flow, and the ultimate shear strength of the specimens increased from 11.47 MPa to 18.31 MPa with a maximum increase of 59.63% when the fiber orientation coefficients of the specimens were 0.64, 0.69, 0.75 and 0.84, respectively. The ultimate flexural strength increased from 7.03 MPa to 19.28 MPa with a maximum increase of 174.25%. Therefore, when mixing PVA fibers with high-strength cementitious composites, it is necessary to pay attention to the distribution of fiber orientation, which can further improve the mechanical properties of the composites and provide reliable support for the crack resistance of modern housing buildings.



(a) Bending stress and orientation coefficient

(b) Shear stress and orientation coefficient

Figure 5: The effect of fiber orientation coefficient on mechanical properties

IV. Cracking resistance of high-strength cementitious composites

Since its inception, cement-based materials have become the most widely used and largest housing construction materials in the world due to their good compressive properties, strong applicability, wide source of raw materials, durability and high temperature resistance. But at the same time, its own still exists many shortcomings, such as self-importance, low tensile strength, poor crack resistance, poor toughness. Especially under the effect of earthquakes, the brittle nature of cementitious materials also restricts its wide application. Therefore, in order to improve the brittle characteristics of cementitious materials, enhance the toughness and improve the safety and durability of structural components, fiber-reinforced cementitious composites are proposed, which have a good performance in the enhancement of toughness, durability and other aspects, and have a good prospect of application in the actual construction of modern housing buildings.

IV. A. Specimen design and fabrication and calculation of results

IV. A. 1) Test piece design and fabrication

The test of PVA-FRCC composites was divided into two for comparison, one with PVA length of 10mm, its addition of 2.4%, 1.8%, 1.2%, 0.6% four grades for comparison, and one with PVA incorporation of 1.8%, and its fiber lengths of 10mm, 12mm, 14mm, 16mm, 18mm, and 20mm respectively for comparison. The effect of PVA fiber length on the crack resistance of high strength cementitious composites was explored. Comparison was achieved by adding cement mortar samples without added PVA fibers to each set of PVA-FRCC composite tests.

Sample in the production of the sample based on the experimental existence of defects, the thickness of the sample, the water-cement ratio to make suitable changes, certain elements borrowed from the "fiber concrete and mortar shrinkage crack test method" in the rules. Using the appropriate water-cement ratio of 0.65, ash-sand ratio of 2:3, the sample is a flat sheet, the size of 500mm * 500mm * 50mm, the border is equipped with a spacing of 50mm single row of pegs 100mm long. mold frame using 55mm * 50mm * 55mm channel steel production, the bottom plate should be 5mm thick steel plate, brush oil and then lay polyethylene film isolation layer. Apply the technique of first mixing method to make specimens, the specific steps are as follows:

(1) Artificially mix cement and sand before adding PVA fiber to achieve mixing.

(2) Add water to the dry-mixed material and keep mixing until the PVA fiber is evenly integrated into the cement mortar.

(3) Pour the mixed material into the mold, apply vibrator to vibrate, when the surface separates from the water layer, apply spatula to smooth.

IV. A. 2) Calculation and evaluation of results

The cracking resistance ratio γ calculated from the length and width of the cracks that appeared on the specimens during the plate test was used as the basis for the evaluation of this test. Firstly, the cracks were classified into 5 levels according to the crack width d, and each level of crack width corresponded to a weight value, i.e. $[d \geq 3] \in 3, [2,3) \in 2, [1,2) \in 1, [0.5,1) \in 0.5, [d < 0.5] \in 0.25$. The cracking index corresponding to each crack was obtained by multiplying the length of each crack and its corresponding weight value, and the cracking index of the specimen was obtained by adding up the cracking indexes of each crack, which was denoted as W, in order to evaluate the degree of cracking of the specimens of PVA-FRCC cementitious composites.

The unit of cracking index is mm, which is calculated by the following formula:

$$W = \Sigma\left(A_i \cdot l_i\right) \tag{16}$$

Where W is the cracking index, A_i is the weight value corresponding to a crack, and l_i is the crack length corresponding to the weight value. The cracking resistance ratio can be expressed as a percentage of the difference between the average cracking index of the cementitious composite base mix and the average cracking index of the externally doped cementitious composite to be tested and the ratio of the average cracking index of the cementitious composite base mix.

The cracking resistance ratio γ can be calculated from the following equation and the result is accurate to 1%. i.e:

$$\gamma = \frac{W_0 - W_i}{W_0} \times 100\% \tag{17}$$

where γ is the cracking resistance ratio, a positive value indicates that the external admixture plays a role in improving the cracking resistance of cementitious composites, and a negative value indicates that the external admixture plays a role in reducing the cracking resistance of cementitious composites. W_i is the average cracking index of cementitious composites with external admixtures to be tested, and W_0 is the average cracking index of cementitious composites with base mix ratio.

IV. B. Crack resistance of PVA-FRCC composites

IV. B. 1) Effect of PVA dosage on early cracking performance

In order to analyze the effect of PVA doping on the early cracking performance of cementitious composite specimens, this paper prepared PVA-FRCC composites under semi-closed conditions and investigated the circular strain curves under semi-closed conditions with different PVA fiber doping. Figure 6 shows the circular strain curves of the specimens under semi-closed conditions, and Table 3 shows the cracking indexes under semi-closed conditions.

From the figure, it can be seen that the circular compressive strain of the specimens doped with PVA fibers was smaller than that of the control group after 5 h from the beginning of the initial setting, and among the cement mortar specimens doped with PVA fibers, the circular compressive strain of the specimens doped with 0.6 wt.% was the smallest, and the circular compressive strain of those doped with 2.4 wt.% was the largest, which indicated that the total shrinkage of mortar specimen doped with PVA fibers of 2.4 wt.% was the smallest.

As can be seen from the table, the circular cracking compressive strains of the specimens with PVA fiber doping of 0.6 wt.%, 1.2 wt.%, 1.8 wt.%, and 2.4 wt.% were reduced by 8.85%, 26.86%, 16.44%, and 33.84%, respectively, as compared to the control group. The cracking time of the four groups of toroidal specimens was relatively close, concentrated between 102h and 106h, among which the specimens with PVA fiber content of 1.8wt.% had the longest cracking time, followed by the specimens with PVA fiber content of 0.6wt.%, and then the specimens with PVA fiber content of 2.4wt.% and 1.2wt.%, and the specimens with PVA fiber content of 1.2wt.% had the shortest cracking time.

In addition, the circular strain curve has a typical “three-stage” law. The first stage is the slight expansion stage, which occurs within 5h-20h after the initial setting of the specimen, and the compressive strain of the ring has a slight tendency to decrease with the age, which is due to the intense hydration reaction at the early stage of hydration, resulting in the temperature of the specimen increasing, making the specimen have a slight expansion, and the compressive stress on the ring decreases. The second stage is the contraction stage, which occurs after the specimen is initially set for 20h, and the compressive strain on the rings shows a steady growth trend as the age increases. This is due to the fact that after 20h, the circular specimen continues to hydrate and consume water, and in the dry environment of water evaporation and dissipation of water, resulting in the specimen dry shrinkage and self-shrinkage deformation is larger, and the compressive stress on the circular ring increases. The third stage is the instantaneous cracking stage, which occurs when the specimen cracks, and the instantaneous decrease in the compressive strain of the rings becomes positive, which is due to the fact that when the ring specimen reaches the limit of tensile strength, the specimen cracks, the constraint condition on the rings disappears, and the compressive stress decreases.

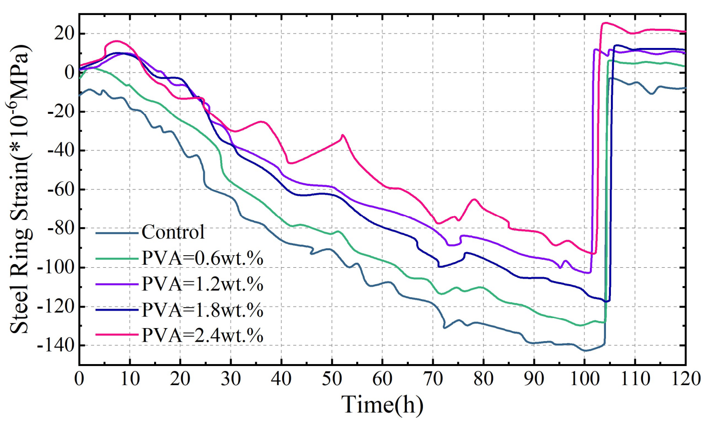


Figure 6: The circular strain curve of the semi-enclosed condition

Table 3: Cracking index under semi-enclosed conditions

PVA (wt.%)	Cracking time (h)	Cracking strain (*10^{-6}MPa)
Control	103.9	-139.94
0.6	104.1	-127.56
1.2	102.3	-102.35
1.8	105.7	-116.94
2.4	102.5	-92.59

IV. B. 2) Effect of PVA Fiber Length on Cracking Performance

The dosage of PVA fibers was fixed at 1.8%, and the fiber length was changed (10 mm, 12 mm, 14 mm, 16 mm, 18 mm, 20 mm) by replacing it with T1~T6. The effect of fiber length on the cracking resistance of cementitious composites was investigated, and the experimental results are shown in Fig. 7. C in the figure is the control group.

Based on the test results, the following conclusions were drawn:

(1) As the fiber length increases, the initial cracking time of cementitious composites increases and then decreases, indicating that there exists an optimal fiber length value that can delay the emergence of early cracks in the composites, which is 14 mm in this test. The initial cracking time of specimens T3~T5 is later than that of the reference specimen, which indicates that the doped fiber length of 10~18mm can delay the appearance of early cracks in composites. The fiber length beyond this range has no delaying effect on the emergence of early cracks in composites, and even accelerates the emergence of early cracks.

(2) In terms of the number of cracks, the specimens incorporated with fibers are less than the reference specimen, in which there are only 2 cracks in the cementitious composites when the fiber length is 14 mm (specimen T3), which indicates that the PVA fibers can effectively reduce the generation of cracks under this condition.

(3) The maximum crack length and maximum crack width of cementitious composites with PVA fibers were reduced compared with the reference specimen. This indicates that the addition of a certain length of PVA fibers in cement mortar can effectively slow down the extension of cracks and refine the cracks, but if the length of the fibers is too long, the length-to-diameter ratio of the fibers increases, and the anticracking effect of the fibers on the cementitious composites is weakened.

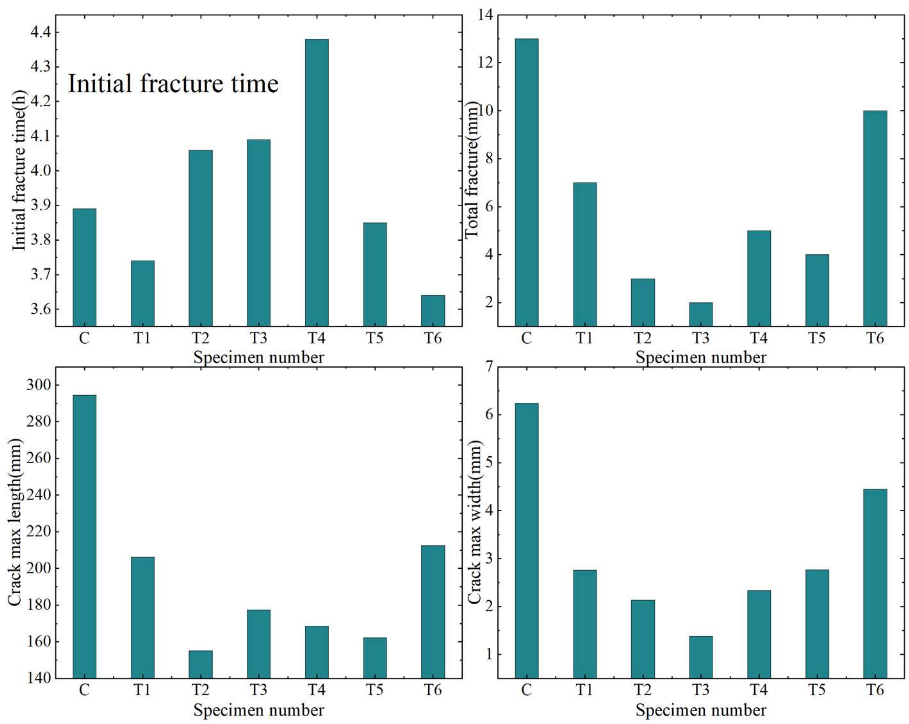


Figure 7: Effect of PVA fiber length for anti-cracking

IV. C. Housing construction applications and implementation effects

After rigorous technical research and construction organization design, based on the high strength cementitious composite material preparation technology proposed by the research, a project department poured the concrete works of a housing building in November 2023, the size of which was constructed according to the 1:1 size of the on-site entity, and the construction environment and the construction conditions simulated the actual on-site situation, to determine whether the construction process, the concrete maintenance, and the anti-cracking properties of the concrete meet the requirements. The solid project is divided into 2 times of construction, the first construction base, size 2.6m (width) * 20m (height) * 3m (length), the base at least 30 days in advance of the side walls poured, the main reinforcement is properly arranged, the distribution of reinforcement according to the design specifications for installation. The concrete is made of PVA-FRCC high-strength cementitious composite material designed in this paper. Before starting the pouring, the mixing station selects the raw materials to be used for the side walls of the roof slab of the main body of the housing building for this model pouring, and the temperature of the raw materials is measured before use. And according to the construction program, sensors were set up at key locations to detect deformation and temperature in preparation for the subsequent temperature control of the mass concrete model. After the pouring was completed, geotextile+colorful strips were used to fully wrap the concrete and formwork to avoid excessive temperature difference between inside and outside of the concrete. After demolding, the sidewall concrete was covered with double quilt + colorful strips until the end of the curing period. During the curing period, sprinkle water on the concrete surface every 3h to reduce the temperature.

Typical observation points were selected, and the same batch of mixed concrete mix was molded into a control group with the same specifications under the same construction environment and at a location similar to the observation point. During the whole pouring process, during the temperature-controlled time (November 22 to December 5, 2023) of the tunnel body sidewall model curing, no water seepage and slurry seepage occurred in the concrete, the mix had better encapsulation, and the grade of early cracking resistance of the hardened concrete was in accordance with the design requirements.

Considering the structural integrity of the housing construction project, it is not possible to carry out destructive testing of the structure. For this reason, surface cracks were observed in the concrete of the constructed housing building and its control group 2 months after the pouring. It was found that tiny through cracks with length of about 1-1.5 mm were observed on the front and side of the control group, while no cracks were observed on the surface of any of the cementitious composite test groups using PVA-FRCC. This shows that the findings of the article are useful as a guide for practical concrete construction for housing buildings.

V. Conclusion

(1) The dosage of PVA fiber has a large effect on the compressive strength of high-strength cementitious composites, and the compressive strength of 2.4% PVA fiber doped can reach 47.34±6.14 MPa, and the average compressive strength is 16.23% higher than that before doping. With the increase of PVA fiber doping, the compressive strength of high-strength cementitious composites was significantly increased.

(2) According to the test results, the tensile ultimate stress showed a tendency of increasing and then decreasing with the increase of PVA fiber doping. Compared with the control group, the ultimate tensile stress of the PV1 group increased the most, with an increase of 1.144 MPa, and the ultimate tensile stress of the PV4 group decreased the most, with a decrease of 0.988 MPa.

(3) When the fiber orientation coefficients of the specimens were 0.64, 0.69, 0.75 & 0.84, respectively, the ultimate shear strength increased from 11.47 MPa to 18.31 MPa, with a maximum increase of 59.63%. The ultimate flexural strength increased from 7.03 MPa to 19.28 MPa with a maximum increase of 174.25%.

(4) The circular cracking compressive strains of specimens with PVA fiber doping of 0.6 wt.%, 1.2 wt.%, 1.8 wt.%, and 2.4 wt.% were reduced by 8.85%, 26.86%, 16.44%, and 33.84%, respectively. The doped fiber lengths of 10-18 mm retarded the appearance of early cracks in the composites.

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