

Flexural Properties of Coconut Fiber Hybrid Multi-walled Carbon Nanotube Reinforced Foam Concrete

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Received: 26 March 2026, Accepted: 17 September 2026, Published online: 05 October 2026

Abstract

In this study, the enhancement mechanism of flexural properties of foamed concrete was systematically discussed by using a hybrid system of multi-walled carbon nanotube (MWCNT) and coconut fiber. The study is divided in two parts. Firstly, the effect of MWCNT content and foaming method on the flexural strength of foamed concrete was studied. It was found that using a physical foaming process, the addition of MWCNT content in the range of 0.08 wt.% to 0.17 wt.% better improved the flexural strength compared to chemical foaming. But both methods reach their maximum strength at 0.2 wt.% with improvements around 110–119% compared with the reference group (without reinforcements). Secondly, the load-deflection curve characteristics of foamed concrete reinforced with fixed coconut fiber content and various MWCNT dosages were analyzed. By using a piecewise model for the load-deflection curve, it was found that the experimental data were well predicted ($R^2 > 0.98$), especially when the reinforcement content is 0.2 wt.%. In addition, the strengths of the foam concrete prepared in this study are higher than for similar studies in the literature. In summary, MWCNT-coconut fiber composite system can effectively improve the flexural properties of foamed concrete, providing a strong basis for the high-performance design of lightweight and sustainable building materials.

Keywords

foam concrete, multi-walled carbon nanotube, coconut fiber, flexural strength, load deflection curve

1 Introduction

Over the past thirty years, the continuous progress of materials science led to the development of cement-based concrete materials, especially foam concrete, which is a special cement-based porous material. These materials attracted more and more attention due to their unique properties (low weight, high specific stiffness) and wide application potential. The final parts density is mainly controlled by the amount of foaming agent and the mortar [1]. Both components provide flexibility and significant advantages in a variety of architectural and engineering applications, especially due to better fluidity, self-compaction and self-sustained properties, as well as good thermal and sound insulation properties. This is why they became a hot topic for current research and development in the field of architecture.

However, with the rapid development of modern architecture and engineering technology, the requirements for building materials are becoming more and more strict, especially for applications requiring high strength, excellent durability and excellent environmental adaptability [2]. Traditional cement concrete materials have inherent limitations, such as low flexural strength and susceptibility to erosion and damage in humid environments. Compared with compressive strength, flexural strength is very low [3, 4], making it difficult to meet the high requirements of specific projects for material strength and toughness [5, 6]. Therefore, improving the performance of materials has become one of the most important directions of current building materials research.

In order to improve the strength of concrete materials without losing properties, the most widely used method is to add short fibers with specific properties and contents, which can be randomly distributed in the cement matrix as reinforcing materials. The research on the performance of single fiber reinforced concrete materials is well-known, especially for fibers based on polypropylene [7], polyvinyl alcohol [8], basalt [9], banana [10], sisal [11], jute [12], fiber [13] and coconut [14]. However, when a single fiber type, limited improvement in concrete performances is observed [15, 16]. This is because although these fibers can effectively deflect/stop crack propagation, it is difficult to significantly modify or improve the fracture process (crack propagation) at a larger scale, thus limiting the overall performance of standard composite.

To improve on composites properties, the concept of hybrid system was proposed where a combination of two or more different fibers are used together to generate synergistic effects. Over the years, several fibers were mixed together to determine the optimum formulation depending of the final property investigated. For example, Quan et al. [17] reported on the evolution of flexural toughness by combining bamboo and basalt fibers. Li et al. [18] studied the effect of straight fiber, hook-end fiber and corrugated fiber-like steel fiber mixed with polypropylene fiber on the properties of concrete. It was found that hook-end steel fiber showed the best bending performance, while the straight steel fiber and polypropylene fiber showed the best synergistic effect. Dawood et al. [19] found that the synergistic effect of glass fiber and polypropylene fiber significantly improved the flexural toughness of the matrix. Jin et al. [20] added basalt fiber and coconut shell fiber to improve the strength, durability and environmental protection of the material. With more in depth research on mixed fiber systems, significant progresses have been made on composite grids and fiber-reinforced grids as reinforcement methods [21, 22]. These studies showed that the reinforcement methods based on combining fibers and two-way grids had the highest potential in improving the material properties.

Although the research on hybrid reinforcement has been quite extensive, there are relatively few studies on the application of reinforcements with different dimensions and properties - especially nano-scale MWCNT and macro-scale natural fibers (such as coconut shell fibers) in foamed concrete. Although limited, the information available mainly focusses on compressive and tensile strength, but less on flexural strength. In this study, carbon nanotubes

and coconut shell fibers were mixed together to improve the performance of foamed concrete. A focus is made on the potential unique synergistic effect between both fibers: on the one hand, a natural/biobased fiber (coconut) has advantages such as low density, good specific mechanical properties and strong renewability. It also has excellent tensile toughness to improve the toughness of concrete [23]. On the other hand, carbon nanotubes play a different role by improving the microstructure of concrete and giving it special properties the fillers [24], nucleation [25] and micro-crack bridging [26] of carbon nanotube can effectively connect and enhance the particles or pores in the concrete matrix, therefore preventing the formation and expansion propagation of micro-cracks [27]. The micro-pores and defects in the foam concrete filled with carbon nanotube have a direct effect of the porosity of the concrete leading to different compaction of the material [28]. MWCNT addition can also promote the uniform distribution and stable existence of bubbles (nucleating agent effect) [29], as well as improving the overall strength and durability of the material (reinforcement) [30].

Therefore, the hybrid system (carbon-coconut) is expected to generate synergy at multiple macro-micro scales to overcome the limitations of using a single fiber, thereby more effectively improving the key mechanical properties of foamed concrete, especially flexural properties. The purpose of this study is to quantify the effect and explain the mechanism of this hybrid enhancement strategy on the flexural strength of foamed concrete. Furthermore, different foaming methods (chemical and physical) and used to determine the effect of MWCNT contents on the load-deflection curves of foam concrete. For prediction, a piecewise function for the load-deflection curves is proposed, and the mechanical behavior of foam concrete under different stress stages is accurately described and quantified to evaluate the mechanical properties of the specimens. All the information is used to provide a theoretical basis and guidelines to optimize the formulation and production of improved foam concrete.

2 Materials and methods

2.1 Materials

Conch brand PO42.5 ordinary Portland cement was selected. In order to improve the fluidity of concrete mixture and the bubble structure inside the foam concrete, a polycarboxylate superplasticizer produced by Hongxiang Construction Admixture Company in Laiyang City, Shandong (China) was added.

In order to stabilize the bubbles nucleated and improve bubble stability and cementitious slurry during concrete foaming, a calcium stearate foam stabilizer produced by Hebei Baiyilian Chemical Co., Ltd. (China) was selected with a density of 1.08 g/cm³. The addition of a surfactant is also beneficial to improve the MWCNT dispersion and produce a stable suspension. The surfactant selected is polyvinylpyrrolidone produced by Xilong Science Co., Ltd. (China) with a density of 1.144 g/cm³ and of analytical purity (AR). In this experiment, the Physical foaming agent produced by Henan Yipeng Chemical Co., Ltd. was selected. The solid content was 50 ± 2% and the PH value was 6–7. The chemical foaming agent selected is H₂O₂ produced by Henan Huize Bioengineering Co., Ltd.

The small particle size and large specific surface area of silica fume enable it to actively participate in the secondary hydration reaction of cement to enhance the bonding force of the material. At the same time, the silica fume particles that are not directly involved in the reaction effectively fill the small gap between the cement paste and sand particles. This filling effect can further improve the overall strength of cement-based composites. The silica fume produced by Longze Water Purification Material Co., Ltd., Gongyi City, Henan (China), with a specific surface area above 15 m²/g was used. In order to ensure that the coconut fiber can be uniformly and fully dispersed in the foam concrete, limiting agglomeration and keep the coconut fiber length [31, 32], the initial length selected was 20 mm. The basic properties of coconut fiber, H₂O₂ and MWCNT are reported in Table 1. Coconut fiber was purchased from Jiangxi Jiagaocheng Import and Export Trade Co., Ltd., and carbon nanotubes were MWCNT produced by Hangzhou Kangji New Material Co., Ltd., Zhejiang Province. At the same time, 0.5% NaOH was used for coconut fiber alkaline treatment, to effectively remove the surface impurities, making the fiber surface

more rough and highly improving the fiber-matrix interfacial adhesion, and more effectively improve the overall performance of the foam concrete.

2.2 Specimen preparation

The focus of this work is to study the effect of fiber hybridization on the flexural properties of foam concrete. The experimental plan was established according to the Chinese standard foam concrete application technical specification (JGJ-T341-2014) [33]. The preparation of the test block is shown in Fig. 1. The test is divided in two parts. In the first part, a discussion on the effect of MWCNT on the flexural strength under different foaming methods is provided. The water-cement ratio was fixed at 0.4, and a standard size of 40 mm × 40 mm × 160 mm was adopted. Six MWCNT contents (0, 0.05, 0.1, 0.15, 0.2, 0.3 wt.% of cement) were used and all the formulations are presented in Table 2. Specimen grouping and naming was carried out according to the type of foaming (physical or chemical) and MWCNT content. Physical foaming was coded as W, while chemical foaming is coded as H. For example, W-C0 represents a foamed concrete prepared by physical foaming with without (0%) MWCNT.

In the second part, the effect of MWCNT and coconut fiber on the flexural properties of foamed concrete was studied. Non-standard specimens of 100 mm × 100 mm × 400 mm were prepared for flexural test. The volume content of coconut fiber was fixed at 0.4% [14], the MWCNT contents investigated and codes are the same as in the first part (Table 2). For example, C0-XW0.4 indicates that the MWCNT content is 0 %, so only coconut fiber is present (0.4%). All mix proportions are given in kg per cubic meter of hardened foamed concrete; air voids from foam occupy volume but have negligible mass, so the sum of solid components does not reach 1000 kg/m³. All the formulations are presented in Table 3.

Table 1 Properties of the fibers used in this study

Coconut fiber					
Diameter (mm)	Density (g/cm ³)	Water content (%)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation at break (%)
0.15–0.35	1.2	10~12	128–157	3.86–5.60	21.2–40.3
MWCNT					
Diameter (nm)	Length (mm)	Purity (%)	Specific surface area (m ² /g)		
0–10	5–30	>97	20–270		
H ₂ O ₂					
Colour	State	Concentration (%)	Degree of stability (%)		
colourless	fluid	35.6%	98.5%		

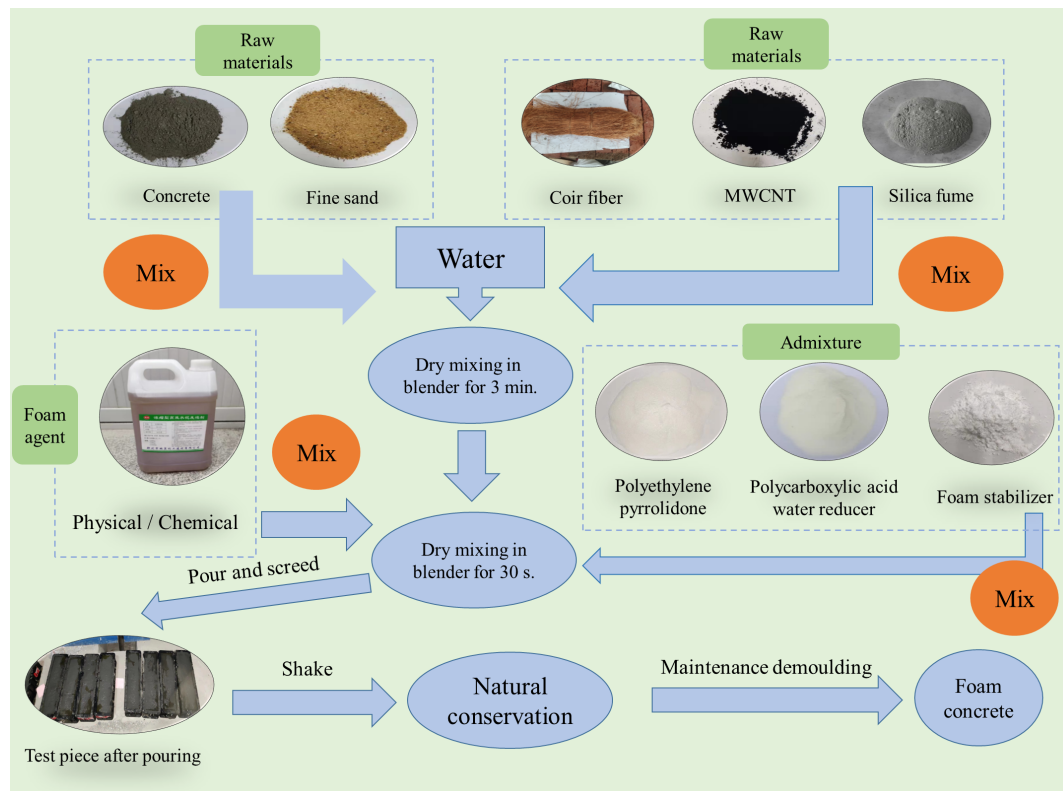


Fig. 1 Specimen preparation steps

Table 2 Formulations of foamed concrete with different MWCNT contents and foaming methods (first part)

Code	Cement (g)	Silica fume (g)	Fine sand (g)	H ₂ O ₂ (g)	Water reducing agent (g)	Foam stabilizer (g)	Water (g)	Physical foaming foam content (g)	MWCNT (g)
W-C0	1000	100	1200	–	3	0.9	400	0.0	0.0
W-C0.05	1000	100	1200	–	3	0.9	400	1.2	0.5
W-C0.1	1000	100	1200	–	3	0.9	400	2.4	1.0
W-C0.15	1000	100	1200	–	3	0.9	400	3.6	1.5
W-C0.2	1000	100	1200	–	3	0.9	400	4.8	2.0
W-C0.3	1000	100	1200	–	3	0.9	400	6.0	3.0
H- C0	1000	100	1200	60	3	0.9	400	–	0.0
H- C0.05	1000	100	1200	60	3	0.9	400	–	0.5
H- C0.1	1000	100	1200	60	3	0.9	400	–	1.0
H- C0.15	1000	100	1200	60	3	0.9	400	–	1.5
H- C0.2	1000	100	1200	60	3	0.9	400	–	2.0
H- C0.3	1000	100	1200	60	3	0.9	400	–	3.0

Note: Mix proportions in Table 2 are given by mass, based on 1000 g of cement.

Table 3 Formulations of foamed concrete with fixed coconut fiber content and different MWCNT contents (second part).

Code	Cement (kg)	Silica fume (kg)	Fine sand (kg)	H ₂ O ₂ (kg)	Water reducing agent (kg)	Foam stabilizer (kg)	Water (kg)	Fiber (kg)	MWCNT (g)
C0-XW0.4	450	45	540	5	1.575	0.9	202.5	1.2	0.000
C0.05-XW0.4	450	45	540	5	1.575	0.9	202.5	1.2	225.0
C0.1-XW0.4	450	45	540	5	1.575	0.9	202.5	1.2	450.0
C0.15-XW0.4	450	45	540	5	1.575	0.9	202.5	1.2	675.0
C0.2-XW0.4	450	45	540	5	1.575	0.9	202.5	1.2	900.0
C0.3-XW0.4	450	45	540	5	1.575	0.9	202.5	1.2	1350

2.3 Characterizations

2.3.1 Flexural strength test

After the specimens reach the test age of 28 days under the specified curing conditions, the three-point bending flexural strength of these test specimens is tested. The test was carried out on a testing machine produced by Shaoxing Kent Machinery and Electronics Co., Ltd., model YAW-300. In this experiment, the flexural strength of 40 mm × 40 mm × 160 mm prism blocks was evaluated, and three samples were prepared in each group to evaluate the influence of carbon nanotubes on the flexural strength of foamed concrete under different foaming methods.

2.3.2 Four-point flexural strength test

We use four-point bending strength test to evaluate the mechanical properties of materials. This test adopts four-point loading method, and the span of two bearings is three times the height of the test beam, that is, 300 mm. The test was carried out by the electronic universal testing machine of MTS Meister Industrial System (China) Co., Ltd., and the maximum load was 300kN. The loading rate of this experiment is controlled by displacement, and the loading rate is set to 0.05mm/min. In the experiment, standard trabecular specimens with the size of 100mm × 100mm × 400mm were selected, and each group contained four specimens to ensure the reliability of the results. In order to optimize the test conditions and reduce the interference of external factors, a new loading frame is specially designed and applied in this test, as shown in Fig. 2. The frame is tightly fixed on the specimen by bolts, which effectively eliminates the possible deformation and torsion of the bearing during loading, thus ensuring the accuracy of the test results.

3 Results and discussion

3.1 Effect of MWCNT

Due to its high strength and high modulus, combined with excellent electrical and thermal conductivity, MWCNT can effectively enhance the mechanical strength, durability, and electrical conductivity of foam concrete. MWCNT can form a strong network, therefore preventing crack propagation and

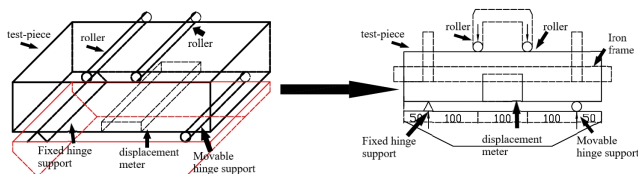


Fig. 2 Four-point flexural test diagram in a three-dimensional space diagram and in a plane graph

improving compressive strength. At the same time, its nano-sized effect can improve the microstructure of concrete and enhance its compaction and uniformity [26, 34, 35]. In this first part, coconut fiber was not added, and the flexural properties of foamed concrete under different foaming methods were only discussed after adding MWCNT.

Table 4 and Fig. 3 show the strength improvement rate and flexural strength during various foaming techniques with MWCNT addition. It is possible to see minor variations in the flexural strength of the specimens made using various foaming techniques by comparing them in Fig. 3 and Table 4. Specifically, concrete foamed by chemical foaming has a marginally higher flexural strength than concrete foamed by physical foaming. The maximum flexural strength of specimens made using the chemical foaming method is 3.79 MPa, whereas the maximum flexural strength of specimens made using the physical foaming method is 3.60 MPa. The primary cause of this phenomenon is the distinction in foaming mechanism: physical foaming involves the foaming system maintaining a high level of stability, which in turn prompts the formation of a greater number of more uniform bubbles (closed cells) [36]. Consequently, the overall density decreases. In contrast, chemical foaming causes a wide range of bubble sizes due to the uneven foaming rate in different areas of the slurry. This process results in a structure with interconnected bubbles (open cells), which diminishes the flexural strength and affects the foam uniformity to a certain extent.

However, if the content of MWCNT exceeds a certain critical point, it will result in a decrease in the flexural strength of concrete. Fig. 3 and Table 4 demonstrate that the flexural strength of foamed concrete is a substantial characteristic, irrespective of the foaming method employed. The reason for this phenomenon is that MWCNT is susceptible to agglomeration at high content, which leads to a reduction in strength.

Table 4 Flexural strength and strength improvement rate under different foaming methods

Code	Flexural strength		Strength increase rate	
	Physical foam (MPa)	Chemical foam (MPa)	Physical foam (%)	Chemical foam (%)
MWCNT-0.00 wt.%	1.71	1.73	00.00	00.00
MWCNT-0.05 wt.%	1.97	2.13	15.20	23.12
MWCNT-0.10 wt.%	2.25	2.57	31.58	48.55
MWCNT-0.15 wt.%	3.04	2.95	77.78	70.52
MWCNT-0.20 wt.%	3.60	3.79	110.5	119.1
MWCNT-0.30 wt.%	3.16	3.44	84.80	98.84

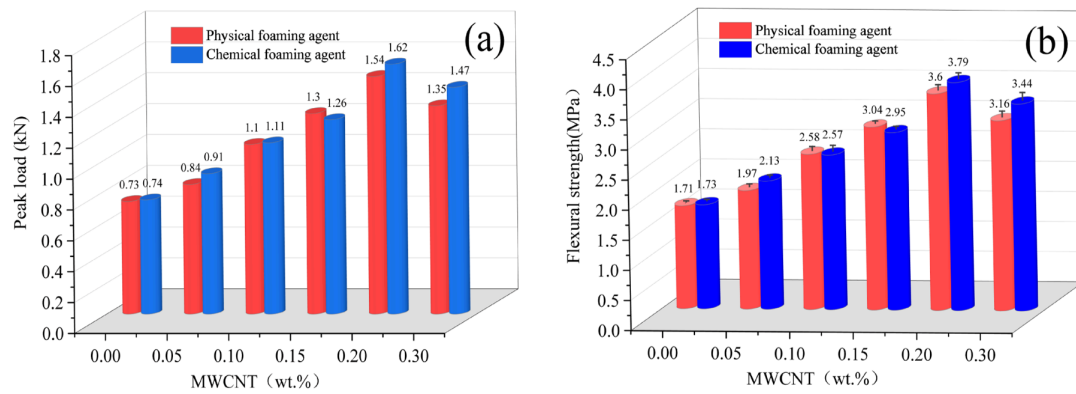


Fig. 3 Strength of foamed concrete with different foaming methods: (a) peak load, (b) flexural strength

3.2 Hybridization effect of coconut fiber and MWCNT

The hybrid effect of coconut fiber and MWCNT can have a significant effect on foamed concrete. Coconut fiber contributes to the advancement of environmentally friendly and sustainable building materials by acting as a natural reinforcing material that improves the biodegradability and durability of concrete. The synergistic effect is substantial following hybridization, which not only enhances the microstructure of the concrete, but also enhances its overall performance, including increased compressive strength and improved crack resistance. In this part, the effect of combining coconut fiber and MWCNT on the performance of foam concrete was discussed.

In Fig. 4, the load-deflection curve of foamed concrete with varying MWCNT contents is illustrated for the hybrid system. It demonstrates that the peak loads of various curves

are similar, but they are distinct. These curves show roughly linear growth prior to reaching the peak load, and then a gradual decrease in load to roughly 50% of its initial value following the peak load. The displacement increases continuously and the rate of decline is relatively slow during this process. However, the area that the curve encloses under various content varies significantly. The area below the curve for the foam concrete increases with increasing MWCNT content as the abscissa directly controls the energy absorbed by the specimen up to failure. The greater this area, the more energy the specimen absorbs under loading, indicating the material's toughness—that is, its ability to withstand deformation and absorb impact energy more efficiently before breaking. This demonstrates that the mechanical qualities of foamed concrete are greatly improved by the addition of coconut fiber and MWCNT. Quantitatively, the area enclosed

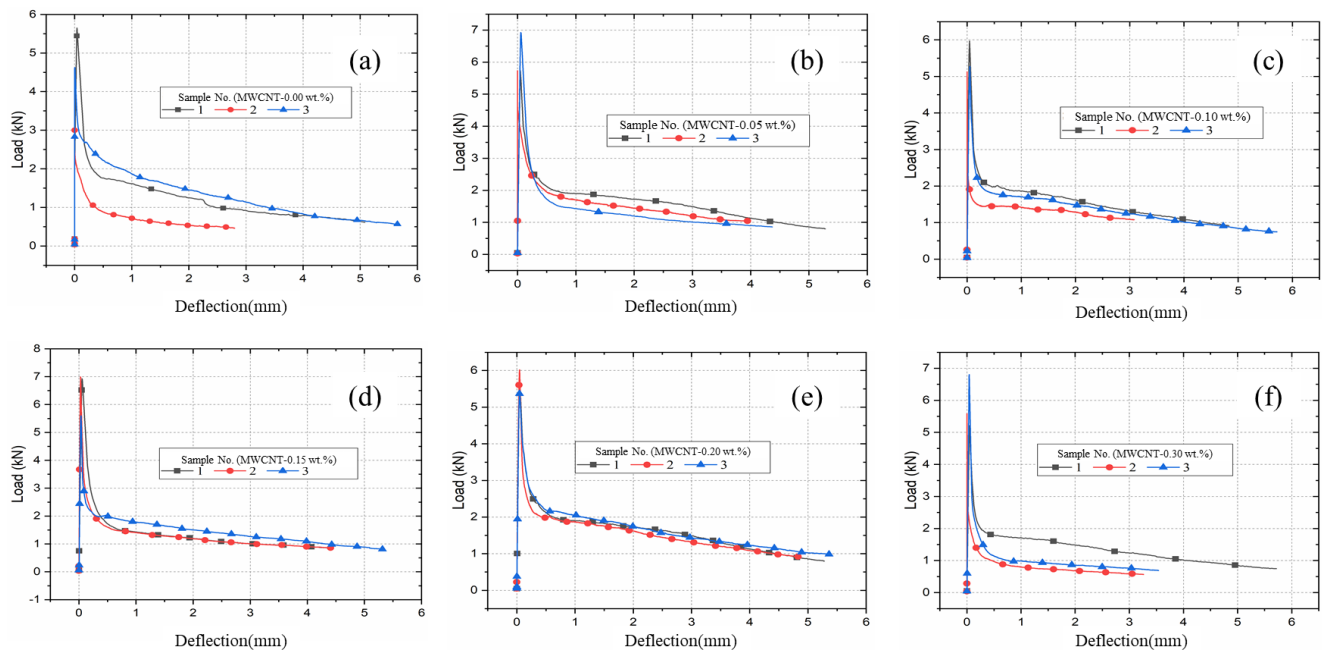


Fig. 4 Load-deflection curves of foam concrete with fixed coconut fiber content and different MWCNT contents: (a) 0.0; (b) 0.05; (c) 0.1; (d) 0.15; (e) 0.2; (f) 0.3 wt.%

by the load-deflection curve represents the energy absorption capacity. Compared with the reference group, the hybrid reinforced specimens achieve higher energy absorption and better toughness, owing to the synergistic bridging effect of coconut fiber and MWCNT.

3.3 Fitting of hybridization effect of hybrid fibers

In the process of data integration, in order to eliminate the inconsistency of deflection measurement points between different tests, the interpolation algorithm built in the Origin software [37] is used to combine the discrete deflection measurement points of different specimens to the equidistant common deflection axis, so as to eliminate the influence of frequency difference of data acquisition between tests and ensure the comparability of subsequent fusion calculation. A multi-curve fusion strategy is used to improve the test data so that the mechanical response of materials under complex loads can be described more accurately [9].

In order to ensure that the fitting model has high accuracy, this study determines to use the piecewise function to fit the load deflection curve by reading the relevant literature [14], such as the linear section and the nonlinear section function fitting model shown in Eq. (1). The material follows Hooke's law in the elastic stage where the stress-strain relationship is linear, and the corresponding load-deflection curve also shows linear response. By using least square fitting, the model can accurately describe the material's stiffness and elasticity. Once the material reaches the plastic or damage stage, nonlinear attenuation characteristics are seen in its mechanical behavior. Consequently, the energy dissipation process driven by micro-crack propagation, interface deboning, and other mechanisms can be accurately described by a double exponential model.

$$y = \begin{cases} A_1 e^{(-x/t_1)} + A_2 e^{(-x/t_2)} + y_0 & a+bx \end{cases} \quad (1)$$

Where the time constants t_1 and t_2 correspond to the relaxation time of different damage mechanisms, and A_1, A_2 are fitting constant, with y_0 is the residual bearing capacity. The fitted parameters are shown in Table 5 and Table 6.

The fitting curve of flexural load-deflection for fiber-reinforced foamed concrete following fiber mixing is depicted in Fig. 5. Parameter values and determination coefficients for the linear and nonlinear function fitting models are shown in Tables 5 and 6, respectively. When the load-deflection curve of the specimen is fitted in sections, it is found that the fitting coefficient R^2 is above 0.98. This means that the fitting model fits the experimental data very well. In the elastic deformation

Table 5 Fitting parameters and determination coefficients of linear segment function model

formula model	content	parameter		decision coefficient R^2
		a	b	
$y=a+bx$	MWCNT-0.00 wt.%	1.89	80.1	0.9846
	MWCNT-0.05 wt.%	0.75	115.02	0.9926
	MWCNT-0.10 wt.%	0.54	98.05	0.9924
	MWCNT-0.15 wt.%	0.25	185.87	0.9972
	MWCNT-0.20 wt.%	0.03	1.19	0.9962
	MWCNT-0.30 wt.%	0.48	108.4	0.9878

stage (low load area), the material response shows significant linear characteristics. After entering the plastic deformation stage, the nonlinear characteristics are highlighted. Thus, the segmented modeling approach can more precisely analyze the deformation properties of materials under various physical mechanisms than the global single model.

3.4 Model fitting verification

In regression analysis, residuals are the primary metric used to assess the model's fit, which is the difference between the predicted and true values of the model. It is verified in this section to further ensure the validity and reliability of the fitting model used in this experiment. This includes the relationship between the model prediction value and the residual error under different MWCNT contents in Fig. 6, the discrete coefficient between the model prediction value and the actual observation value under different MWCNT contents in Fig. 7, Fig. 8 shows the microstructure of different materials when the content of MWCNT is 0.00 wt. %. and the normality of the residual error under different MWCNT contents in Fig. 9.

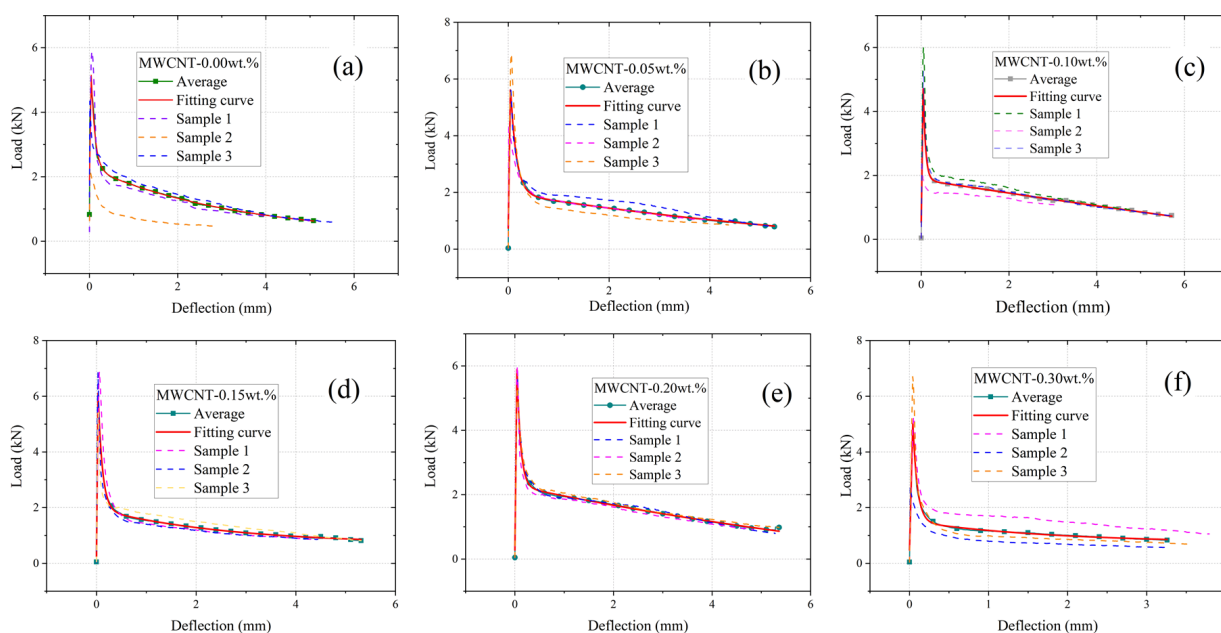
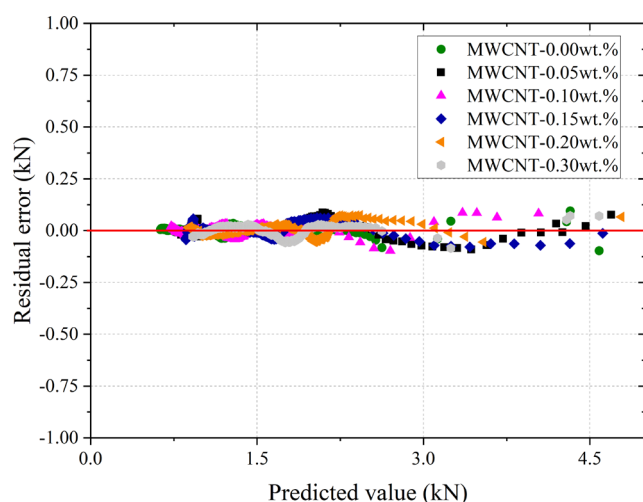
Eq. (2) illustrates the residual calculation, where e_i is the residual of the i data point, y_i is the observed value of the i^{th} data point, and $hat{y}_i$ is the predicted value of the i^{th} data point after fitting the model through the above partial function fitting model. By observing the residual value, the relationship between the visual residual and the independent variable or the predicted value can be evaluated, and the data points with abnormally large residuals can be identified.

$$e_i = y_i - hat{y}_i \quad (2)$$

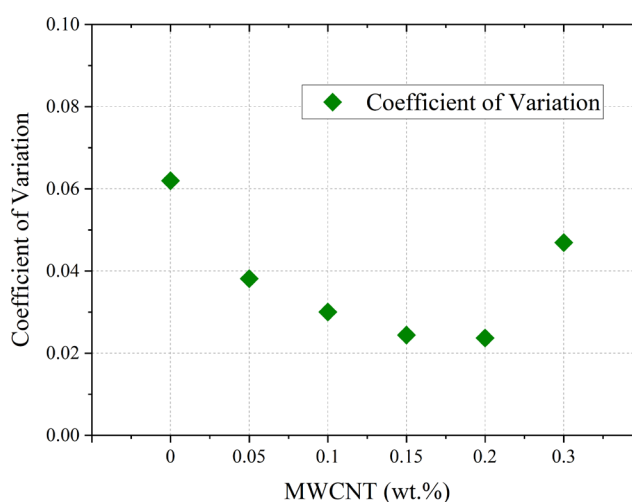
It is evident from Fig. 6, we can see-that the residuals are primarily concentrated with in the interval $[-0.25, 0.25]$. This phenomenon demonstrates that our piecewise function fitting model performs well in terms of prediction performance, with a small discrepancy between the model prediction value and the actual observation value. This indicates

Table 6 Fitting parameters and determination coefficients of nonlinear segment function model

formula model	content	parameter					decision coefficient R^2
		A_1	t_1	A_2	t_2	y_0	
$y = A_{1e}^{(-x/t_1)} + A_{2e}^{(-x/t_2)} + y_0$	MWCNT-0.00 wt.%	4.67	0.09	2.13	3.4	0.15	0.9846
	MWCNT-0.05 wt.%	5.46	0.12	2.52	8.64	-0.55	0.9926
	MWCNT-0.10 wt.%	6.71	0.05	8.18	37.96	-6.31	0.9924
	MWCNT-0.15 wt.%	6.01	0.09	1.27	2.69	0.68	0.9972
	MWCNT-0.20 wt.%	6.41	0.08	3.86	11.79	-1.58	0.9962
	MWCNT-0.30 wt.%	7.29	0.06	0.79	1.81	0.73	0.9878


Fig. 5 Single fitting curve of bending load-deflection of hybrid reinforced foam concrete: (a) 0.00 wt.% MWCNT, (b) 0.05 wt.% MWCNT, (c) 0.10 wt.% MWCNT, (d) 0.15 wt.% MWCNT, (e) 0.20 wt.% MWCNT, (f) 0.30 wt.% MWCNT

Fig. 6 Relationship between the predicted value and the residual of the model at different contents of MWCNT

that the model can accurately represent the relationship between load and deflection in coconut fiber composites with varying MWCNT contents-of MWENT.


Fig. 7 Dispersion Coefficient of Variation at different contents of MWCNT

In addition, the distribution pattern and range of residuals are similar at different MWCNT contents. This consistency shows that the fitting model of the distribution

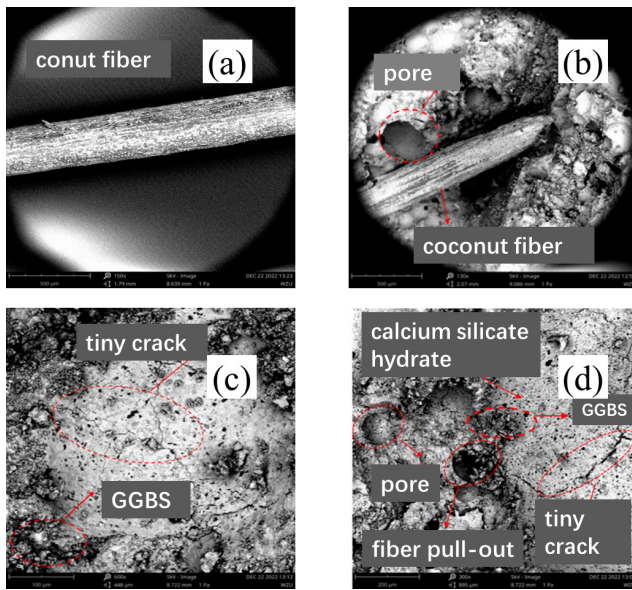


Fig. 8 Microstructure of different materials when the content of MWCNT is 0 (a) coconut fiber; (b) fiber in plain concrete; (c) plain concrete; (d) fiber pull-out

function not only has certain applicability but also shows robustness. The random distribution characteristics of the residuals do not show obvious rules or trends, which further verifies the rationality of the model and shows that there is no significant systematic deviation.

At various MWCNT contents, the dispersion coefficient between the model's predicted value and the actual observed value is illustrated in Fig. 7. The Coefficient of Variation (C_v)

is a relative index used to measure the degree of data dispersion in statistics. Therefore, the C_v is usually used to evaluate the consistency between the predicted value of the model and the actual observed value. In general, the better the model's prediction performance, the lower the dispersion the data is, the closer the model prediction value is to the actual observation value, and the lower the dispersion degree of the data, the smaller the dispersion coefficient. The formula is the ratio of standard deviation to mean, see Eq. (3), where σ is the standard deviation of the residual, μ is the average value of the observed value. In this study, except for the case where the MWCNT content is 0.00 wt. %, the dispersion coefficients at other contents are less than 5 %, indicating that the model has high accuracy and stability for the prediction of these contents. When the content of MWCNT is 0.00 wt. %, the dispersion coefficient is slightly higher. On the one hand, it is because the mechanical behavior of the material is more complicated when there is no co-doped MWCNT. On the other hand, due to the influence of coconut fiber, there is a slight difference between the predicted value of the model and the actual observation value.

MWCNT have excellent mechanical properties. When the content of MWCNT is 0.00 wt. %, there is no such nano-reinforced phase in the composite material. Its microstructure is primarily made up of matrix and coconut fiber, which contributes to its comparatively poor mechanical qualities. It is more likely for fiber pull-out, matrix cracking,

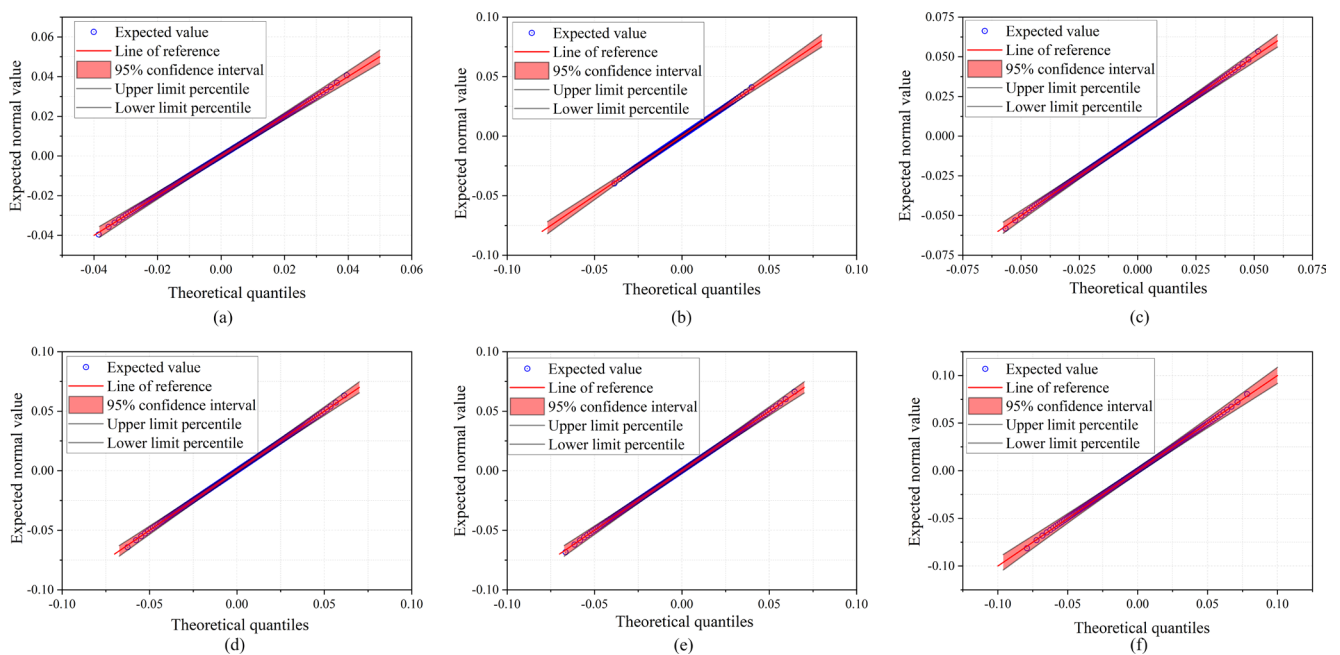


Fig. 9 Normal test Q-Q plots of fitting residuals at different contents of MWCNT: (a) Normal Q-Q diagram of MWCNT-0.00 wt.%; (b) Normal Q-Q diagram of MWCNT-0.05 wt.%; (c) Normal Q-Q diagram of MWCNT-0.10 wt.%; (d) Normal Q-Q diagram of MWCNT-0.15 wt.%; (e) Normal Q-Q diagram of MWCNT-0.20 wt.%; (f) Normal Q-Q diagram of MWCNT-0.30 wt.%

and other types of failure to happen when the material is under stress. This makes the material's mechanical behavior more complicated and the model's predictions less accurate. In addition, in the absence of MWCNT, the dispersion of coconut fibers in the matrix is poor.

$$C_v = \frac{\sigma}{\mu} \quad (3)$$

Fig. 8(a) shows the microstructure of the coconut fiber used in the experiment. The figure clearly illustrates that the coconut fiber's surface is rough and soiled with impurities. The bonding performance and stress transfer efficiency between the fiber and the matrix will be indirectly influenced by the presence of this rough surface and impurities. It is evident from Fig. 8(b) that the surface of the coconut fiber is coated with a cement matrix, suggesting that the fiber can establish a bonding effect with the concrete matrix. However, the bonding is not great due to the impurities and unevenness of the fiber surface. There are some micro cracks visible in the internal structure of the plain foam concrete, as seen in Fig. 8(c). The formation of these micro-cracks is closely related to the porous structure of foamed concrete. A large number of pores are formed inside the foam concrete due to bubble foaming. These pores destroy the continuity of the material to a certain extent, resulting in stress content, which is easy to cause micro cracks. The coconut fiber in Fig. 8(d) is exhibiting the characteristic of pulling away from the cement matrix. This is a result of the insufficient bonding force between the fiber and the matrix, or the destruction of the interface between the fiber and the matrix as a result of external force [38]. These microstructure characteristics include the rough surface of coconut fiber, impurity coverage, pore cracks and fiber pull-out signs. It also further explains that when the MWCNT content is 0.00 wt. %, due to the influence of coconut fiber, there are some differences in the dispersion coefficient between the model predicted value and the actual observed value.

Fig. 9 shows the normal test Q-Q diagram generated at different contents after model fitting. After careful examination, it is discovered that the normality of residuals exhibits a more pronounced and consistent trend when the MWCNT content varies.

The data points on the Q-Q diagram are roughly distributed along the reference line when the MWCNT content is 0.00 wt % and 0.05 wt %, and there is an almost nonexistent deviation. Further analysis of its mean, it can be found that the mean is very close to 0, and the standard deviation is also at a relatively small level. At 0.10 wt%, 0.15 wt%,

and 0.20 wt% of MWCNT, the residuals' normality still holds up well as the content increases. It can be clearly seen from the Q-Q diagram that the data points can follow the reference line distribution well. Although the content has been improved, the overall normality has not been significantly damaged and remains at a relatively good level. This shows that even with medium content, the model can still better fit the distributional features of the data and capture the trends and rules in the data with an excellent fitting effect. The residuals' normality did not degrade much at a higher content of 0.30 wt %, and they continued to perform reasonably well. The data points are close to the reference line in the whole area. Although there may be slight deviations in some nuances compared with low and medium content, the normality is relatively good on the whole.

4 Discussions

4.1 Strength enhancement rate of single doped MWCNT

Fig. 10 compares the flexural strength and strength improvement rate of MWCNT doped into different concrete materials with other researchers [29, 39–42]. Zhang et al. [29] systematically studied the dispersion mechanism and performance improvement of well-dispersed multi-walled MWCNT cement paste; Kerien et al. [39] found that MWCNT can act as a nucleating agent for crystallization; Cui et al. [40] through experiments and molecular dynamics simulation, it is considered that the strengthening mechanism of MWCNT on concrete is mainly due to adsorption and nucleation; Xu et al. [41] focused on the influence of MWCNT on the microstructure and compressive strength of specimens, and confirmed the advantages of bridging and grid filling of

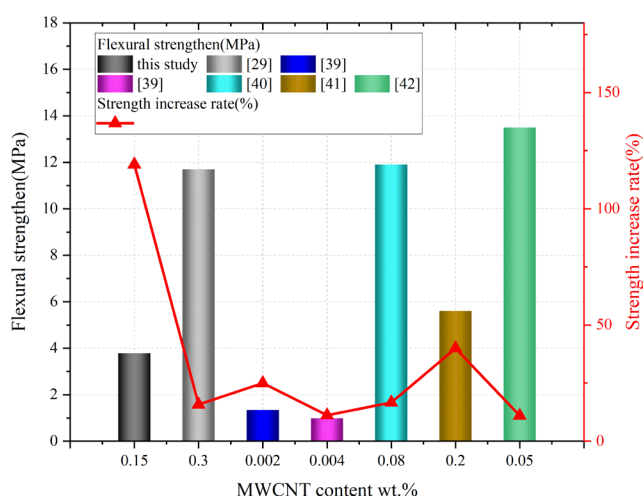


Fig. 10 Comparison of flexural strength and increase rate of materials with different contents of MWCNT

MWCNT again through microscopic tests; Huang et al. [42] used different contents of MWCNT to improve the mechanical properties of cement-based composites.

By comparing Fig. 10, it can be found that this work has achieved a breakthrough improvement in the flexural strength of concrete through the cross-scale synergy of nano-scale enhancement (MWCNT uniform dispersion) and macro-scale regulation (precise curing). The core mechanism is nano-scale enhancement and macro-scale regulation. MWCNT optimizes the microstructure of the matrix through dual paths. On the one hand, it acts as a nano-scale 'bridge' to effectively bridge microcracks and block crack propagation. On the other hand, the surface functional groups catalyze the hydration reaction and promote the formation of dense hydration products. Optimization of hydration products in the dimensions of space (three-dimensional uniform growth) and time (continuous strength development) is ensured by the standard curing system. As a result, the micro-performance improvement is immediately translated into macro-mechanical improvement (with a strength improvement rate of 119%).

4.2 Strength improvement of fibers

Fig. 11 compares the flexural strength of the material under different fiber types added by this experiment and other researchers [7, 8, 21, 43–46]. Falliano et al. [7] added polypropylene superfine fiber; Li et al. [8] The surface of PVA fiber was treated with harmless nonionic surfactant, and its influence on fiber distribution and mechanical properties of foamed concrete was investigated. Falliano et al. [21] studied the grid structure of glass fiber reinforced polymer and found that it significantly improved the performance

of concrete; Yildizel et al. [43] studied the reinforcement effect of PLA⁺ fibers with different shapes on foamed concrete; Yildizel et al. [44] used recycled fiber for reinforcement to improve the mechanical properties of foamed concrete; Bai et al. [45] studied the influence of carbon fiber (CF) content on the properties of foamed concrete; Li et al. [46] analyzed and compared the flexural tensile properties and splitting tensile strength of PVA fiber reinforced foam concrete. It can be found that the foamed concrete prepared in this experiment has excellent flexural strength and is at a high level.

This result confirms the effectiveness and advancement of the materials used in this experiment. This study innovatively co-doped coconut fibers and carbon nanotubes to improve the flexural performance of foam concrete. Coconut fiber is a natural, renewable material. Its unique fibrous structure and good biocompatibility provide additional mechanical support and toughness to foam concrete, helping to resist bending deformation under external forces. Carbon nanotubes, as a nanomaterial, can form a strong network structure within concrete due to their excellent mechanical properties, effectively transmitting and distributing stress, thereby further enhancing the flexural strength of concrete. When these two materials are co-doped into foam concrete in a scientifically appropriate proportion, their synergistic effects can be fully utilized. The large-scale structure of coconut fibers provides macroscopic skeletal support for the concrete, while the small size and excellent connectivity of carbon nanotubes fill the gaps between fibers and the matrix at the microscopic level, enhancing interfacial bonding, thus achieving multi-scale structural optimization from macro to micro. This multi-level structural optimization significantly improves the flexural strength of foam concrete.

In addition, by adjusting the mixing ratio and dispersion state of coconut fiber and MWCNT, the microstructure and pore distribution inside the foamed concrete can be effectively controlled, and its bending performance can be further optimized. The research results not only provide new ideas and methods for the performance improvement of foam concrete materials but also provide useful reference and inspiration for the research and development of other composite materials.

5 Conclusions

In this study, from the perspective of the flexural properties of mixed natural coconut fiber and MWCNT reinforced foam concrete, the mechanical properties of mixed coconut fiber reinforced foam concrete with different contents

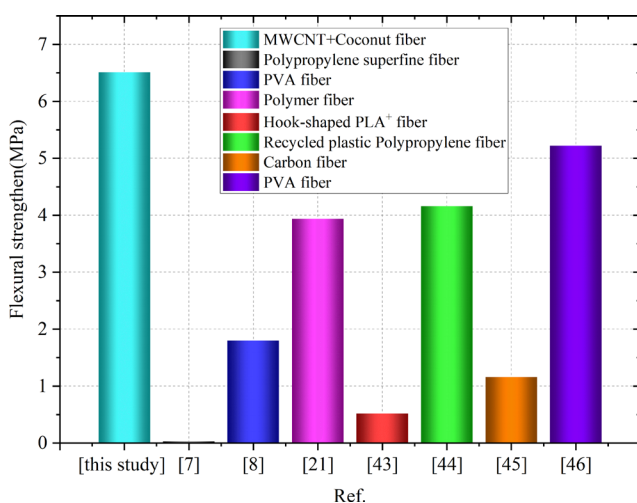


Fig. 11 Comparison of flexural strength of materials under different fiber types

of MWCNT content (0, 0.05, 0.10, 0.15, 0.2, 0.3 wt. %) were studied. The findings show that adding coconut fiber and MWCNT to foam concrete makes it stronger and tougher in a big way. According to the test results, the main conclusions of this study are summarized as follows:

1. The effect of MWCNT content on flexural strength: The addition of MWCNT can effectively enhance the flexural strength of foamed concrete, and the optimum content is 0.2 wt. %. However, the strength will decrease as a result of the agglomeration effect when the content exceeds this optimal ratio.
2. The impact of distinct foaming techniques on strength: Because chemical foaming agent and physical foaming agents have different mechanisms for creating bubbles, their flexural strengths differ in foamed concrete. The strength produced by chemical foaming is relatively high, up to 3.79 MPa, and the strength improvement rate is 119%. The physical foaming makes the bubble distribution more uniform, but the strength is slightly lower, 3.6 MPa, and the strength improvement rate is 110 %.
3. The load-deflection curve characteristics of co-doped MWCNT and coconut fiber: The load-deflection curve of the foam concrete co-doped with MWCNT and coconut fiber shows a similar trend, that is, the initial linear growth, reaching the peak and then falling gently, and the deflection changes little. Compared with the case of only 0.4 % coconut

fiber, the co-doping significantly increases the area under the curve, which indicates that the material consumes more energy during fracture and further improves the flexural toughness.

4. The piecewise function fitting: In this experiment, piecewise function fitting works well to fit the specimen's load deflection curve. This method accurately captures the relationship between load and deflection by fully considering the difference mechanical properties of specimens in different deformation stages. By piecewise fitting, the complex nonlinear curve can be decomposed into simple linear and nonlinear paragraphs.
5. High fitting coefficient and optimal content of the fitting model: The fitting model employed in this experiment has a coefficient exceeding 0.98, which indirectly suggests that the test data is in close proximity to the fitting value. In addition, through model fitting, it is found that the fitting effect is the best when the MWCNT content is 0.2 wt.%, which corresponds to the previous optimal content of strength.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (Grant Number: 51568009), Natural Science Foundation of Zhejiang Province (Grant Number: LY18E080028) and Science and Technology plan Project of Wenzhou, China (Grant Number: S20190001, S20220005).

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