Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 13, No. 2, 2024

Finite Element Analysis of Flexural Performance of Cut Carbon Fiber Reinforced Concrete Hollow Slab

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Abstract: As a kind of light wall material installed on the surface of the main structure, hollow hanging wall board is widely used in prefabricated buildings. Ordinary concrete hollow board can no longer meet the needs of actual engineering. In order to study the influence of the length and content of carbon fiber on the bending performance of concrete hollow board, the optimal length and content of fiber in hollow board are determined. ABAQUS finite element software is used to simulate the whole process of concrete hollow slab with different fiber length and dosage, and the load displacement curve is analyzed. The results show that the bending performance of concrete slabs increases and then decreases with the increase of fiber length and content. When the fiber length is 10mm and the content is 0.24%, the bending performance of concrete hollow slabs is the strongest, and the ultimate load is increased by 27.90%, showing better deformation resistance under the same load.

Keywords: Carbon fiber, fiber reinforced concrete, external wall panels, finite element analysis.

1. Introduction

As a lightweight wall material installed on the surface of the main structure, externally hung hollow wallboard is widely used in prefabricated buildings [1], generally playing a role in strengthening and protecting the main structure and increasing the seismic performance and durability of the building. It mainly bears wind loads and earthquake loads [2]. In recent years, people have paid more and more attention to the durability and flexural rigidity of externally hung hollow wall panels [3]. Adding nano-sio2 [4,5] and fiber materials [6] to concrete is a common method to improve the flexural performance and durability of concrete. Among them, there are many types of fiber materials. Carbon fiber has more excellent strength and corrosion resistance [7]. Adding carbon fiber to concrete can effectively improve the tensile strength, flexural strength, flexural strength and durability of concrete matrix [8], and can effectively inhibit the formation of cracks in concrete and greatly improve the ductility of concrete slabs [9].

In recent years, the research on carbon fiber reinforced concrete has been extensive. Kizilkanat,AB[10] studied short-cut carbon fiber with different volume fractions to improve the mechanical properties and crack resistance of concrete, and the results showed that when the volume fraction of carbon fiber was greater than 0.5%, the strengthening effect on the crack resistance of concrete was better. Y.F.Li[11] studied the compressive and impact resistance of carbon fiber reinforced concrete. Patchen,A[12] used recycled carbon fiber to produce high-performance concrete. As a substitute for steel-fiber concrete, its mechanical properties were even better than those of steel-fiber concrete. Deng Zongcai [13] studied the fracture parameters and fatigue properties of carbon fiber reinforced concrete, and the research showed that carbon fiber reinforced concrete was superior to ordinary concrete in various mechanical properties. Hou Min and Duan Xiaofang [14,15] et al studied the compressive and anti-splitting strength of carbon fiber concrete. The results show that CFRP has strong compressive and splitting strength. In addition, there have been a lot of studies on the dispersion of carbon fiber in concrete and the use of carbon fiber braided mesh to enhance the crack resistance of concrete [16].

In this paper, the finite element method is used to simulate the bending performance of concrete hollow slabs with different carbon fiber content and length, analyze the ultimate bending capacity and mid-span deflection, study the influence of different lengths and contents of carbon fiber on the bending performance of concrete hollow slabs, and then determine the optimal length and content of carbon fiber.

2. Finite Element Simulation

2.1. Fiber-reinforced concrete hollow slab model establishment

A concrete model with a size of 1200mm×400mm×100mm was established using ABAQUS (set according to GB/T50152-2012 "Standard for Experimental Methods of Concrete Structures") and randomly distributed carbon fibers were generated in the concrete area to finally generate a carbon fiber reinforced concrete slab model. The carbon fiber content is 0.12%, 0.24%, 0.36%, 0.48%, and the carbon fiber length is 5mm, 10mm, 15mm, 20mm, respectively. According to the volume conversion of concrete slabs, the number of carbon fiber roots can be converted according to Formula 1-1, and the number of concrete specimens is shown in Table 1.

$$G = \frac{V\varphi}{\pi r^2 l} \qquad \text{Formula 1}$$

Where, V is the volume of concrete test block, φ is the volume fraction of carbon fiber, r is the radius of carbon fiber, and l is the length

Table 1. Numbers and parameters of each specimen

Specimen number	Carbon fiber length (mm)	Carbon fiber content (%)	Carbon fiber number
CF-0-0	0	0	0
CF-5-24	5	0.24	49890
CF-10-24	10	0.24	24945
CF-15-24	15	0.24	16630
CF-20-24	20	0.24	12473
CF-10-12	25	0.12	12473
CF-10-36	30	0.36	37418
CF-10-48	35	0.48	49890

Note: The concrete strength grade is C30, the yield stress of the steel wire mesh is 738.5MPa, the yield stress of the carbon fiber is 3000MPa, and the diameter of the carbon fiber is7 μm .

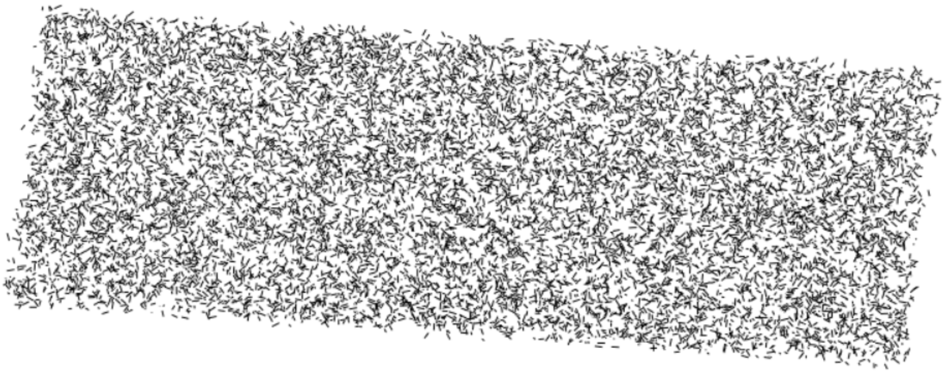


Figure 1. Random distribution of chopped carbon fibers

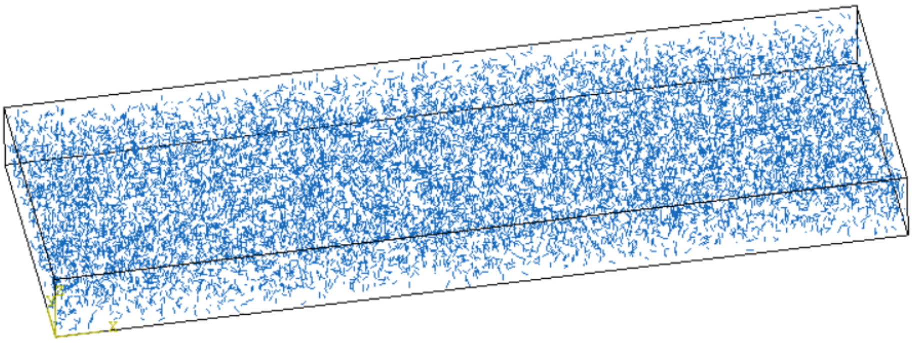


Figure 2. The carbon fiber is randomly distributed in a concrete slab

2.2. Model parameter setting

2.2.1. Model selection

This paper mainly studies the nonlinear analysis of concrete hollow slab in plane, using ABAQUS finite element software for nonlinear analysis, using Newton-raphson iterative method as a solution. This method is solved by gradually applying incremental loads and repeating the equilibrium iterative process. The details are as follows:

(1) concrete material, choose the plastic damage (ConcreteDamagedPlasticity, CDP) model. This model is a damage model based on plasticity and continuity, which describes the inelastic behavior of concrete by combining the plastic damage elasticity under isotropy with the tensile and compressive elasticity first, and is suitable for analyzing the mechanical behavior of concrete under various loading conditions.

(2) The stress state of the rebar can be assumed as the uniaxial stress state, and the model is simulated by a double-broken line model, which is expressed in the form of a double-broken line, in which two broken lines respectively represent the elastic constitutive and inelastic constitutive of the rebar, so as to distinguish the deformation of the material under different loads. Before reaching the yield point, the rebar maintains the ideal elastic behavior. Large plastic deformation occurs, the horizontal stress remains unchanged, and the steel bar is assumed to be the ideal elastic-plastic material.

The selection of the above material models can more accurately describe the mechanical behavior of concrete structures under actual loads.

2.2.2. Material structure

(1) Concrete

In actual engineering, the internal cohesion of concrete materials will be gradually reduced under the influence of loading during the actual stress process, and then all mechanical properties will decline, resulting in internal or external holes or cracks. In order to address this phenomenon in the concrete damage model, scholars proposed the use of damage factors to express this phenomenon. In the Code for Design of Concrete Structures GB50010-2010 (2015 edition), Appendix C gives the damage evolution parameters of concrete below C80, the evolution parameters of concrete compression damage are shown in the following equations 1-2, 1-3, 1-4, 1-5, and the evolution parameters of tensile damage are shown in the following equations 1-6, 1-7,1-8.

$$d_c = \begin{cases} 1-\dfrac{\rho_c n}{n-1+x^n}(x \le 1) \\ 1-\dfrac{\rho_c}{\alpha_c(x-1)^2+x}(x>1) \end{cases} \quad \text{Formula 2}$$

$$\rho_c = \frac{f_{c,r}}{E_C \varepsilon_{c,r}} \quad \text{Formula 3}$$

$$n = \frac{E_c \varepsilon_{c,r}}{E_c \varepsilon_{c,r} - f_{c,r}} \quad \text{Formula 4}$$

$$x = \frac{\varepsilon}{\varepsilon_{c,r}} \quad \text{Formula 5}$$

Formula: $f_{c,r}$ is the representative value of uniaxial compressive strength of concrete; $\varepsilon_{c,r}$ is the peak compressive strain corresponding to the uniaxial compressive strength;

d_c is the evolution parameter of concrete uniaxial compression damage; α_c are the parameters of the descending section of the stress-strain curve of concrete under uniaxial compression, as shown in Table 1-2 below:

Table 2. C20-C60 Parameter Values of concrete uniaxial compression

$f_{c,r}$ （N/mm2）	20	25	30	35	40	45	50	55	60
$\varepsilon_{c,r}$ （10-5）	147	156	164	172	179	185	192	198	203
α_c	0.74	1.06	1.36	1.65	1.94	2.21	2.48	2.74	3.00
$\varepsilon_{cu} / \varepsilon_{c,r}$	3.0	2.6	2.3	2.1	2.0	1.9	1.9	1.8	1.8

In the table: ε_{cu} is the compressive strain of concrete when the stress in the descending section of the stress-strain curve is equal to $0.5 f_{c,r}$.

$$d_t = \begin{cases} 1-\rho_t\left[1.2-0.2x^5\right](x \le 1) \\ 1-\dfrac{\rho_t}{\alpha_t(x-1)^{1.7}+x}(x>1) \end{cases} \quad \text{Formula 6}$$

$$x = \frac{\varepsilon}{\varepsilon_{t,r}} \quad \text{Formula 7}$$

$$\rho_t = \frac{f_{t,r}}{E_c \varepsilon_{t,r}} \quad \text{Formula 8}$$

Where, $f_{t,r}$ is the representative value of uniaxial tensile strength of concrete; $\varepsilon_{t,r}$ is the peak compressive strain corresponding to the uniaxial tensile strength; d_t is the evolution parameter of concrete uniaxial tensile damage; α_t are the parameters of the descending section of the uniaxial tensile stress-strain curve of concrete, as shown in Table 1-3 below

Table 3. Parameter values of concrete uniaxial tensile stress-strain curve

$f_{t,r}(N/mm^2)$	1.0	1.5	2.0	2.5	3.0	3.5	4.0
$\varepsilon_{t,r}(10^{-6})$	65	81	95	107	118	128	137
α_t	0.31	0.70	1.25	1.95	2.81	3.82	5.00

The calculation formulas of damage factors and damage evolution parameters are shown in Equation 1-9:

$$d = 1-\sqrt{1-D} \quad \text{Formula 9}$$

Generally speaking, when the cumulative amount of plastic damage of concrete reaches 0.9, the material is considered to have reached the failure state. Therefore, in this model, the damage factor d value of concrete is set to about 0.9, and the corresponding inelastic strain value is also matched with it. The specific attribute damage parameters of concrete are shown in Table 1-4:

Table 4. Plastic damage parameters of concrete

φ	e	σ_{b0}/σ_{c0}	K_c	v	w_c	w_t
30°	0.1	1.16	0.667	0.001	1	0

(2) Steel reinforcement

In this model, steel wire mesh is used as the stressed steel bar of concrete hollow slab. In order to describe this behavior of steel bars more accurately and facilitate calculation, the double-fold line model suggested in the specification is adopted in this paper. The specific expression is shown in Formula 1-10, and the constitutive relationship of the fold line is shown in Figure 1-1.

$$\sigma_s = \begin{cases} E_s \varepsilon_s & 0 \le \varepsilon_s \le \varepsilon_y \\ f_{y,r} & \varepsilon_y < \varepsilon_s < \varepsilon_u \end{cases} \quad \text{Formula 10}$$

Formula, σ_s is reinforcement stress; E_s is the elastic modulus of reinforcement; ε_s is reinforcement strain; ε_y is the yield strain of the steel bar; $f_{y,r}$ represents the yield strength of the steel bar.

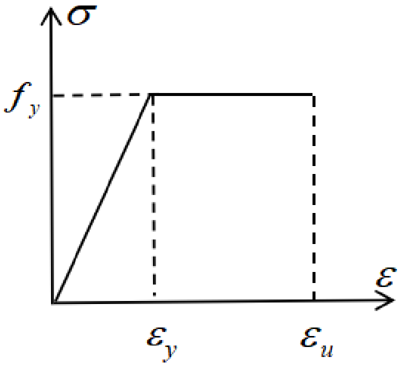
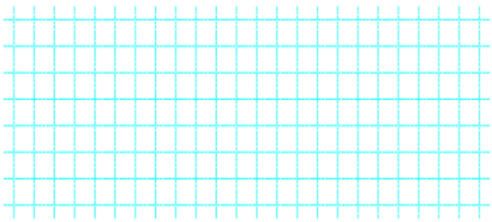


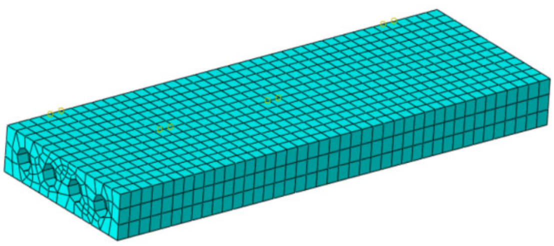
Figure 3. Double line constitutive relationship diagram of steel reinforcement

2.3. Grid division and calculation

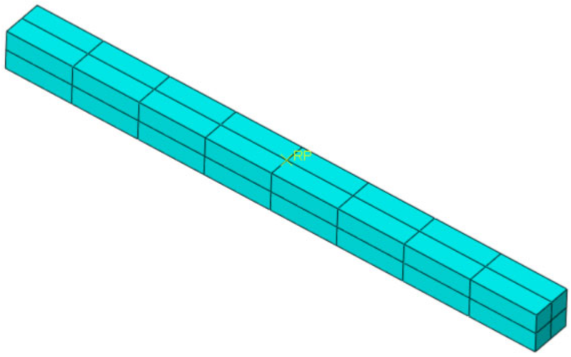
In this model, a three-dimensional octagonal linear hexahedron element (C3D8R) is used to simulate concrete and rigid loading pad and support. The concrete unit size is 30mm×30mm×30mm regular hexahedron first-order solid element, and the rigid loading pad and support unit size is 50mm×25mm×25mm. A two-node linear three-dimensional truss element (T3D2) was used to simulate the wire mesh and cut carbon fiber, and the length of the wire mesh element was 10mm. According to the fiber length, each carbon fiber acts as a unit, and each unit has two nodes. The final finite element model and mesh division are shown in Figure 4 below.



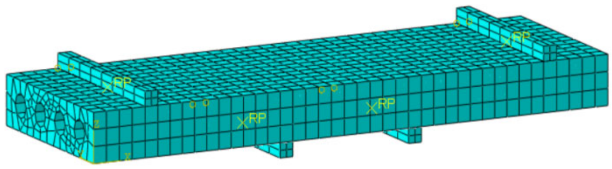
(a) Wire mesh division



(b) Meshing of hollow concrete slabs



(c) Grid division of rigid loading pad and support



(d) Overall meshing

3. Simulation Results of Bending Strength and Analysis

3.1. Effect of fiber content on ultimate bearing capacity and deflection enhancement of concrete hollow slab

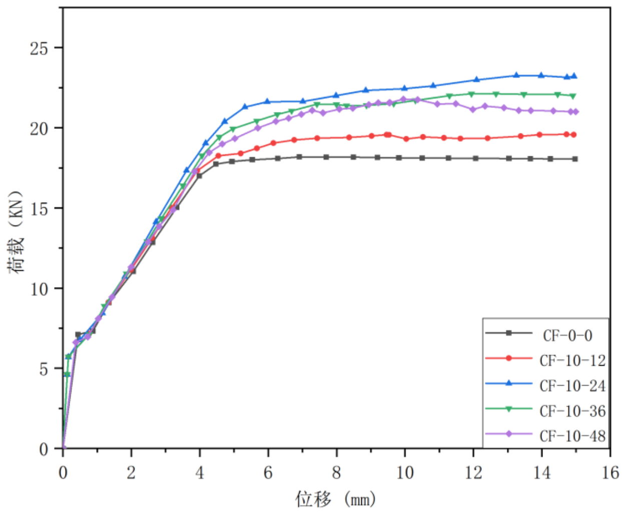


Figure 4. Load-displacement curve of concrete slab with different fiber content

It can be seen from Figure 2-1 that the short-cut carbon fiber has a great enhancement effect on the ultimate bending capacity of concrete. Meanwhile, the short-cut carbon fiber with different content (0.12%, 0.24%, 0.36%, 0.48%) has different enhancement effect on the concrete slab. The detailed comparison data of the ultimate bearing capacity are shown in Table 5.

Table 5. Ultimate bearing capacity of concrete slabs with different fiber content

Component number	CF-0-0	CF-10-12	CF-10-24	CF-10-36	CF-10-48
Ultimate bearing capacity (KN)	18.183	19.574	23.256	22.126	21.792
Enhancement effect	0	7.65%	27.90%	21.69%	19.85%

It can be seen from Table 2-1 that with the increase of fiber content in the case of the same fiber length, the ultimate bending capacity of the concrete slab increases first and then decreases. Among them, the 0.24% cut carbon fiber content has a more obvious effect on the bending strength reduction of the concrete slab, and the ultimate bending capacity of the concrete slab increases by 27.9% compared with the concrete slab without carbon fiber. It can be seen from Figure 2-1 that under the same load, the deflection of the short-cut carbon fiber concrete slab with 0.24% content is the smallest.

3.2. Influence of fiber length on ultimate bearing capacity and deflection of concrete hollow slab

It is known that different fiber content has different effects on the flexural performance of concrete hollow slabs, and 0.24% cut carbon fiber has the largest effect on the flexural performance of concrete hollow slabs. The effects of different lengths of chopped carbon fiber (5mm, 10mm, 15mm, 20mm) on the ultimate flexural capacity of concrete hollow slabs were studied with 0.24% chopped carbon fiber as the object. It can be seen from Figure 2-2 that under the same concrete content, different fiber lengths have different strengthening effects on the ultimate flexural capacity of concrete slabs. The detailed comparison of ultimate bearing capacity is shown in Table 6.

Table 6. Ultimate bearing capacity of concrete slabs with different fiber lengths

Component number	CF-0-0	CF-5-24	CF-10-24	CF-15-24	CF-20-24
Ultimate bearing capacity (KN)	18.183	21.453	23.256	22.460	21.254
Enhancement effect	0	17.98%	27.90%	23.52%	16.89%

According to Table 3-2, under the same carbon fiber content, different fiber lengths have different reinforcement effects on concrete slabs, With the increase of fiber length, the ultimate bearing capacity of concrete slabs first increases and then decreases. Among them, 10mm carbon fiber has the most obvious effect on the ultimate bending capacity of concrete slabs, which increases by 27.9% compared with the ultimate bending capacity without carbon fiber. Meanwhile, it can be seen from Figure 2-2 that the mid-span deflection of 10mm short-cut carbon fiber concrete slab is the smallest.

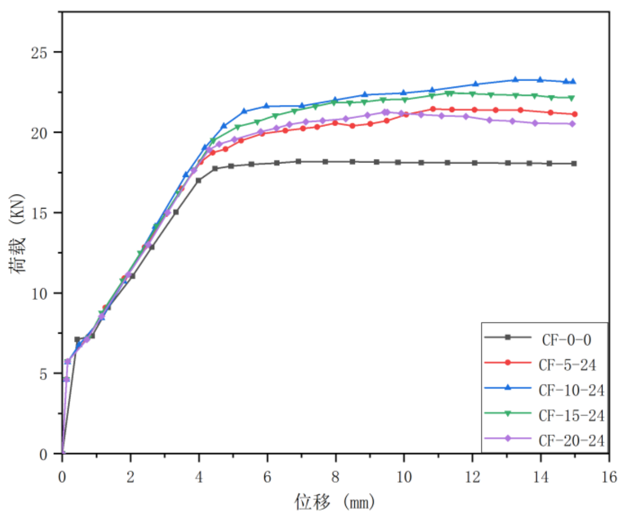


Figure 5. Different load displacement curves of concrete slabs with different fiber contents

3.3. Cause Analysis

(1) Generally, after 24 hours of concrete pouring, the concrete matrix rapidly loses water, resulting in plastic shrinkage of the concrete matrix, resulting in a large number of cracks. The addition of short-cut carbon fiber can effectively resist the tensile stress caused by plastic shrinkage of concrete. At the same time, the short-cut carbon fiber is small in weight and light in volume, and is disorganized in the concrete slab. Not only the friction resistance between itself and the concrete matrix is closely connected between the aggregate and the aggregate, but also because of its small volume, it can fill the pores generated in the concrete matrix, so that the aggregate is more dense, thus improving the ultimate bearing capacity of concrete.

(2) After adding short-cut carbon fiber into the concrete hollow slab, when the concrete slab is subjected to external load, the initial defects inside the slab will slowly expand into cracks. When the cracks are large, the carbon fiber will build a bridge between the cracks to effectively transfer part of the tensile stress through the action of fiber. Due to the good tensile properties of carbon fiber, the concrete cracks will be expanded under the action of external forces. It is necessary to overcome the bonding force between the concrete matrix and carbon fiber, improve the deformation ability of concrete, and reduce the deflection of concrete slab.

(3) Excessive volume of carbon fiber will lead to poor concrete fluidity and fiber concentration, which will affect the enhancement effect of carbon fiber on concrete performance. Excessive length of carbon fiber may reduce the dispersion of fiber and increase the bending degree of fiber in concrete, resulting in the phenomenon of fiber knotting and clumping. As a result, the performance enhancement effect of fiber on concrete decreases.

4. Conclusions

(1) Short-cut carbon fiber can effectively improve the flexural performance of concrete. With the increase of fiber content and length, the ultimate flexural capacity of fiber reinforced concrete slab increases first and then decreases;

(2) When the volume fraction of carbon fiber is 0.24%, the

ultimate flexural capacity of the fiber reinforced concrete slab increases the most, which is about 27.9% higher than that of the concrete slab without carbon fiber;

(3) In the case of the same volume fraction, the carbon fiber with a length of 10mm has the most obvious strengthening effect on the concrete slab;

(4) The addition of carbon fiber can also effectively improve the deformation resistance of concrete slabs. Under the same load, fiber-reinforced concrete slabs exhibit smaller mid span deflection compared to concrete slabs without fibers. Among them, carbon fiber with a fiber length of 10mm and a volume fraction of 0.24% has the most significant strengthening effect on concrete slabs.

References

[1] X-G Wu, Zhang X-S, Tao X-K, et al. Mechanical behavior test and analysis of HEH sandwich external wall panel[J]. ADVANCES IN CONCRETE CONSTRUCTION, 2022, 13(2): 153-162.

[2] Y-H Xie, Zhou T, Chen Z-H, et al. Wind load resistance of prefabricated ALC-rock wool external wall panel system[J]. JOURNAL OF BUILDING ENGINEERING, 2024, 92.

[3] T-P Sah, Lacey A-W, Hao H, et al. Prefabricated concrete sandwich and other lightweight wall panels for sustainable building construction: State-of-the-art review[J]. JOURNAL OF BUILDING ENGINEERING, 2024, 89.

[4] M-J Mei, Wu L-S, Wan C-C, et al. Mechanical properties of nano SiO2 and fiber-reinforced concrete with steel fiber and high performance polypropylene fiber[J]. MATERIALS RESEARCH EXPRESS, 2021, 8(10).

[5] P Zhang, Zhao Y-N, Li Q-F, et al. Mechanical properties of fly ash concrete composite reinforced with nano-SiO2 and steel fibre[J]. CURRENT SCIENCE, 2014, 106(11): 1529-1537.

[6] J-L Liu, Jia Y-M, Wang J. Experimental Study on Mechanical and Durability Properties of Glass and Polypropylene Fiber Reinforced Concrete[J]. FIBERS AND POLYMERS, 2019, 20(9): 1900-1908.

[7] Gu Juan, Jiang Jingshan, Lu Chenxian, et al. Research review of fiber reinforced concrete [J]. Science and Technology Innovation and Productivity,2022,(11):26-29.

[8] Xin Ming, WANG Xue-Zhi, TONG Huan. Review of research on durability of fiber reinforced concrete [J]. Journal of Liaoning University of Technology (Natural Science Edition), 20,40(01):35-39.

[9] Chen Lihong, Meng Hongrui, Hui Yali. Application of carbon fiber in concrete [J]. Concrete,2006,(04):29-31.

[10] A-B Kizilkanat. Experimental Evaluation of Mechanical Properties and Fracture Behavior of Carbon Fiber Reinforced High Strength Concrete[J]. PERIODICA POLYTECHNICA-CIVIL ENGINEERING, 2016, 60(2): 289-296.

[11] Yeou-Fong Li, Lee Kun-Fang, Ramanathan Gobinathan-Kadagathur, et al. Static and dynamic performances of chopped carbon-fiber-reinforced mortar and concrete incorporated with disparate lengths[J]. Materials, 2021, 14(4): 972.

[12] A Patchen, Young S, Penumadu D. An Investigation of Mechanical Properties of Recycled Carbon Fiber Reinforced Ultra-High-Performance Concrete[J]. MATERIALS, 2023, 16(1).

[13] Deng Zongcai, Xue Huiqing. Bending toughness of hybrid fiber reinforced ultra-high performance concrete [J]. Journal of Harbin Engineering University,2023,44(8):1288-1294. (in Chinese)

[14] Hou Min, Tao Yan, Tao Zhong, et al. Basic Mechanical properties and analysis of short-cut carbon fiber concrete [J]. Concrete,2020,(1):74-77.

[15] Duan Xiaofang, Yuan Jiaojiao. Study on Mechanical properties of carbon fiber reinforced concrete [J]. Journal of Jiangsu Polytechnic of Architecture,2022,22(3):8-12.

[16] Liu Cao-Rui, Shi Jian-Jun, Wei Wang-Cheng, et al. Evaluation and optimization of dispersion properties of chopped carbon fiber in concrete [J]. Polymer Materials Science and Engineering, 2023, 39(07): 103-112. (in Chinese)