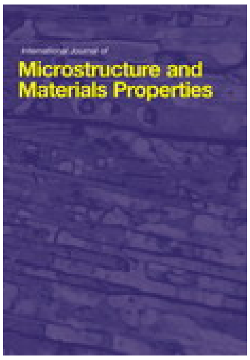

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An influence of composite nano materials on tensile properties of concrete members

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An influence of composite nano materials on tensile properties of concrete members

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Abstract: In order to improve the tensile properties and prediction effect of concrete members, this paper studies the influence of composite nanomaterials on the tensile properties of concrete members. Firstly, the concrete members containing composite nanomaterials were prepared, the compressive strength of the concrete members was calculated by compressive mathematical function, the tensile properties of the concrete members were analysed according to the tensile mechanism, and the compressive stress-strain curve of the nanofibre concrete members was obtained. The tensile constitutive function of nanofibre ultra-high performance concrete (UHPC) was constructed to analyse the influence of composite nanomaterials on the tensile properties of concrete members. The experimental results show that the ultimate tensile strength and elastic ultimate tensile strength of concrete members with the proposed method can reach 11.54 MPa and 9.56 MPa, and the prediction accuracy of tensile properties can reach 99%, indicating that the proposed method can improve the tensile properties of concrete members.

Keywords: compressive mathematical function; ultimate tensile strength; flexural strength; tensile constitutive function; UHPC; ultra-high performance concrete.

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1 Introduction

Concrete is widely used in many fields such as buildings, bridges, tunnels, ports and roads because of its excellent characteristics such as wide source of raw materials, convenient construction and good economy (Kich et al., 2022). With the progress of science and technology and the rapid development of social economy, people have higher and higher requirements for concrete structures. The structural forms are constantly developing towards thin-walled light-weight, super large span, super high-rise and so on. However, the development of new structure is seriously restricted by the defects of ordinary concrete, such as heavy self-weight, low tensile capacity and poor crack resistance. In addition, over the past 40 years of reform and opening up, China has made remarkable achievements in infrastructure construction, and China has become a real construction country (Lengxiujuan et al., 2020). However, the current situation of building structures in China is that there are many diseases and short service life. It is of great significance to strengthen the inspection, maintenance and reinforcement of existing structures, and the reinforcement of existing concrete structures often uses concrete with better performance as the foundation. Therefore, adding composite nano materials to concrete members can effectively improve the reliability of existing structural reinforcement of concrete members (Ma, 2021). Therefore, relevant scholars have made some progress in the research on the tensile properties of concrete members.

Wu et al. (2021) puts forward an analysis method for the influence of nano SiO_2 on the tensile properties of concrete components (Wu et al., 2021). SiO_2 concrete components are prepared by melt blending method to fill the pores of cement with nano fine particles, so as to improve the compactness of concrete and the properties of concrete. The tensile properties of composites are studied. This method can effectively improve the tensile properties of concrete members, but the tensile strength of concrete members is low. Zhu et al. (2021) puts forward a method for the influence of hydration responsive nano materials on the tensile properties of concrete components (Zhu et al., 2021), calculates the compressive strength and corrosion resistance coefficient of nano concrete components by using nuclear magnetic resonance technology, analyses the organisational structure of nano concrete components by thermal analyser, establishes the prediction function of concrete compressive strength GM (1,1) by using grey system theory, and predicts the tensile properties of nano concrete components by GM (1,1) function, This method can effectively improve the accuracy of predicting the tensile properties of concrete members, but the compressive stress is low.

In view of the problems of low tensile strength and poor compressive stress resistance of concrete members in the above methods, this paper proposes a research method for the tensile performance of composite nano-concrete members. The specific experimental ideas are as follows:

Firstly, composite nano materials are prepared for concrete components. The concrete components containing composite nano materials are prepared, and the compressive strength of concrete components is calculated through the compressive mathematical function, and the flexural strength of concrete components and the failure load of concrete components are calculated according to the specifications;

Secondly, the compressive stress-strain curve of concrete members is obtained. According to the tensile mechanism, the tensile properties of concrete members are analysed, and the compressive stress-strain curves of nanofibre reinforced concrete members are obtained;

Then, the tensile properties of concrete members with nanofibres are calculated. The tensile constitutive function of nanofibre ultra-high performance concrete (UHPC) was constructed to analyse the effect of composite nano materials on the tensile properties of concrete members.

Finally, through the ultimate tensile strength, elastic ultimate tensile strength and the tensile prediction effect of concrete members, the influence of composite nano materials on the tensile performance of concrete members is verified, and the conclusion is drawn.

2 Preparation of concrete components with composite nano materials

2.1 Component design and fabrication

In the test, the concrete component with added nanofibre as the test sample is mainly characterised by moderate outer diameter and length, high purity, and excellent mechanical and electrical properties. See Table 1 for the main technical parameters.

Table 1 Main technical parameters of nanofibre concrete components

Nature	*Parameter*	*Nature*	*Parameter*
external diameter(nm)	3–15	Purity (%)	>97
Length(μm)	15–30	Bulk density (g/cm^3)	0.06–0.09
Specific surface area(m/g)	250–270	Conductivity (s/cm)	>100

In this experiment, nanofibre reinforced concrete components were designed and manufactured. The mechanical properties of axial tension members are studied through axial tension tests on specimens with changed relevant parameters (Hedong and Zhu, 2020). See Table 1 for the detailed parameters of nanofibre reinforced concrete members. See the main symbol table above for the relevant symbol meanings in the table, where α is the carbon content of nanofibre and ζ_s is the constraint effect coefficient of nanofibre, which can be calculated according to formulas (1) and (2):

$$\alpha = A_s / A_c \tag{1}$$

$$\zeta_s = A_s f_y / A_c k \tag{2}$$

where A_s and f_y are the cross-sectional area and yield strength of nanofibres respectively, A_c and f_{ck} are the cross-sectional area and axial compressive strength standard value of concrete respectively, and $f_{ck} = 0.67 f_{cu.k}$ and $f_{cu.k}$ are the compressive strength of concrete components.

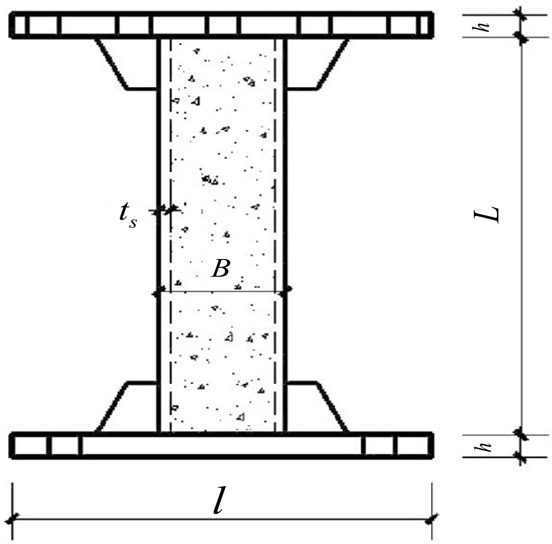
The number in the front of the sample number is the external diameter of nanofibre, the number at the end represents the strength grade of the core concrete of the sample is C30, C40 and C50 respectively, and the number 0 represents that the sample is a concrete component. The parameters of concrete members are shown in Table 2.

Table 2 Parameters of concrete members

Serial number	*Test piece no*	L (mm)	$D \times t_s$ (mm)	A	f_{cu} /*MPa*	ζ_s
1	89–40	460	89 × 3.5	0.178	40	2.02
2	114–40	460	114 × 3.5	0.135	40	1.54
3	139–40	460	139 × 3.5	0.109	40	1.24
4	114–30	460	114 × 3.5	0.135	30	2.05
5	114–50	460	114 × 3.5	0.135	50	1.23
6	114–0	460	114 × 3.5	0.135	–	–

The concrete members used in the test piece are made of Q235 steel plates with a thickness of 3.5 mm by crimping welding. First, the nanofibre concrete members and end plates are made according to the design size. The upper and lower plates are made of 400 × 400 × 25 mm thick steel plates, which are connected with the concrete members by welding. The upper and lower plates are provided with 8 bolt holes with a diameter of 32 mm according to the requirements of the experimental device, Used for connection between bolt and experimental device (Ge and Zhang, 2021; Khalifa and El-Kady, 2022; Aghayari and Al-Mwanes, 2019). See Figure 1, $l \times b \times h$ for the design of concrete components.

Figure 1 Design diagram of concrete components



The specific fabrication process of concrete components is as follows:

1 The concrete member and the end plate are cut according to the design dimensions. In order to prevent the end plate from buckling and deformation early in the loading process, four stiffening ribs are set at the contact position between the end plate and the concrete member. The rib height is 60mm, and the length of the upper and lower ribs are 30 mm and 60 mm respectively.

2 First, align the geometric center of the lower concrete member with the lower end plate accurately and keep the concrete member vertical, weld the concrete member with the lower end plate, and then position weld the four stiffeners according to the design position.

3 Before pouring concrete, the inner wall of the steel pipe at the position 1/3L from the upper port shall be polished smooth, and the strain gauge shall be pasted, and then treated with waterproof glue. In order to prevent the high temperature of welding from damaging the strain gage wire during the welding of the upper end plate, a 5 mm small hole is drilled between the two stiffening ribs at the lower end, and the strain gauge connecting wire is threaded out (Yang and Fang, 2020).

4 After the waterproof glue is solidified, the concrete shall be mixed according to the mix proportion and poured. In order to prevent the internal strain gauge from falling off, the manual mixing method is used in the mixing process, that is, while pouring concrete, the leather hammer is used to hammer outside the concrete component to complete the vibration work.

5 After the initial setting of concrete, the end shall be ground flat and the upper end plate and stiffener shall be welded. In order to cure the core concrete, a small hole with a radius of 15 mm is reserved at the centre of the upper end plate, and water is injected into the hole during the curing period to ensure the smooth progress of concrete curing.

6 In the early stage of concrete curing, paint the outer surface of concrete members evenly to prevent the outer concrete members from rusting due to humid environment and make the test pieces more beautiful (Choi et al., 2019).

7 Before the test, in order to solve the void phenomenon of the end plate caused by concrete shrinkage, after the concrete curing period, epoxy resin is injected into the water injection hole of the upper end plate to fill the gap between the concrete shrinkage and the end plate.

3 Influence of composite nano materials on tensile properties of concrete members

3.1 Obtaining the compressive stress-strain curve of concrete members

In order to analyse the influence of composite nano materials on the tensile performance of concrete members, it is necessary to calculate the compressive stress of concrete members. Therefore, a compressive mathematical function of concrete members is proposed. According to this function, the compressive stress-strain curve of UHPC members (Chen et al., 2021) is obtained, and its expression is as shown in formula (3):

$$y = \frac{\varsigma x}{\varsigma - 1 + x^{\varsigma k}} \tag{3}$$

where y is the stress of concrete member, unit: MPa; x is the strain of concrete member; ς represents the compressive coefficient of concrete members, $\varsigma = 0.8 + f / 17$, $k = 0.67 + f / 62$; f is the compressive strength of concrete member, unit: MPa.

However, formula (3) is only applicable to the members with compressive strength lower than 100 MPa, while the strength values of each group of members in the experiment are above 150 MPa, so the direct application deviation of the formula is large. Therefore, it is necessary to further study the stress-strain function of ultra-high strength specimens.

Calculate the flexural strength of the member according to formula (3) provided in the specification (Liu et al., 2020). The member is a non-standard test piece. According to the specification, the result shall be multiplied by 0.85.

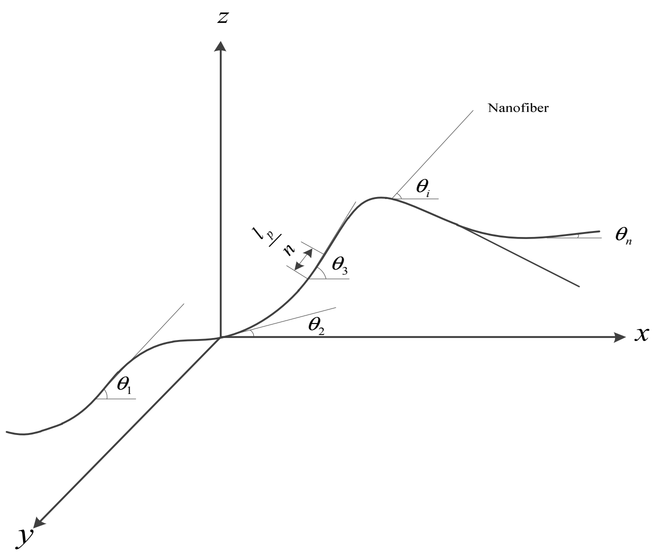
$$f_f = \frac{Fl}{bh^2} \tag{4}$$

where f_f refers to the flexural strength of UHPC test block, unit: MPa; F refers to the load measured when the UHPC component is damaged, unit: N; l refers to the distance between instrument supports, unit: mm; b refers to the width of the side of UHPC test block, unit: mm; h refers to the height of the side of UHPC test block, unit: mm.

3.2 Calculation of tensile properties of concrete members with nanofibres

According to the compressive stress-strain curve of concrete members obtained in Section 3.1, the tensile properties of concrete members subjected to nanofibres are calculated. According to the tensile mechanism analysis of nanofibre UHPC, the effective length, direction and adhesion with the matrix of the fibre have an impact on the tensile properties of UHPC, and the same is true for nanofibres (Kim et al., 2020). In order to obtain the effective length of the nano along the stress direction, the nanofibre with any length of l_p in the space is selected for mechanical analysis, as shown in Figure 2.

Figure 2 Spatial distribution of nanofibres



If the nanofibres with length l_p are divided into n equal parts, the fibre length is composed of n infinitesimal segments with length of $\frac{l_p}{n}$. The included angle between each segment and xoy sides is θ_i. The length of each segment projected to the x axis is $\frac{l_p}{n} cos\theta_i$, of which, $0 \le cos\theta_i \le 1$. Nanofibres are arbitrary. It can be seen from Figure 2 that the average effective length of any nanofibre with a length of l_p projected to the x axis is:

$$l_p = \lim_{n\to\infty} \frac{1}{n} \sum_{i=1}^{n} \frac{l_p}{n} cos\theta_i = \lim_{n\to\infty} \frac{l_p}{n} \cdot \frac{1}{n}(1+2+\cdots+n) = \frac{l_p}{2} \tag{5}$$

According to the calculation method of residual tensile strength of nanofibre UHPC, the residual tensile strength that nanofibre UHPC can bear after UHPC cracking is:

$$\sigma_t = \tau_p l_p{}' \rho_p \frac{4}{\pi^2 d_p} = \tau_p l_p \rho_p \frac{2}{\pi^2 d_p} \tag{6}$$

where l_p is the nanofibre length; d_p is the diameter of nanofibres; ρ_p is PVA fibre content; τ_p is the bonding stress between nanofibre and matrix.

When the adhesion between the nanofibre and the matrix is strong enough, the nanofibre will break, and the tensile strength is determined by the ultimate tensile strength σ_t of the fibre (Kampmann et al., 2021):

$$\sigma_t = \rho_p f_{fu1} \tag{7}$$

where f_{fu1} is the ultimate tensile strength of nanofibres.

Thus, the critical fibre characteristic rate of fibre pullout and breaking obtained from equation (6) is equal to equation (7), which is expressed as equation (8):

$$\left(\frac{l_p}{d_p}\right)_{pcrit} = \frac{f_{fu1}}{0.203\tau_p} \tag{8}$$

Therefore, the tensile constitutive function of nanofibre UHPC can be expressed as (Fernández et al., 2021):

1 Nanofibres not broken: Namely: $\left(\frac{l_p}{d_p}\right) < \left(\frac{l_p}{d_p}\right)_{pcrit}$

$$\sigma_t = \begin{cases} E_{UHPC}{}^{\varepsilon} & \varepsilon \le \varepsilon_{tc} \\ \tau_p l_p \rho_p \dfrac{2}{\pi^2 d_p} & \varepsilon > \varepsilon_{tc} \end{cases} \tag{9}$$

2 Nanofibre breakage：Namely：$\left(\frac{l_p}{d_p}\right) \ge \left(\frac{l_p}{d_p}\right)_{pcrit}$

$$\sigma_t = \begin{cases} E_{UHPC}{}^{\varepsilon} & \varepsilon \le \varepsilon_{tc} \\ \rho_p f_{fu1} & \varepsilon > \varepsilon_{tc} \end{cases} \tag{10}$$

where $\varepsilon_{tc} = \frac{f_{tu}}{E_{UHPC}}$, is the ultimate elastic strain; E_{UHPC} is the elastic modulus of UHPC; ε_{tu} is the ultimate tensile strain, taken as 0.01.

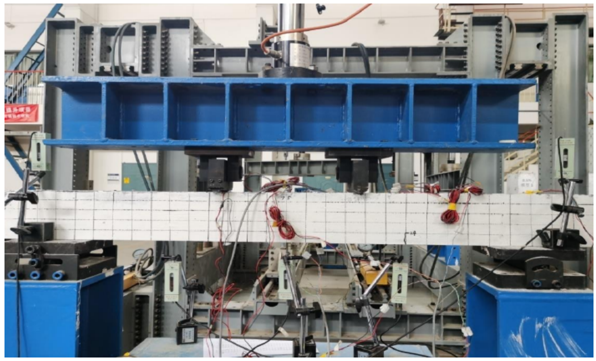
At this time, the tensile constitutive function of nanofibre UHPC is obtained, and the influence of composite nanomaterials on the tensile properties of concrete members is analysed.

4 Experiment

4.1 Experimental design

The two-point symmetrical concentrated load was used in the test, and the concentrated load was applied by manual hydraulic jack, reaction frame and load sensor. Preloading shall be carried out before loading. The formal loading method is monotonic step-by-step loading until the test carbon nanotube concrete member is damaged. At the beginning of the test loading, the load shall be controlled with an increment of 5 kn. After cracks occur, the load shall be controlled with an increment of 10 kn. After the load at all levels is applied, the reading shall be carried out when the load sensor value is no longer changed, as shown in Figure 3.

Figure 3 Loading test diagram for shear test of carbon nanotube concrete members (see online version for colours)



In this paper, the tensile effect of concrete members is analysed by three indexes, including compressive strength, tensile strength and prediction effect of tensile performance. The specific experimental indexes are designed as follows:

1 Compressive strength of concrete members with fibre content: definition: λ = Average compressive strength/average compressive strength of the control group; λ Indicates the increase of compressive strength of other groups on the basis of the 28th control group.

2 Influence of composite nanomaterials on tensile properties of concrete members: The higher the tensile strength is, the better the tensile property of the concrete member is. Conversely, the lower the tensile strength is, the worse the tensile property of the concrete member is.

3 Prediction effect of tensile properties of concrete members

The higher the prediction accuracy of the tensile properties of concrete members, the better the prediction effect of the tensile properties of concrete members; otherwise, the worse the prediction effect of the tensile properties of concrete members. The calculation formula of prediction accuracy h_{cc} of tensile properties of concrete members is:

$$h_{cc} = \frac{h_n}{h_s} \times 100\% \quad (11)$$

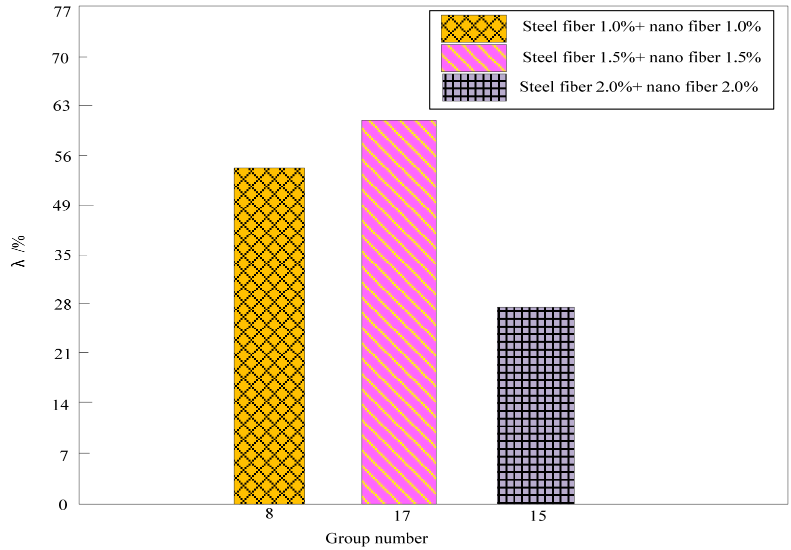
In the above formula, h_n represents the accurate prediction data of the tensile properties of concrete members, and h_s represents all the prediction data of the tensile properties of concrete members.

4.2 Experimental result

4.2.1 Effect of fibre content on compressive strength of concrete members

In order to verify the influence of different fibre content on the compressive strength of concrete members, 28 groups of concrete members with different fibre content were designed, and the λ The influence of fibre content on the compressive strength of concrete members is shown in Figure 4.

Figure 4 Effect of fibre content on compressive strength of UHPC (see online version for colours)



It can be seen from the analysis of Figure 4 that UHPC with high compressive strength can be obtained with the addition of different amounts of fibre and steel fibre; With the increase of total fibre content, the increase of UHPC compressive strength first increased and then decreased; Under the same other conditions, the compressive strength of UHPC is relatively low compared with the lower fibre content (total content 2.0%), and when the fibre content is higher (total content 4.0%). The main reasons for the above results are as follows:

1 The nanofibres have a large surface area and need more cement mortar to wrap them, that is, the workability of UHPC matrix becomes worse when the content of nanofibres increases.

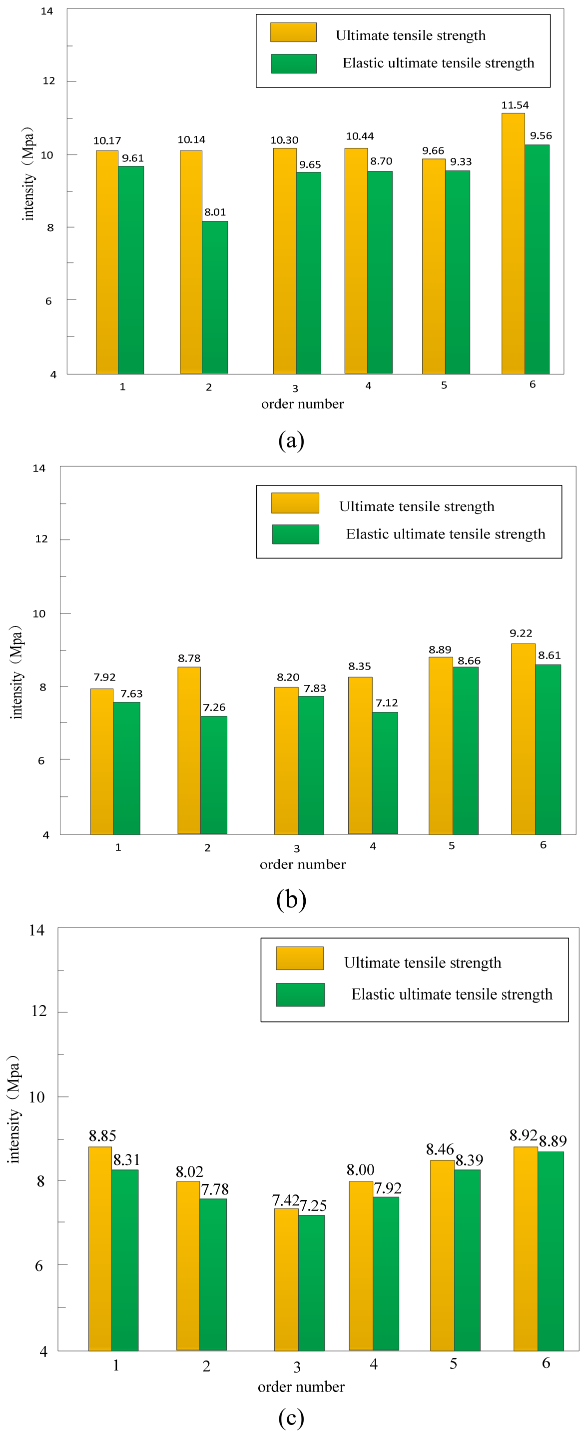
2 Steel fibre has strong bridging and interlacing effect. With the increase of steel fibre content, this interlacing effect will continue to strengthen, showing a significant ‘scaffolding’ phenomenon, reducing the fluidity of UHPC and the hydration degree of cement, and then affecting the compressive strength of UHPC.

Therefore, when two or more fibres are used in UHPC preparation, the total fibre content should not exceed 3.0%, and when a single fibre is used, the fibre content should not exceed 2.0%.

4.2.2 Effect of composite nano materials on tensile properties of concrete members

In order to verify the effect of composite nano materials on the tensile properties of concrete members, the effects of different nanofibres on the ultimate tensile strength and elastic ultimate tensile strength of concrete members under the methods of Wu et al. (2021) and Zhu et al. (2021) and this method are analysed. The results are shown in Figure 5.

Figure 5 Ultimate tensile strength and elastic ultimate tensile strength of fibre blending groups: (a) paper method; (b) Wu et al. (2021) method and (c) Zhu et al. (2021) method (see online version for colours)



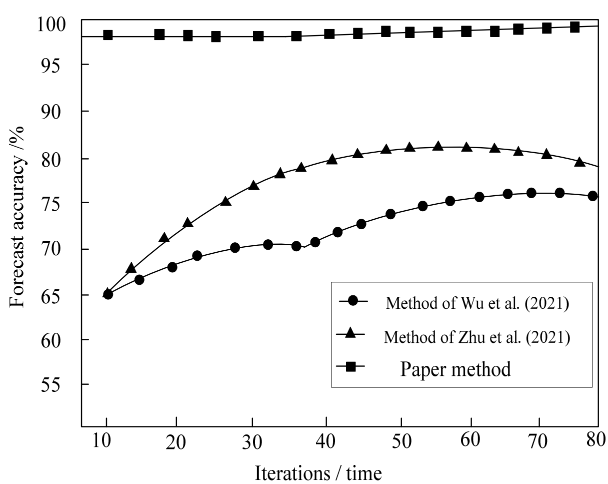
Nano composite serial numbers 1~6 represent 2 mm, 5 mm, 8 mm, 10 mm, 16 mm and 20 mm of nanofibres respectively. It can be seen from Figure 5 that when the nanofibre is 2 mm, the ultimate tensile strength of the concrete member under the method of Wu et al. (2021) is 7.92 MPa, the ultimate tensile strength of the concrete member under the method of Zhu et al. (2021) is 8.85 MPa, and the ultimate tensile strength of the concrete member under the method of this paper can reach 10.17 MPa; When the nanofibre is 20 mm, the ultimate tensile strength of concrete members under the method of Wu et al. (2021) is 9.22 MPa, the ultimate tensile strength of concrete members under the method of Zhu et al. (2021) is 8.92 MPa, and the ultimate tensile strength of concrete members under this method can reach 11.54 MPa; When the nanofibre is 2 mm, the elastic ultimate tensile strength of concrete members under the method of Wu et al. (2021) is 7.63 MPa, the elastic ultimate tensile strength of concrete members under the method of Zhu et al. (2021) is 8.31 MPa, and the elastic ultimate tensile strength of concrete members under the method of this paper is 9.61 MPa; When the nanofibre is 20 mm, the elastic ultimate tensile strength of concrete members under Wu et al. (2021) method is 8.61 MPa, the elastic ultimate tensile strength of concrete members under Zhu et al. (2021) method is 8.89 MPa, and the elastic ultimate tensile strength of concrete members under this method is 9.56 MPa;

It can be seen from the above data that adding nanofibres to concrete members can effectively improve the tensile properties and elastic ultimate tensile strength, and the method in this paper has the best effect on improving the tensile properties.

4.2.3 Prediction effect of tensile properties of concrete members

In order to verify the influence of different methods on the tensile properties of concrete members, the methods in Wu et al. (2021) and Zhu et al. (2021) and this paper are used to predict the tensile properties of concrete members. The results are shown in Figure 6.

Figure 6 Prediction effect test results



According to the analysis of Figure 6, when the number of iterations is 10, the accuracy of prediction of tensile properties of concrete members by the method of Wu et al. (2021) is 65%, the accuracy of prediction of tensile properties of concrete members by the method of Zhu et al. (2021) is 65%, and the accuracy of prediction of tensile properties of concrete members by the method of this paper is 98%; When the number of reference is 50, the accuracy of the method in Wu et al. (2021) is 74%, the accuracy of the method in Zhu et al. (2021) is 80%, and the accuracy of the method in this paper is 99%; The accuracy of this method is much higher than that of other methods, which shows that this method can effectively improve the accuracy of prediction of tensile properties of concrete members.

5 Conclusion

This paper analyses the influence of composite nano materials on the tensile properties of concrete members. Prepare concrete components containing composite nano materials, calculate the compressive strength of concrete components through the compressive mathematical function, analyse the tensile performance of concrete components according to the tensile mechanism, obtain the compressive stress-strain curve of nanofibre concrete components, construct the tensile constitutive function of nanofibre UHPC, and analyse the impact of composite nano materials on the tensile performance of concrete components. The experimental results show that:

1 When two or more fibres are used in the preparation of UHPC, the total fibre content should not exceed 3.0%, and when a single fibre is used, the fibre content should not exceed 2.0%. The surface area of nanofibres makes the workability of UHPC matrix worse when the amount of nanofibres increases. With the increase of steel fibre content, the bridging and interleaving effect of steel fibre makes concrete members exhibit a significant ‘scaffolding binding phenomenon, which reduces the fluidity of UHPC and the hydration degree of cement, thus affecting the compressive strength of UHPC.

2 When the nanofibre is 20 mm, the ultimate tensile strength of concrete members under this method can reach 11.54 MPa, and the elastic ultimate tensile strength is 9.56 MPa. Adding nanofibres to concrete members can effectively improve the tensile performance and elastic ultimate tensile strength. The tensile performance of this method can be improved best.

3 The accuracy of this method can reach 99%, which shows that this method can effectively improve the tensile performance of concrete members, and the prediction accuracy has also been significantly improved.

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