Electronic Journal of Structural Engineering

Original Article

Cite this: DOI:10.56748/ejse.24623

Received Date:16 April 2024
Accepted Date: 18 August 2024

1443-9255
https://ejsei.com/ejse

Mechanical properties and damage modeling of hybrid fiber reinforced concrete under freeze-thaw cycles

Lixun Liao [a], Haoyuan Yuan [a,b,c] *, Jianping Xian [a,b], Jiahao Zhang [a,b], Yu Lei [a,b] and Hao Wang [a,b]
[a] CCCC Second Highway Engineering Co., Ltd, Xi'an 710065, China
[b] Research and Development Center on Construction Technology of Long Bridge and Tunnel in Mountain Areas, CCCC, Xi'an 710199, China
[c] Highway School, Chang'an University, Xi'an 710064, Shaanxi, China
* Corresponding author: yhymao@163.com

Abstract

This study aimed to investigate the mechanical properties of steel-polyacrylonitrile hybrid fiber reinforced concrete (SPHFRC) and its durability under freeze-thaw damage. Firstly, the mechanical properties of hybrid fiber reinforced concrete (HFRC) were studied by compressive strength and flexural strength tests. Secondly, with the help of rapid freeze-thaw test, the variation rules of mass loss rate and relative dynamic elastic modulus were characterized. Based on the test results and freeze-thaw damage theory, the evolution equation of freeze-thaw damage of hybrid fiber reinforced concrete (HFRC) based on Weibull distribution was established. The results show that the enhancement effect of hybrid fiber on the mechanical strength of concrete is better than that of single mixed fiber, especially in the improvement of flexural strength; Accordingly, compared with the single mixing of steel fibers or single mixing of polyacrylonitrile fibers, hybrid fibers are more effective in improving the durability of concrete against freezing and this improvement effect increases with the increase of steel fiber content; The freeze-thaw damage model of Weibull distribution can better reflect the freeze-thaw damage process of hybrid fiber reinforced concrete (HFRC) .Through the freeze-thaw damage evolution curve, it can be found that after 500 freeze-thaw cycles(About 70 years of concrete life in northern China), the freeze-thaw damage degree of the hybrid fiber reinforced concrete (HFRC) with different steel fiber content has been very close, which means that the influence of steel fiber content on the freeze-resistant performance of hybrid fiber reinforced concrete (HFRC) will be limited. This study provides a theoretical basis and technical basis for the design of concrete structures in alpine regions.

Keywords

Hybrid fiber reinforced concrete, Mechanical property, Freeze-thaw cycle, Frost resistance, Freeze-thaw damage model

1. Introduction

As one of the most used construction materials in the field of civil engineering, concrete is widely used in various building structures because of its rich composition, simple casting method, and low price (Xie et al., 2021). However, building structures located in cold regions inevitably suffer from freeze-thaw cycles. Under freeze-thaw conditions, the alternation of positive and negative temperatures will cause uneven cracks within the concrete, which will seriously shorten the service life of building structures (Wang et al., 2022; Wang et al., 2023). Ordinary concrete is no longer able to meet the increasingly severe demands of use, so the enhancement of the strength and frost durability of concrete in cold regions is an urgent problem to be solved. The addition of cementitious supplementary materials, polymers, concrete admixtures, and various types of fiber materials to concrete are commonly used methods of strengthening and toughening, and among these methods addition of fibers is one of the most desirable methods (Liu et al., 2022; Zhao et al., 2023).

Currently, the fibers that have been gradually promoted for use in engineering practice include steel fibers, basalt fibers, polypropylene fibers, and carbon fibers (Xia et al., 2023; Vairagade et al., 2023; Khan et al., 2023). Among them, steel fiber is the most used concrete reinforcing fiber (Devi Keerthika Esakki et al., 2023; Koushkbaghi et al., 2018). Numerous studies have shown that steel fibers can enhance and toughen concrete, while effectively improving the durability of concrete materials (Hu et al., 2018; Wang et al., 2014). According to the research on the effect of steel fibers on concrete properties by (Shi et al., 2020), steel fibers can significantly improve the tensile properties of concrete, improve the generation, and inhibit the development of cracks in concrete after compression. Still, the improvement of compressive strength is small and significantly reduces the ease of concrete. Research on the effect of steel fibers on the freezing performance of concrete by (Han et al., 2022) found that the freezing performance of concrete with steel fibers was found to be 26% higher than that of the concrete matrix, and the degree of improvement was not affected by the shape of the steel fibers. However, it was shown that concrete cracking under freeze-thaw cycles is a multi-scale, multi-stage process, and steel fibers can effectively inhibit the expansion of macroscopic cracks through bridging, while microscopic cracks need to be restrained by flexible fibers with smaller geometrical dimensions. At the same time, the inherent physicochemical properties of steel fibers are limited in their ability to improve the performance of concrete (Wang et al., 2012; Teng et al., 2018). Therefore, according to the theory of composite materials, if fibers with different functions, sizes, or constitutive relationships are combined with concrete to form a HFRC, the fibers can complement each other's properties at different stages and structural levels, resulting in a "positive mixing effect", which improves the performance of the concrete to a greater extent (El-Mal et al., 2015; Li et al., 2015). Research on the damage characteristics and microstructure of steel-polypropylene HFRC under freeze-thaw cycles by (Xia et al., 2023) found that the freeze-thaw cycles had an adverse effect on the physical and mechanical properties of the specimens, and the addition of fibers reduced the degree of damage to the concrete, and the improvement effect of the hybrid fibers was more obvious. According to the research on the mechanical properties and freeze durability of steel-polypropylene HFRC under freeze-thaw cycle by (Luo et al., 2020), steel-polypropylene hybrid fibers had a significant effect on the frost resistance of concrete after freeze-thaw cycles, and the effect on the splitting tensile strength was greater than that on the compressive strength. According to the analyzed the void characteristics of steel-polypropylene HFRC and its relationship with the permeability and salt freeze-thaw resistance through experiments by (Wang et al., 2022) found that the hybrid fibers enhanced the compressive strength and splitting tensile strength of concrete under salt freeze-thaw cycles, but the hybrid fibers have a negatively affect the permeability of concrete. Based on the results, scholars have also developed some freeze-thaw damage models to predict the service life of concrete, such as microscale model, cohesive zone model, peridynamic Model, and Weibull distribution model (Peng et al., 2022; Kenny et al., 2014; Wu et al., 2023; Zhong et al., 2024). Among these models, the Weibull distribution model is widely used in reliability analysis and life tests of various life tests. In addition, compared with other prediction models, Weibull distribution is relatively simple and more accurate analysis and prediction can be obtained for small sample data. Meanwhile, when predicting freeze-thaw damage life of fiber reinforced concrete, most researchers adopted the evolution law of freeze-thaw damage of Weibull distribution and concluded that Weibull distribution model can be better applied to freeze-thaw damage simulation and life prediction of concrete (Zheng et al., 2024; Xiao et al., 2019). At the same time, it can be seen from the above literature review that most of the existing studies used steel-polypropylene fibers for hybrid, while polyacrylonitrile fibers has the excellent surface force and adhesion, as well as high-temperature resistance, high strength, and wear resistance (He et al., 2021). Research has shown that polyacrylonitrile fibers can effectively improve the strength of concrete, and the enhancement effect on the frost resistance and impermeability of concrete is better than that of polypropylene fibers (Fan et al., 2015; Zeng et al., 2021; Cen et al., 2008). However, relatively speaking, there are more research on the strength and frost durability of concrete with single-mixed steel fibers or single-mixed polyacrylonitrile fibers, while the research on the influence law of steel-polyacrylonitrile hybrid fibers on the mechanical properties of concrete and the frost durability has rarely been reported. At the same time, the study of freeze-thaw damage evolution law and freeze-thaw damage model of HFRC under freeze-thaw cycle is not perfect enough to grasp the durability and life prediction of HFRC. Therefore, it is urgent to carry out corresponding experimental and theoretical research.

In summary, this article investigates the damage characteristics of SPHFRC under freeze-thaw cycles and explores the influence of steel fiber content and fiber hybridization on the mechanical properties, mass loss rate, and relative dynamic elastic modulus of concrete. In addition, to characterize the degree of damage to HFRC structures under freeze-thaw cycles, a freeze-thaw damage evolution equation for SPHFRC based on Weibull distribution was proposed according to the experimental results. The relevant research provides a theoretical basis for the design of concrete structures in alpine regions.

2. Experimental Programs

2.1 Materials

Cement

Cement adopts Shanshui brand ordinary Portland cement with strength grade P.O. 42.5, and the detailed indicators of the cement are given in Table 1.

Fly-ash

Fly ash is of class F, grade II, and its performance parameters are shown in Table 2.

Sand

Sand is the Dawen River sand that has been washed and dried, and the fineness modulus is 2.84.

Aggregate

Coarse aggregate is continuously graded gravel of 5mm-20mm produced by Guoshun quarry, and the grading curve is shown in Figure 1.

Type of superplasticizer use

Polycarboxylate high-performance water reducing agent URC-3 was used as superplasticizer, and the water reducing rate was 33 %.

Fibers and its properties

Hybrid fibers are mainly made of polyacrylonitrile fibers and steel fibers, as shown in Figure 2. The technical indicators of the fiber are shown in Table 3.

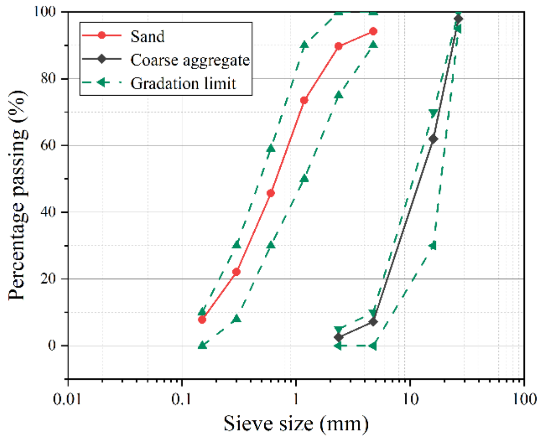


Fig. 1 Grading curves of coarse and fine aggregates

(a) (b)

Fig. 2 Hybrid Fibers (a) Polyacrylonitrile fiber; (b) Steel fiber

2.2 Mix proportions and test design

Referring to the C50 concrete mix proportion design requirements stipulated in the specification JGJ 55-2011 (Specification for mix proportion design of ordinary concrete, 2011), and combined with the preliminary trial test to determine the C50 concrete benchmark proportion. The water-cement ratio is taken as 0.32, and the water reducing agent mixing amount is 1.5% of the total mass of cementitious materials. At the same time, to consider the effect of steel fiber content on the mechanical properties of HFRC, ordinary concrete as a control group, keep the concrete mix proportion unchanged, add different contents of steel fiber and polyacrylonitrile fiber for the test group, steel fiber volume fraction were 0.8%, 1.0% and 1.2%, polyacrylonitrile fiber volume fraction of 0% and 0.1%, the test of a total of 6 groups, and the concrete mix for each group is shown in Table 4.

Table 1. Chemical, physical and mechanical properties of cement

SiO_2 /%	MgO /%	Al_2O_3 /%	Fe_2O_3 /%	CaO /%	Density /g.cm^{-3}	Specific surface area /cm^2. g^{-1}	Fineness /%	Compress strength/MPa	
								3d	28d
20.58	1.05	5.89	3.71	63.82	3.15	3582	3.2	21.3	46.8

Table 2. Physical and chemical characteristics of fly ash

SiO_2/%	MgO /%	Al_2O_3 /%	Fe_2O_3 /%	CaO /%	Density/g.cm^{-3}	Specific surface area /cm^2. g^{-1}
51.62	1.25	21.73	10.34	2.87	2.38	3157

Table 3. Fiber technical indicators

Fiber type	Diameter /mm	Fiber aspect ratio	Density /g.cm^{-3}	Modulus of elasticity /GPa	Tensile strength /MPa	Fiber geometry
Steel fiber	0.8	50	7.8	210	1150	End hook type
Polyacrylonitrile fiber	0.1	150	1.18	18	550	Long straight fiber

Table 4. Mix proportions of HFRC

Mix proportion serial number	Mix ratio / (kg.m^{-3})							Fiber content/ (kg.m^{-3})	
	Cement	Fly ash	Sand	Coarse aggregate		Water	Water reducer		
				5~10	10~25			Steel fiber	Polyacrylonitrile fiber
SD0-P0	400	100	756	400	600	160	7.5	0	0
SD80-P0	400	100	756	401	602	160	7.5	80	0
SD0-P1.1	400	100	756	400	600	160	7.5	0	1.1
SD95-P1.1	400	100	756	398	596	160	7.5	95	1.1
SD80-P1.1	400	100	756	401	602	160	7.5	80	1.1
SD65-P1.1	400	100	766	404	607	160	7.5	65	1.1

2.3 Experimental Procedure

Mixing procedure

The mixing method refers to the provisions of the specification JG/T 472-2015 (Steel fiber reinforced concrete, 2015). Firstly, according to the mix proportion of HFRC test, coarse aggregate, sand, cement, fly ash, and other materials will be added to the mixer pre-mixed for 90s, followed by steel fibers, polyacrylonitrile fibers several times sprinkled into the mixer mixing uniformly, and then add the water and water reducer mixing for 150s. After the concrete is uniformly mixed, the material can be discharged. The specimen was poured according to the requirements of JTG 3420-2020 (Testing methods of cement and concrete for highway engineering, 2020), the formed specimen was covered with plastic film, and was demolded after 24 hours of maintenance in the laboratory environment, finally placed in a standard chamber with a temperature of (20±2) °C and relative humidity greater than 95% for maintenance. After reaching the target age of 7 days and 28 days, it is taken out for subsequent performance tests.

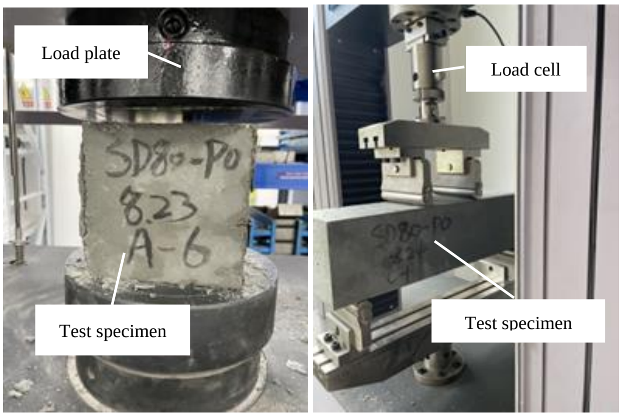
According to the different fiber volume fractions, six sets of specimens were made for compressive, flexural strength, and freeze-thaw cycle tests respectively, with three sets of parallel specimens made for each group, totaling 54 specimens.

Workability test

Concrete slump was tested according to the standard JTG 3420-2020 (Testing methods of cement and concrete for highway engineering, 2020). The concrete was mixed evenly and added to the standard slump in three times, each vibrating 25 times. Afterwards, the vertical distance between the top of the mold and the highest point of the sample surface is recorded.

Mechanical tests - compressive & flexural tests

Mechanical performance tests were conducted following the requirements specified in the specification GB/T 50081-2019 (Standard for test methods of concrete physical and mechanical properties, 2019), and 150 mm × 150 mm × 150 mm standard cubic specimens and 150 mm × 150 mm × 550 mm prismatic specimens were prepared. Three sets of parallel specimens were set up for each set of tests to record the compressive and flexural strengths at 7d and 28d respectively. The compressive strength test was conducted by YAW-1000 automatic compression testing machine with a compression rate of 0.7 MPa/s. The flexural strength test was conducted by ETM-504D microcomputer-controlled electronic universal testing machine, which utilized double-point loading to apply the load with a loading rate of 0.07 MPa/s, as shown in Figure 3. The results were taken as the average of the three groups of parallel specimens.



(a) (b)

Fig. 3 Mechanical performance test. (a) Compression; (b) Flexural

Frost resistance test - mass loss and relative dynamic elastic modulus

Freeze-thaw cycling tests were carried out according to the rapid frost method stipulated in GB/T 50082-2009 (Standard for test methods of long-term performance and durability of ordinary concrete, 2009) (specimen size: 400mm × 100mm × 100mm). To eliminate the influence of the unsaturation of the specimen on the test results, the specimens were taken out 24 hours before the start of the test and immersed in 20 °C ± 2 °C water for 48 hours. Then the specimens were taken out and put into the rapid freeze-thaw test machine for freeze-thaw test, as shown in Figure 4. Every after 25 freeze-thaw cycles, the specimens were taken out and the mass loss rate M and relative dynamic elastic modulus Er of the specimens were tested. The calculation formulas are shown in Eq. (1) and Eq. (2).

$$M = \frac{M_0 - M_n}{M_0} \quad (1)$$

$$E_r = \frac{f^2{}_n}{f^2{}_0} \quad (2)$$

Fig. 4 Rapid Freeze-Thaw Teste

where M is the mass loss rate of the specimen after n freeze-thaw cycles, %; M0 is the mass of the specimen before the freeze-thaw cycles, g; Mn is the mass of the specimen after n freeze-thaw cycles, g; Er is the relative dynamic elastic modulus of the specimen after n freeze-thaw cycles, %; fn is the transverse fundamental frequency of the specimen after n freeze-thaw cycles, hz; f0 is the transverse fundamental frequency of the specimen before the freeze-thaw cycles, hz.

3. Results and Discussions

3.1 Slump

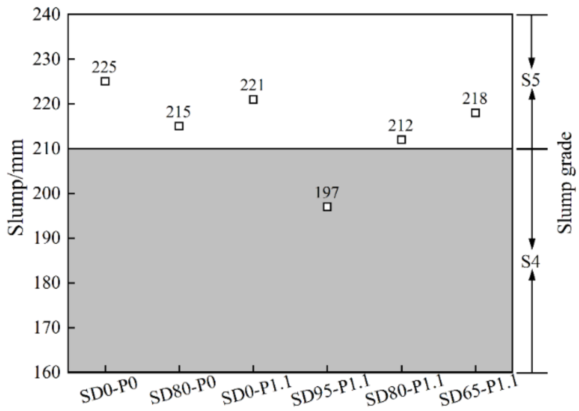


Fig. 5 Slump of HFRC

Figure 5 shows the slump test results of concrete mixes with different fiber contents. As can be seen from Fig. 5, the slump of SD95-P1.1 is in the range of 160~210 mm, which can be divided into S4 according to specification GB 50164-2011 (Zeng et al., 2021), and the slumps of the remaining five groups of mixes are all higher than 210 mm, which belongs to the S5 level. The incorporation of steel fibers and polyacrylonitrile fibers produced different degrees of slump loss in the HFRC, and the amount of loss all increased with the increase of the volume fraction of steel fibers. This is mainly due to the increase of fiber content leads to the increase of friction resistance between fiber and cement mortar, which further reduces the fluidity of concrete, thus making slump decline. However, the results of each group always remained within a narrow range (190-225 mm), so the six groups of HFRC had good fluidity.

3.2 Compressive strength test

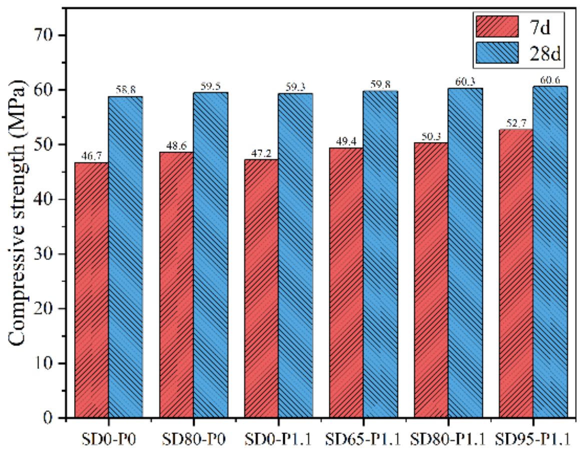


Fig. 6 Compressive strength of concrete

As can be seen in Figure 6, the addition of fibers can improve the compressive strength of concrete. The compressive strength of single-mixed steel fiber and polyacrylonitrile fiber concrete SD80-P0, SD0-P1.1 at the age of 7 days compared with ordinary concrete SD0-P0 increased by 4.07% and 1.07%, and the age of 28 days compared with ordinary concrete SD0-P0 increased by 1.19% and 0.85%, indicating that the compressive strength enhancement effect of single-mixed steel fiber concrete is better than single-mixed polyacrylonitrile fiber concrete, which is because steel fibers have good stiffness and toughness, and absorb energy through their deformation when they are subjected to external forces, thus increasing the compressive strength of concrete. Meanwhile, compared with ordinary concrete SD0-P0, the compressive strength of steel and polyacrylonitrile HFRC SD65-P1.1, SD80-P1.1, SD95-P1.1 increased by 5.78%, 7.71% and 12.85% at 7 days, and 1.70%, 2.55% and 3.06% at 28 days, indicating that the compressive strength enhancement effect of steel fiber is more significant with the increase of steel fiber admixture, and the enhancement effect of HFRC is better than single-mixed steel fiber and single-mixed polyacrylonitrile fiber concrete. This is mainly because the high modulus of elasticity of steel fibers and polyacrylonitrile fibers positive synergistic effect can effectively improve the concrete internal compactness and structural integrity, under compressive stress effectively inhibit the expansion of the internal cracks, thus improving the compressive strength of concrete. However, the compressive strength growth rate of HFRC at 28 days is less than that at 7 days, which means that the hybrid fiber has a better effect on enhancing the compressive strength of concrete in the early stage. Similarly, the steel polypropylene HFRC reported by (Emad et al., 2022) also came to the same conclusion that due to the inertness of the concrete, the compressive strength after age of 7 days is not affected by the addition of hybrid fibers.

3.3 Flexural Strength Test

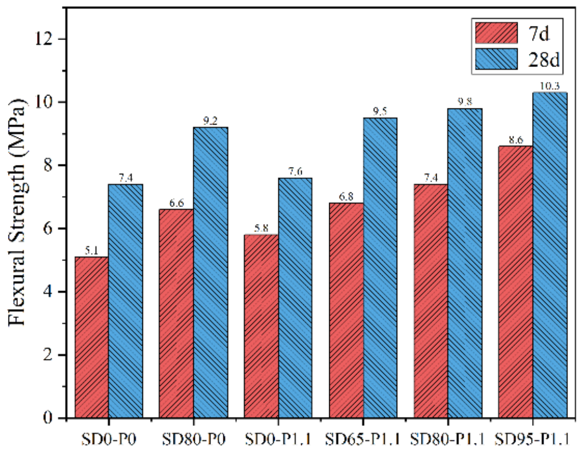


Fig. 7 Flexural strength of concrete

As can be seen in Figure 7, the flexural strength and compressive strength have the same trend of change, and the addition of fibers makes the flexural strength of concrete increase. Compared with ordinary concrete, at the age of 7 days and 28 days, the flexural strength of single-mixed steel fiber concrete SD80-P0 was increased by 26.92% and 24.32%, while the flexural strength of single-mixed polyacrylonitrile fiber concrete SD0-P1.1 was increased by 11.53% and 2.70%, which shows that the enhancement effect of steel fibers on the flexural strength of concrete is better than that of polyacrylonitrile fibers. This is due to the strong agglomeration of the polyacrylonitrile fiber, which is not easy to disperse in the concrete, and cannot well produce a synergistic effect with the concrete matrix, so the effect of reinforcing the flexural strength of the concrete is not strong, which is also consistent with the conclusion that polyacrylonitrile fibers are prone to form lumps or flocculation in concrete, according to scanning electron microscopy (SEM) observations by (Norma et al. , 2021; Cao et al., 2020).At the same time, the flexural strength of steel fiber and polyacrylonitrile fiber hybrid concrete SD65-P1.1, SD80-P1.1, and SD95-P1.1 at the ages of 7 and 28 days increased by 30.77 %, 42.31 %, 65.38 % and 28.38 %, 32.43 %, 39.19 %, respectively. The results show that the flexural strength enhancement effect of hybrid fiber on concrete is better than that of single-mixed steel fiber and polyacrylonitrile fiber, and this enhancement effect increases with the increase of steel fiber content. In addition, through comparison, it can be found that the effect of fiber on the flexural strength of concrete is significantly greater than that of compressive strength, which is mainly because of the nature of concrete damages the cracks and expansion, fiber concrete compressive strength enhancement is only through the fibers to improve the internal compactness of the concrete and the structural integrity, and flexural strength enhancement is mainly through the fiber to absorb the formation of cracks in the energy of the fracture surface, inhibit the further expansion of cracks, thus improving the flexural strength of concrete. Therefore, the improvement effect of fiber on the flexural strength of concrete is significantly greater than the compressive strength. Following studies conducted by (Fu et al., 2021) on basalt-polypropylene HFRC, the same conclusion was reached.

4. Analysis of Freeze-Thaw test results of HFRC

4.1 Frost resistance test

Mass loss

The mass loss rate can quantitatively reflect the degree of surface spalling of concrete under freeze-thaw cycles (Duan et al., 2023), and the mass loss rate test results of each group of specimens are shown in Table 5. To analyze the effect of freeze-thaw cycles on the mass loss rate of fiber reinforced concrete more intuitively, the trend of the mass loss rate of fiber reinforced concrete with the number of freeze-thaw cycles is plotted in Figure 8.

Table 5. Test results of mass loss rate

Number of freeze-thaw cycles	Mass loss rate /%					
	SD0-P0	SD80-P0	SD0-P1.1	SD65-P1.1	SD80-P1.1	SD95-P1.1
0	0	0	0	0	0	0
25	0.18	0.05	0.1	0.05	0.03	0.01
50	0.32	0.08	0.18	0.08	0.06	0.03
75	0.85	0.12	0.35	0.14	0.08	0.06
100	1.35	0.28	0.67	0.22	0.18	0.05
125	1.76	0.53	1.05	0.44	0.36	0.18
150	2.15	0.61	1.19	0.52	0.45	0.25
175	2.55	0.86	1.41	0.78	0.67	0.49
200	2.96	1.03	1.79	0.91	0.73	0.57
250	3.35	1.42	2.12	1.22	0.93	0.93
300	3.85	1.83	2.55	1.60	1.28	1.13
350	4.35	2.15	2.87	1.79	1.53	1.38

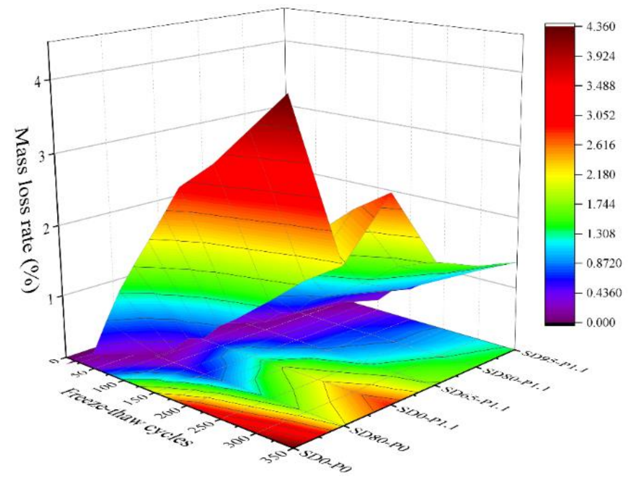


Fig. 8 Mass loss rate

In general, the smaller the rate of mass loss of concrete for the same number of freeze-thaw cycles, the better its frost resistance. It can be seen from Table 5 and Figure 8 that the mass loss rate of six types of concrete was positively correlated with the number of freeze-thaw cycles, and the mass loss rate of the concrete specimens increased with the increase of the number of freeze-thaw cycles. When the number of freeze-thaw cycles is less than 75, the mass loss of each concrete specimen is 0.85%, 0.12%, 0.35%, 0.135%, 0.08%, and 0.055%, which are less than 1%, indicating that the surface of these concrete specimens is only slightly spalled, and when the number of freeze-thaw cycles is greater than 75, the growth of the mass loss rate of ordinary concrete is significantly greater than that of fiber concrete. Meanwhile, under the same number of freeze-thaw cycles, the size of the mass loss rate of each concrete was ranked as SD0-P0>SD0-P1.1>SD80-P0>SD65-P1.1>SD80-P1.1>SD95-P1.1. At the end of the freeze-thaw cycle (350 cycles), SD0-P1.1, SD80-P0, SD65-P1.1, SD80- P1.1, SD95-P1.1, SD95-P1.1 mass loss rate than the ordinary concrete SD0-P0 reduced by 33.93%, 50.67%, 58.97%, 64.94%, and 68.38%, which indicates that the addition of fibers can significantly improve the antifreeze performance of concrete, the polyacrylonitrile and steel hybrid fibers to improve the antifreeze performance of concrete is better than the single-mixed steel fibers and single-mixed polyacrylonitrile fibers, and this improvement effect increases with the increase of steel fiber content.

Relative dynamic elastic modulus

The internal damage of concrete under freeze-thaw cycles can be represented by the relative dynamic elastic modulus, and the test results are shown in Table 6. Same as the mass loss rate, the trend of relative dynamic elastic modulus of fiber reinforced concrete with the number of freeze-thaw cycles is plotted in Figure 9.

Table 6. Test results of relative dynamic elastic modulus

Number of freeze-thaw cycles	Relative dynamic elastic modulus /%					
	SD0-P0	SD80-P0	SD0-P1.1	SD65-P1.1	SD80-P1.1	SD95-P1.1
0	100	100	100	100	100	100
25	98.90	99.20	99.00	99.50	99.75	99.80
50	98.40	98.95	98.70	99.14	99.60	99.65
75	97.30	98.43	97.60	98.88	99.40	99.55
100	96.20	97.70	97.00	98.46	98.75	99.25
125	95.60	97.10	96.85	98.00	98.45	98.90
150	95.00	96.82	96.20	97.67	98.05	98.40
175	94.20	96.35	95.70	97.22	97.65	98.00
200	93.40	96.15	95.25	96.87	97.32	97.55
250	92.50	95.75	94.75	96.39	96.94	97.12
300	91.50	95.00	94.16	96.00	96.52	96.88
350	89.90	94.60	93.52	95.89	96.00	96.42

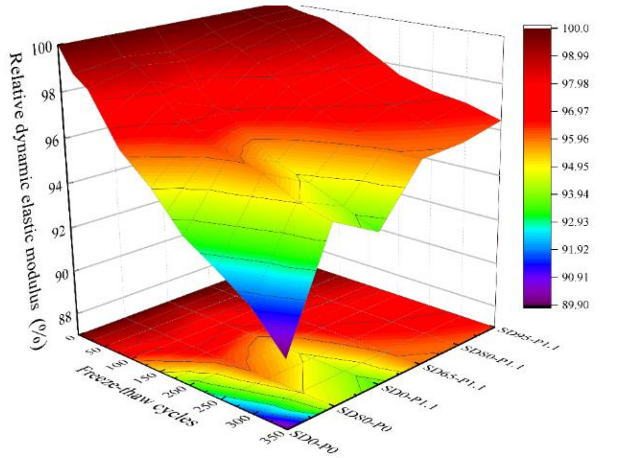


Fig. 9 Relative dynamic elastic modulus

It can be seen from Table 6 and Figure 9 that with the increase of freeze-thaw cycles, the relative dynamic elastic modulus of concrete specimens decreases gradually, and the decrease rate of ordinary concrete specimens is the largest. The relative dynamic elastic modulus of ordinary concrete continues to decrease with the increase of freeze-thaw cycles, while the attenuation of the relative dynamic elastic modulus of fiber reinforced concrete can be divided into two stages. Before 75 freeze-thaw cycles, the bond stress of the internal fibers of the concrete counteracts the freezing and expansion stresses generated by the internal pore water, which suppresses the generation of microcracks in the internal concrete under the freezing and thawing action, thus making the loss of relative dynamic elastic modulus smaller. However, after 75 freeze-thaw cycles, as the freezing and expansion stress of internal pore water gradually increases, the bond stress between fibers is not enough to resist the freezing and expansion stress, the microcracks inside the concrete increase, and the relative dynamic elastic modulus decreases. Meanwhile, under the same number of freeze-thaw cycles, the relative dynamic elastic modulus of HFRC increases with the increase of steel fiber content. SD95-P1.1 HFRC shows better frost resistance, and its relative dynamic elastic modulus still reaches 96.42% until the end of 350 freeze-thaw cycles. The inclusion of steel fibers and polypropylene acrylic fibers further enhances the freeze-thaw damage resistance of concrete.

4.2 Freeze-thaw damage model based on Weibull distribution

The causes of freeze-thaw damage of concrete materials are complex, and the data obtained by experiments often have significant discreteness. Weibull distribution is a failure theory based on the chain model combined with probability theory and mathematical statistics, which can accurately predict the situation of small samples, and it is the theoretical basis of reliability analysis and life prediction, after the continuous development of the Weibull distribution of life prediction has been widely used in several fields (Qiao et al., 2019; Guo et al., 2019; Xia et al., 2023). Therefore, it is completely feasible to predict the freeze-thaw damage life of fiber hybrid concrete by Weibull distribution. According to the Weibull distribution model, if f(n) represents the failure probability density function of concrete after n freeze-thaw cycles, the expression of f(n) is shown in Eq. (3):

$$f_{(n)} = \frac{\beta}{\eta}\left(\frac{n}{\eta}\right)^{\beta-1} exp\left(-\left(\frac{n}{\eta}\right)^{\beta}\right) \tag{3}$$

Where β is the shape factor, η is the scale factor, n is the number of freeze-thaw cycles.

The failure probability distribution function F(n) can be obtained by integrating the failure probability density function, as shown in Eq. (4):

$$F(n) = 1 - exp\left(-\left(\frac{n}{\eta}\right)^{\beta}\right) \tag{4}$$

Then the failure probability of concrete after n freeze-thaw cycles is Pf(n), which is expressed as Eq. (5):

$$P_f(n) = 1 - exp\left(-\left(\frac{n}{\eta}\right)^{\beta}\right) \tag{5}$$

From Eq. (5), the failure probability function of Weibull distribution increases gradually with the increase of the number of freeze-thaw cycles. When the number of freeze-thaw cycles reaches N, the concrete is destroyed, then Pf(n)=1, and the concrete damage degree D(n)=1. Since Pf(n) and D(n) follow the same variation pattern as the number of freeze-thaw cycles increases, the failure probability Pf(n) can be equivalent to the damage degree D(n), namely:

$$P_f(n) = D(n) \tag{6}$$

The freeze-thaw damage evolution equation of concrete based on Weibull distribution can be obtained, as shown in Eq. (7):

$$D(n) = 1 - exp\left(-\left(\frac{n}{\eta}\right)^{\beta}\right) \tag{7}$$

For ease of calculation, applying mathematical transformations to the above equation while taking logarithms on both sides of the equation yields Eq. (8):

$$ln\left[ln\frac{1}{1-D(n)}\right] = \beta\, ln(n) + \beta\, ln\left(\frac{1}{\eta}\right) \tag{8}$$

Taking Eq. (8) as a linear function Y=AX+B can be obtained in the form of Y =ln[ln(1/1-D(n))], X =ln(n), A =β, B =βln(1/η). Through the linear regression calculation of the test results, as shown in Figure 10, the values of parameters A and B can be calculated as shown in Table 7.

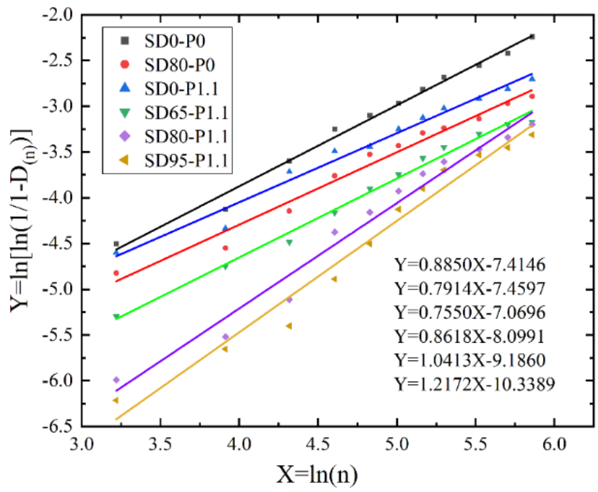


Fig. 10 Linear regression of freeze-thaw damage to concrete

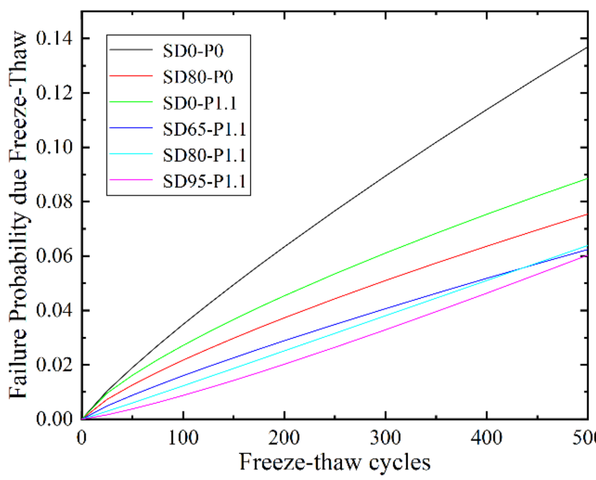


Fig. 11 The change curve of failure probability due freeze-thaw with the number of freeze-thaw cycles.

Table 7. Regression coefficients A, B and correlation coefficient R2

Serial number	A	B	R^2
SD0-P0	0.885	-7.415	0.9901
SD80-P0	0.791	-7.460	0.9786
SD0-P1.1	0.755	-7.070	0.9785
SD95-P1.1	0.862	-8.099	0.9904
SD80-P1.1	1.041	-9.186	0.9741
SD65-P1.1	1.217	-10.339	0.9724

Since A=β, B=βln(1/η), the parametersβ, η and the concrete freeze-thaw damage evolution equation D(n) can be calculated as shown in Table 8.

Table 8. Regression coefficientβ, η and freeze-thaw damage equation D (n)

Serial number	β	η	η-1×10-3	D(n)	R2
SD0-P0	0.885	4352.611	0.2297	$D(n) = 1 - exp\left(-\left(\frac{n}{4352.611}\right)^{0.885}\right)$	0.9901
SD80-P0	0.791	12470.235	0.0802	$D(n) = 1 - exp\left(-\left(\frac{n}{12470.235}\right)^{0.791}\right)$	0.9786
SD0-P1.1	0.755	11663.720	0.0857	$D(n) = 1 - exp\left(-\left(\frac{n}{11663.720}\right)^{0.755}\right)$	0.9785
SD95-P1.1	0.862	12035.208	0.0831	$D(n) = 1 - exp\left(-\left(\frac{n}{12035.208}\right)^{0.862}\right)$	0.9904
SD80-P1.1	1.041	6796.802	0.1471	$D(n) = 1 - exp\left(-\left(\frac{n}{6796.802}\right)^{1.041}\right)$	0.9741
SD65-P1.1	1.217	4892.608	0.2044	$D(n) = 1 - exp\left(-\left(\frac{n}{4892.608}\right)^{1.217}\right)$	0.9724

In Table 8, the fitting accuracies of the freeze-thaw damage evolution equations of the six groups of concrete specimens are all above 0.97, indicating that high fitting accuracies between the freeze-thaw damage evolution equations and the experimental data, which can accurately predict the degree of freeze-thaw damage of concrete. The failure probability due freeze-thaw Pf(n) can be equivalent to the damage degree D(n). To more intuitively represent the evolution law of HFRC with the number of freeze-thaw cycles, this paper plots the change curve of failure probability due freeze-thaw with the number of freeze-thaw cycles according to the freeze-thaw damage evolution equation D(n), as shown in Figure 11.

According to Figure 11, the degree of failure probability due freeze-thaw is gradually increasing with the increase in the number of freeze-thaw cycles. Compared with fiber concrete, ordinary concrete shows more serious freeze-thaw damage, indicating that the addition of fibers can effectively improve the freeze-thaw resistance of concrete. The freeze-thaw damage degree of SD95-P1.1 is always the smallest, and its freeze-thaw failure ability is optimal, which is also consistent with the experimental results of the mass loss rate and the relative dynamic elastic modulus, indicating that the model of freeze-thaw damage evolution established in this paper is reliable. At the same time, it can be found that the failure probability due freeze-thaw of SD65-P1.1, SD80-P1.1, and SD95-P1.1 are 0.062, 0.064, and 0.060 respectively under 500 freeze-thaw cycles (About 70 years of concrete life in northern China). The failure probability due freeze-thaw of the three HFRC are already very close, which means that the effect of steel fiber content on the freeze-thaw resistance of HFRC after 500 freeze-thaw cycles will be limited.

5. Conclusion

In the existing studies, most researchers used steel fibers, polypropylene fibers, or basalt fibers for hybridization to investigate the effect of fiber hybridization effect on the mechanical properties of concrete. However, there are few studies on the performance and durability of SPHFRC under the influence of multiple factors (Vikrant et al., 2023; Mohamed et al., 2024; Köksal et al., 2023; Zeng et al., 2023). Therefore, this paper takes SPHFRC as the research object, and analyzes the effects of steel fiber content, fiber hybridization and freeze-thaw cycle on the mechanical properties and durability of concrete through experiments. At the same time, according to the freeze-thaw damage theory, the freeze-thaw damage evolution equation of SPHFRC under the action of freeze-thaw cycle is proposed. From the present research, the following conclusions can be drawn:

1. The addition of fibers can improve the compressive and flexural strength of concrete, and the enhancement effect of hybrid fibers on the mechanical strength of concrete is better than that of single mixing of fibers, especially in flexural strength enhancement. At the same time, the growth rate of compressive and flexural strength of HFRC under 28 days is less than that of 7 days, indicating that the hybrid fiber has a better effect on enhancing the strength of concrete in the early stage.
2. Freeze-thaw cycle will adversely affect the physical properties of concrete. With the increase of freeze-thaw cycles, the mass loss rate of concrete gradually increases, and the relative dynamic elastic modulus gradually decreases. The addition of fibers can effectively improve the resistance of concrete under the action of freeze-thaw cycle, especially the hybrid fiber, and this improvement effect increases with the increase of steel fiber admixture in the hybrid fiber.
3. Based on the regression analysis of the experimental results, the freeze-thaw damage evolution equation of HFRC with Weibull distribution was established. Through the freeze-thaw damage evolution curve, it was found that the damage degree of the three kinds of HFRC was very close under 500 freeze-thaw cycles (About 70 years of concrete life in northern China), which means that the influence of steel fiber content on the freeze-thaw resistance of HFRC will be limited after 500 freeze-thaw cycles.

Research limitations and future research focus

This article aims to investigate the influence of fiber type and fiber content on the mechanical properties and frost resistance of concrete. However, the above research has some limitations in many aspects. For example, the effect of changing polyacrylonitrile fiber on mechanical strength and freeze-thaw damage, and the effect of fiber addition on the change of concrete pore structure have not been studied. Future studies can consider the effects of the internal pores of the concrete matrix on the durability performance of concrete and the effects of varying the fiber content on the mechanical properties and freeze-thaw damage of concrete. In addition, the effect of fiber dispersion on the mechanical properties and frost resistance of concrete can be further investigated from the meso-structure.

Conflicts of Interest

The authors declare no conflict of interest.

References

Cen, G.P.; Ma, G.Q.; Wang, S.T.; Zhang, L.J. (2008). Durability of synthetic fiber reinforced concrete for airport pavement. Journal of Traffic and Transportation Engineering, Vol.8 (Issue 3), pages 43-45. https://DOI: 10.3321/j.issn:1671-1637.2008.03.010.

Cao, S.; Zheng, D.; Yilmaz, E.; Yin, Z.Y.; Xue, G.L.; Yang, F.D. (2020). Strength development and microstructure characteristics of artificial concrete pillar considering fiber type and content effects. Construction and Building Materials, Vol.256, 119408.ISSN 0950-0618, https://DOI: 10.1016/j.conbuildmat.2020.119408.

Esakki, A.K.D.K.; Dev, S. K. A.; Gomathy, T.; Gifta, C.C. (2023). Influence of adding steel -glass-polypropylene fibers on the strength and flexural behaviour of hybrid fiber reinforced concrete. Materials Today: Proceedings, Vol.5, 55. https://DOI: 10.1016/j.matpr.2023.05.055.

Duan, M.H.; Qin, Y.; Li, Y.; Zhou, H. (2023). Durability and damage model of polyacrylonitrile fiber reinforced concrete under freeze–thaw and erosion. Construction and Building Materials, Vol.394, 132238. https://DOI: 10.1016/j.conbuildmat.2023.132238.

El-Mal, A.S.S.H.; Sherbini, A. S.; Sallam, H.E.M. (2015). Mode II fracture toughness of hybrid FRCs. International Journal of Concrete Structures and Materials, Vol.9(Issue 4), pages 475-486. https://DOI:10.1007/s40069-015-0117-4.

Alwesabi, E.A.H.; Bakar, B.H.A.; Alshaikh, I.M.H.; Abadel, A.A.; Alghamdi, H.; Wasim, M. (2022). An experimental study of compressive toughness of steel–polypropylene hybrid fibre-reinforced concrete. Structures, Vol.37, pages 379-388. https://DOI: 10.1016/j.istruc.2022.01.025.

Fan, S. (2015). Mechanical and durability performance of polyacrylonitrile fiber reinforced concrete. Materials Research, Vol.18, pages 1298-1303. https://DOI:10.1590/1516-1439.021915.

Fu, Q.; Xu, W.R.; Bu, M.X.; Guo, B.B.; Niu, D.T. (2021). Effect and action mechanism of fibers on mechanical behavior of hybrid basalt-polypropylene fiber-reinforced concrete. Structures, Vol.34, pages 3596-3610. https://DOI: 10.1016/j.istruc.2021.09.097.

GB/T 50081-2019, Standard for test methods of concrete physical and mechanical properties. China Architecture & Building Press, Beijing, China, 2019.

GB/T 50082-2009, Standard for test methods of long-term performance and durability of ordinary concrete. China Architecture & Building Press, Beijing, China, 2009.

Guo, X.K.; Qiao, H.X.; Zhu, B.R.; Wang, P.H.; Wen, S.Y. (2019). Accelerated life testing of concrete based on three-parameter Weibull stochastic approach. KSCE Journal of Civil Engineering, Vol.23 (Issue 4), pages 1682-1690. https://DOI:10.1007/S12205-019-0995-0.

Hu, A.X.; Liang, X.W.; Yu, J.; Shi, Q.X.; Li, L. (2018). Experimental study of uniaxial tensile characteristics of ultra-high-performance concrete. Journal of Hunan University (Natural Sciences), Vol.45(Issue 9), pages 30-37. https://DOI: 10.16339/j.cnki.hdxbzkb.2018.09.004.

Han, J.H.; Zhang, W.J.; Liu, Y. (2022). Experimental study on freeze–thaw resistance of steel fiber-reinforced hydraulic concrete with two-grade aggregate. Journal of Building Engineering, Vol.60, 105181. https://DOI: 10.1016/j.jobe.2022.105181.

He, J.X. (2021). Study on mechanical properties of steel/polyacrylonitrile hybrid fiber concrete. M.A. thesis, Xiangtan University, Xiangtan.

JGJ 55-2011, Specification for mix proportion design of ordinary concrete. China Architecture & Building Press, Beijing, China 2011.

JG/T 472-2015, Steel fiber reinforced concrete. China Architecture & Building Press, Beijing, China, 2015.

JTG 3420-2020, Testing methods of cement and concrete for highway engineering. China Communications Press, Beijing, China, 2020.

Khan, M.S.; Hashmi, A.F.; Shariq, M.; Ibrahim, S.M. (2023). Effects of incorporating fibres on mechanical properties of fibre-reinforced concrete: A review. Materials Today: Proceedings, Vol.5, 106. https://DOI: 10.1016/j.matpr.2023.05.106.

Koushkbaghi, M.; Kazemi, M.J.; Mosavi, H.; Mohseni, E. (2019). Acid resistance and durability properties of steel fiber-reinforced concrete incorporating rice husk ash and recycled aggregate. Construction and Building Materials, Vol.202, pages 266-275. https://DOI: 10.1016/j.conbuildmat.2018.12.224.

Kenny, N.; Dai, Q.L. (2014). Numerical investigation of internal frost damage of digital cement paste samples with cohesive zone modeling and SEM microstructure characterization. Construction and Building Materials, Vol.50, pages 266-275. https://DOI: 10.1016/j.conbuildmat.2013.09.025.

Köksal, F.; Gencel, O.; Unal, B.; Durgun, M. Y. (2012). Durability properties of concrete reinforced with steel-polypropylene hybrid fibers. Science and Engineering of Composite Materials, Vol.19(Issue 1), pages 19-27. https://DOI:10.1515/secm.2011.0064.

Liu, C.J.; Hunag, X.C.; Wu, Y.Y.; Deng, X.W.; Zheng, Z.L.; Yang, B. (2022). Studies on mechanical properties and durability of steel fiber reinforced concrete incorporating graphene oxide. Cement and Concrete Composites, Vol.130, 104508. https://DOI: 10.1016/j.cemconcomp.2022.104508.

Li, C.G.; Dong, C.Q.; Qin, Q.J.; Xiang, L.L.; Ma, L.; Huo, X.Y.; Xing Z.Y. (2015). Experimental research on mechanical properties of Nano-SiO2 hybrid fiber concrete. Materials Reports, Vol.29, pages 48-52.

Luo, D.M.; Wang, Y.; Niu, D.T. (2020). Evaluation of the performance degradation of hybrid steel-polypropylene fiber reinforced concrete under freezing-thawing conditions. Advances in Civil Engineering, Vol.21, 8863047. https://DOI:10.1155/2020/8863047.

Mohamed, O.; Zuaiter, H. (2024). Fresh properties, strength, and durability of fiber-reinforced geopolymer and conventional concrete: a review. Polymers, Vol.16(Issue 1), 141. https://DOI:10.3390/polym16010141.

Norma, G.B.; Dinis, L.T.; Tiago, M.R.; Nuno, C.T.; Eduardo, N.B.P.; Vítor, M.C.F.C. (2021). Effect of polyacrylonitrile fiber on the properties of alkali-activated ceramic/slag-based mortar. Journal of Building Engineering, Vol.44, 103367. https://DOI: 10.1016/j.jobe.2021.103367.

Peng, R.X.; Qiu, W.L.; Jiang, M. (2022). Micromechanical modeling of frozen concrete by micro-deformation of multi-phase composite material. Composite Structures, Vol.301, 116224. https://DOI: 10.1016/j.compstruct.2022.116224.

Qiao, H.X.; Guo, X.K.; Zhu, B.R. (2019). Accelerated life test of concrete under multiple factors based on three-parameter Weibull distribution. Materials Reports, Vol.33(Issue 4), pages 639-643. https://DOI: 10.11896/cldb.201904014.

Shi, X.J.; Park, P.; Rew, Y.H.; Huang, K.J.; Sim, C.W. (2020). Constitutive behaviors of steel fiber reinforced concrete under uniaxial compression and tension. Construction and Building Materials, Vol.233, 117316. https://DOI: 10.1016/j.conbuildmat.2019.117316.

Teng, S.; Afroughsabet, V.; Ostertag, C.P. (2018). Flexural behavior and durability properties of high-performance hybrid-fiber-reinforced concrete. Construction and Building Materials, Vol.182, pages 504-515. https://DOI: 10.1016/j.conbuildmat.2018.06.158.

Vikrant, S.V.; Shrikrishna, A. D. (2023). Hybrid fibre reinforced concrete -A state of the art review. Hybrid Advances, Vol.3, 100035. https://DOI: 10.1016/j.hybadv.2023.100035.

Wang, R.J.; Hu, Z.Y.; Li, Y.; Wang, K.; Zhang, H. (2022). Review on the deterioration and approaches to enhance the durability of concrete in the freeze–thaw environment. Construction and Building Materials, Vol.321, 126371. https://DOI: 10.1016/j.conbuildmat.2022.126371.

Wang, R.G.; Xie, M.; Zhang, J. (2023). Mechanical properties and damage model of modified recycled concrete under freeze-thaw cycles. Journal of Building Engineering, Vol.78, pages 107-680. https://DOI: 10.1016/j.jobe.2023.107680.

Wang, Y.; Niu, D.T.; Song, Z.P. (2014). Durability of Steel Fiber Reinforced Concrete Under Combined Effect of Flexural Loading and Acid Rain Erosion. Materials Reports, Vol.28, pages 120-124. https://DOI: 10.11896/j.issn.1005-023X.2014.24.028.

Wang, P.; Huang, Z.; Zhou, D.; Wang, X.D.; Zhang, C. (2012). Impact mechanical properties of concrete reinforced with hybrid carbon fibers. Shock and Vibration, Vol.31, pages 14-18. https://DOI: 10.3969/j.issn.1000-3835.2012.12.004.

Wang, Y.; Zhang, S.H.; Niu, D.T.; Fu, Q. (2022). Quantitative evaluation of the characteristics of air voids and their relationship with the permeability and salt freeze–thaw resistance of hybrid steel-polypropylene fiber–reinforced concrete composites. Cement & Concrete Composites, Vol.125, 104292. https://DOI: 10.1016/j.cemconcomp.2021.104292.

Wu, P.; Liu, Y.P.; Peng, X.H.; Chen, Z.G. (2023). Peridynamic modeling of freeze-thaw damage in concrete structures. Mechanics of Advanced Materials and Structures, Vol.30, pages 2826-2837. https://DOI: 10.1080/15376494.2022.2064015.

Xie, C.P.; Cao, M.L.; Yin, H.; Guan, J.F.; Wang, L.J. (2021). Effects of freeze-thaw damage on fracture properties and microstructure of hybrid fibers reinforced cementitious composites containing calcium carbonate whisker. Construction and Building Materials, Vol.300, pages 123-872. https://DOI: 10.1016/j.conbuildmat.2021.123872.

Xia, W.; Lu, S.; Bai, E.L.; Xu, J.Y.; Du, Y.H. (2023). Research on mechanical properties of carbon nanotubes-carbon fiber composite modified concrete. Materials Reports, Vol.37, pages 110-118. https://DOI: 10.11896/cldb.22010125.

Xiao, Q.H.; Cao, Z.Y.; Guan, X.; Li, Q.; Liu, X.L. (2019). Damage to recycled concrete with different aggregate substitution rates from the coupled action of freeze-thaw cycles and sulfate attack. Construction and Building Materials, Vol.221, pages 74-83. https://DOI: 443/10.1016/j.conbuildmat.2019.06.060.

Xia, D.T.; Yu, S.T.; Yu, J.L.; Feng, C.L.; Li, B.; Zheng, Z.; Wu, H. (2023). Damage characteristics of hybrid fiber reinforced concrete under the freeze-thaw cycles and compound-salt attack. Case Studies in Construction Materials, Vol.18, e01814. https://DOI: 10.1016/j.cscm. 2022.e01814.

Zhao, C.G.; Wang, Z.Y.; Zhu, Z.Y.; Guo, Q.Y.; Wu, X.R.; Zhao, R.D. (2023). Research on different types of fiber reinforced concrete in recent years: An overview. Construction and Building Materials, Vol.365, 130075. https://DOI: 10.1016/j.conbuildmat.2022.130075.

Zhong, C.H.; Fan, Z.W.; Zhou, J.Z.; Shi, J.N. (2024). Study on frost resistance of stainless-steel fiber recycled concrete based on response surface method and Weibull distribution. Water Resources and Hydropower Technology, Vol.3, pages 1-14. https://DOI: 10.1746.TV.20231101.0919.002.html.

Zheng, Y.X.; Lv, X.M.; Hu, S.W.; Zhuo, J.B.; Wan, C.; Liu, J.Q. (2024). Mechanical properties and durability of steel fiber reinforced concrete: A review. Journal of Building Engineering, Vol.82, 108025. https://DOI: 443/10.1016/j.jobe.2023.108025.

Zeng, Y.S.; Tang, A.P. (2021). Comparison of effects of basalt and polyacrylonitrile fibers on toughness behaviors of lightweight aggregate concrete. Construction and Building Materials, Vol.282, 122572. https://DOI: 10.1016/j.conbuildmat.2021.122572.

Zeng, Z.H.; Li, C.X.; Chen, Z.Y.; Lu, Ke. (2022). Study on mechanical properties and optimum fiber content for basalt/polyacrylonitrile hybrid fiber reinforced concrete. Advances in Materials Science and Engineering. https://DOI:10.1155/2022/4181638.