



Research paper

Mechanical properties of polypropylene fiber reinforced concrete short columns under freeze-thaw cycles

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Abstract: To investigate the effect of polypropylene fibers on the mechanical properties of concrete structures in cold regions, obtain an appropriate amount of polypropylene fiber content, and improve the frost resistance of the structure, freeze-thaw cycle tests were conducted on three groups of reinforced concrete short column specimens with different polypropylene fiber contents. The depth of surface damage of the specimen was detected using ultrasonic method. The stress process and failure of the specimen were analyzed through axial compression test, and the corresponding changes in compressive toughness were discussed. A formula for calculating the axial compressive bearing capacity of polypropylene fiber reinforced concrete short columns after freeze-thaw cycles was established. The test results indicate that the addition of polypropylene fibers can reduce the compressive bearing capacity of reinforced concrete short columns. An appropriate amount of polypropylene fiber can enhance the frost resistance, ductility and toughness of concrete components, and the recommended volume fraction of polypropylene fiber is 0.08–0.12%.

Keywords: freeze-thaw cycle, polypropylene fiber, surface damage, compressive toughness

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1. Introduction

Freeze-thaw is one of the key factors considered in the structural design of landform areas such as high mountains, permafrost areas, and iceberg areas. Frost heave can cause continuous damage to concrete from the outside to the inside, thereby reducing its mechanical properties [1, 2]. Many researches on how to improve the frost resistance of concrete and recycled concrete have been conducted [3–6]. Adding fibers to concrete or recycled concrete to improve its frost resistance is one of the important research directions currently.

Fiber reinforced concrete is a composite concrete with concrete as the matrix and metal and non-metal fibers as reinforcement materials. During freeze-thaw cycles, fibers can inhibit the development of micro cracks within the concrete matrix and play a role in crack resistance and toughening, thereby improving the frost resistance of the concrete matrix [7–9]. Chen and Bao [10] compared and analyzed the effects of polypropylene fibers and steel fibers on the frost resistance of concrete through experiments. It was found that polypropylene fibers can reduce the weakening of concrete strength caused by freeze-thaw cycles, while steel fibers can significantly improve the flexural and tensile strength of concrete. Zhong et al. [11] studied the toughening mechanism of steel fibers on concrete matrix and found that steel fibers can significantly improve the toughness of concrete after peak. Steel fibers have a significant crack resistance effect and are widely used in engineering. However, in areas subjected to freeze-thaw cycles, a water rich environment makes steel fibers prone to corrosion. Rust expansion causes pressure on the concrete surrounding the steel fibers, leading to cracking along the direction of the steel fibers, which is not conducive to the frost resistance of concrete.

Chen et al. [12] studied the injury of the fiber reinforced concrete after freezing and thawing cycle, the results showed that polypropylene fibers are evenly distributed and less prone to clustering in concrete. The width of cracks after the failure of polypropylene fiber reinforced concrete is relatively narrow, and the inhibitory effect on freeze-thaw damage is also more pronounced. Therefore, in special environments, polypropylene fibers can replace steel fibers as concrete reinforcement materials to achieve better results.

Chen et al. [13] studied the durability properties of macro-polypropylene fiber reinforced Concrete when it is placed in different environments—including resistance to freezing and thawing cycles, sulfate, acid attacks, and obtained a suitable fiber content. Zhao et al. [14] employed the split Hopkinson pressure bar and digital pulse shaping technology to study the dynamic compression performance and constitutive relation of polypropylene fiber reinforced high-strength Concrete in the cold regions under the deteriorating effect of freeze-thaw cycle, and got the dynamic increase factor. Zheng et al. [15] studied the effect of microwave heating modification on the frost resistance of fiber-reinforced self-compacting recycled concrete, and analyzed the changing trend of parameters such as elastic modulus mass, peak stress, peak strain, ultimate strain, Poisson's ratio with the number of frozen fusion.

The research on the frost resistance of polypropylene fiber reinforced concrete mainly focuses on the compressive strength, microscopic pore structure, and plastic cracking of the specimen level [16, 17]. There are few studies on the freeze-thaw cycles of polypropylene fiber reinforced concrete components. To study the changes in frost resistance, ductility, toughness, bearing capacity of reinforced concrete components under freeze-thaw action

after adding polypropylene fibers and obtain suitable values for the amount of polypropylene fiber admixture, and to provide a reference for the design of concrete structures in frozen areas, under 200 freeze-thaw cycles, the changes in frost heave damage, bearing capacity, and compressive toughness of concrete axial compression short column specimens with three different polypropylene fiber contents is compared and analyzed. The corresponding formulas for calculating the ultimate bearing capacity of concrete axial compression short column specimens are established.

2. Test materials and plans

2.1. Component design

This experiment used type 42.5 rapid-setting Portland cement (P·C42.5R). The aggregate is natural limestone crushed stone with a particle size of 5–20 mm. The sand is made of natural fine sand with a fineness modulus of 0.7. The water is ordinary tap water, and the water reducer adopts carboxylic acid high-efficiency water reducer, with a water reduction rate of $\geq 20\%$. The fibers are made of polypropylene crack resistant fine fibers. The material parameters are shown in Table 1.

Concrete mixing ratio: The design strength grade of concrete was C30, with a water cement ratio of 0.45. The corresponding concrete mixing ratio was: cement: river sand: aggregate: water = 367:682:1114:154, and the water reducing agent dosage was 1%.

Three sets of blending schemes with polypropylene fiber volume ratios of 0.05%, 0.10%, and 0.15% were designed, with two specimens in each group. Short column specimens were equipped with four longitudinal bars with a diameter of 12 mm and a grade of HRB400. The hoop reinforcement adopted HPB300 steel bars with a diameter of 6 mm, and a spacing of 100 mm between dense areas and 150 mm between non dense areas. The protective layer thickness of the specimens was 25 mm. The main dimensions and reinforcement parameters of the specimen are shown in Fig. 1, and the units of measurement in the diagram are all in millimeters.

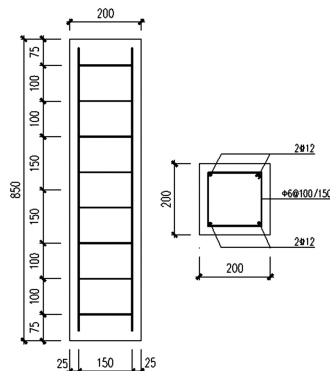


Fig. 1. Specimen size and reinforcement

Table 1. Mechanical performance of polypropylene fibers

Aspect ratio/ μm	Section Type	Tensile strength /MPa	Elastic modulus /GPa	Density/ kg/L
167	Bundle monofilament	> 458	> 3.5	0.91

2.2. Test plans

Freeze-thaw cycle test plan: The freeze-thaw cycle test plan shall be designed in accordance with the “Rapid Freezing Method” for the concrete frost resistance test specified in the “Long term Performance and Durability Test Plan for Ordinary Concrete” (GJ/T 50082-2009). The experiment was conducted in the high and low temperature humidity and heat test chamber of the Tunnel Laboratory at Chongqing Jiaotong University. Three sets of axially compressed short columns and corresponding nine 150 mm short columns $150 \times 150 \times 150$ mm cube in water for four days before the experiment to fully saturate it. The number of freeze-thaw cycles in this test was 200 times, and the time of each test was less than 4h, of which the thawing time was 1h. When completely frozen, the temperature of the core area of the short column was controlled at $(-18 \pm 2)^\circ\text{C}$; when completely thawed, it was controlled at $(5 \pm 2)^\circ\text{C}$. In order to probe the temperature, change of the test piece during the freeze-thaw cycle, a temperature probe was embedded in the core area of the concrete short column.

Static loading scheme: The static loading test of the axial compression short column was completed in the structural engineering test hall of Chongqing Jiaotong University, and the loading device selected was YAW-1000F 1000-ton press. Two displacement sensors were added horizontally along the loading platform to measure the longitudinal deformation of the specimens. The top of the column was leveled with dry sand to ensure uniform stress on the specimens. Before the formal loading, 3 cycles of preloading were carried out with a preload of 100 kN. After the formal loading begins, the load was graded according to 1/10 of the estimated failure load. When the short column specimen cracked, the loading value was reduced to the original 1/2 and slowly loaded until the specimen reached its ultimate load. The loading holding time for each level was 2 minutes. The cube test block was continuously and uniformly loaded at a speed of 0.5 MPa per second. When the cube test specimen approached failure, the test throttle was stopped until the specimen failed, and the failure load was recorded at this time.

3. Test results and analysis

3.1. Surface damage depth

After 200 freeze-thaw cycles, the surfaces of three sets of specimens and corresponding test blocks were subjected to varying degrees of freeze-thaw damage. The main manifestation was the appearance of pits and pores on the surface of the concrete, among which the surface damage of the short column with a volume fraction (ρ_v) of 0.10% polypropylene fiber was relatively

minimal. However, none of the three groups of components showed common slag dropping, cracking, and surface concrete peeling that occur when ordinary concrete was subjected to freeze-thaw [18]. This indicates that adding polypropylene fibers can effectively improve the frost resistance of concrete structures and suppress the development of micro cracks and pores.

To obtain the depth of surface damage on the components, a non-metallic ultrasonic testing analyzer was used to detect the three groups of components. Six measuring points were set along the length direction of the component to test the sound time values of different ultrasonic propagation lengths. The spacing between measuring points was 30 mm, and each short column was tested three times.

According to the ranging and average sound time value of each component measuring point, the “time-distance” diagram is drawn, as shown in Fig. 2. Considering that different wave velocities of sound waves in different media cause the turning points in Fig. 2, regression analysis is used to establish the linear equation y_f of damaged concrete and the linear equation y_a of undamaged concrete, with R^2 being the corresponding goodness of fit.

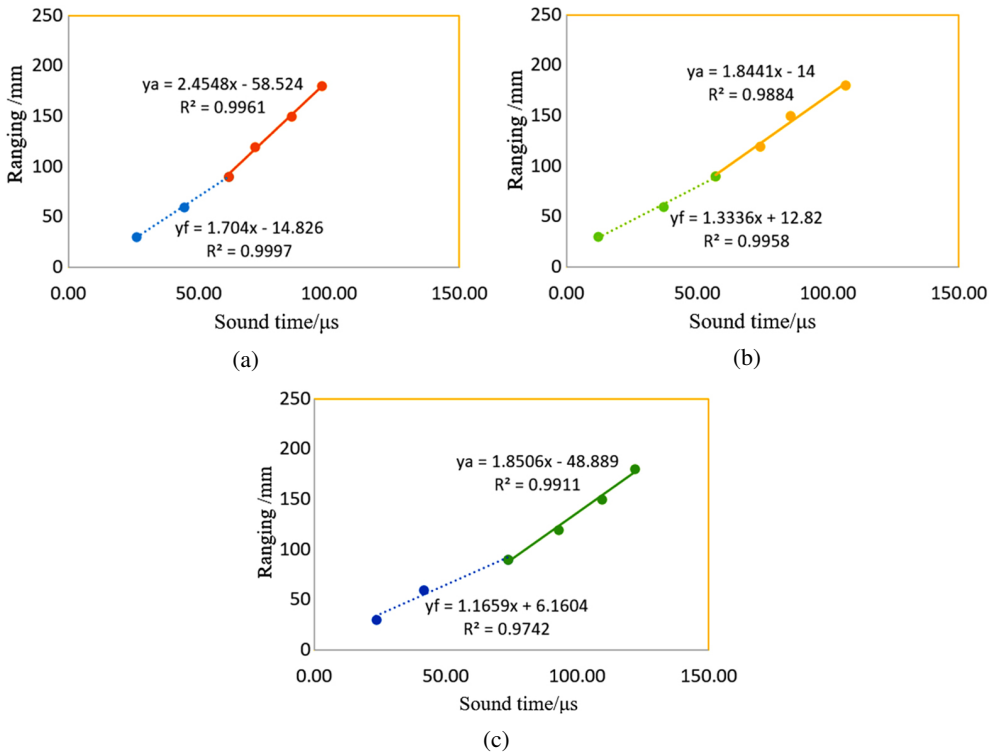


Fig. 2. Relationship of sound time and ranging ($\rho_v =$): (a) 0.05%, (b) 0.1%, (c) 0.15%

According to the intercept and slope of the damaged concrete linear equation and the undamaged concrete linear equation in Fig. 2, the damage layer thickness of each group of components after 200 freeze-thaw cycles can be calculated. The results are shown in Table 2.

Table 2. Calculation results of freeze-thaw damage thickness

Fiber volume fraction ρ_v /%	Freeze-thaw damage thickness/mm
0.05	17.92
0.10	15.83
0.15	22.23

As shown in Table 2, after 200 freeze-thaw cycles, these three groups of polypropylene fiber short columns suffered varying degrees of freeze-thaw damage. Among them, when the volume fraction of polypropylene fiber is 0.15%, the short columns are most severely damaged, with a damage layer thickness of 22.23 mm and the most obvious surface defects. When the fiber volume fraction is 0.10%, the gain in structural frost resistance is most significant; the thickness of the damaged layer is the smallest, and the area of pits and pores is also the smallest. This indicates that the addition of polypropylene fibers within a reasonable range can effectively suppress the development of concrete cracks during freeze-thaw processes and enhance the structural frost resistance.

3.2. Axial compression test

Three sets of specimens were loaded according to the static loading scheme. In the initial stage of loading, the specimen was basically within the elastic working range, and the axial deformation of the short column was roughly linearly related to the external load. There were no obvious cracks on the surface of the specimen. When the load was increased to 40% of the failure load, the concrete on the surface of the component reached its ultimate tensile strain, and small cracks appeared. At this time, a faint “click” sound can be heard when the concrete split. As the load continued to increase, concrete cracking intensified and the width of surface cracks increased. When the load reached about 80% of the failure load, the lateral deformation of the short column further increased. A large number of cracks appeared on the side, continuously spreading to the surrounding areas; when reaching the failure load, the longitudinal reinforcement underwent significant compressive deformation.

During loading, it was found that as the load increased, cracks developed, but the phenomenon of concrete falling was not severe. The integrity and continuity of the specimens remained well, indicating that randomly distributed polypropylene fibers can effectively improve the mechanical properties of concrete, enhance the crack resistance of concrete materials, and delay the development of macroscopic cracks in concrete.

The failure mode of axial compression short column specimens of reinforced concrete with different volume ratios of polypropylene fiber is shown in Fig. 3.

Fig. 4 shows the measured load displacement curves of three sets of axially compressed specimens. It can be observed that after freeze-thaw cycles, the ultimate bearing capacity of the specimens generally decreases as the polypropylene fiber content increases. This is consistent with the conclusion [19] that the addition of polypropylene fiber has no significant effect on the structural bearing capacity or will reduce the structural bearing capacity. According to Swamy

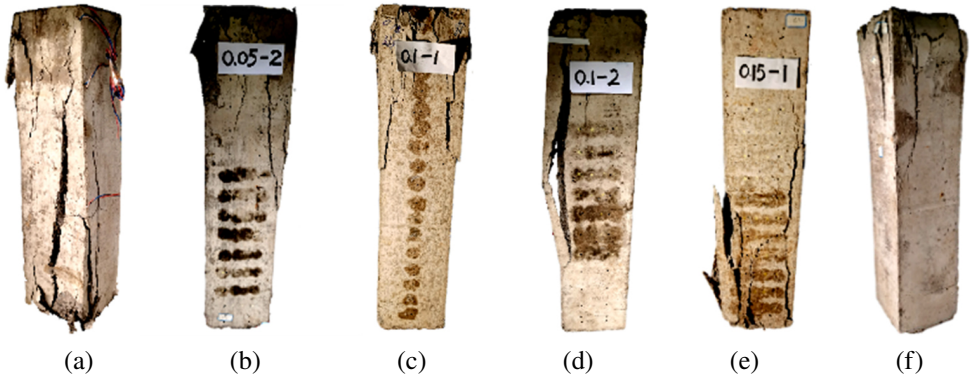


Fig. 3. Failure modes of the specimens ($\rho_v =$): (a) 0.05%-1, (b) 0.05%-2, (c) 0.10%-1, (d) 0.10%-2, (e) 0.15%-1, (f) 0.15%-2

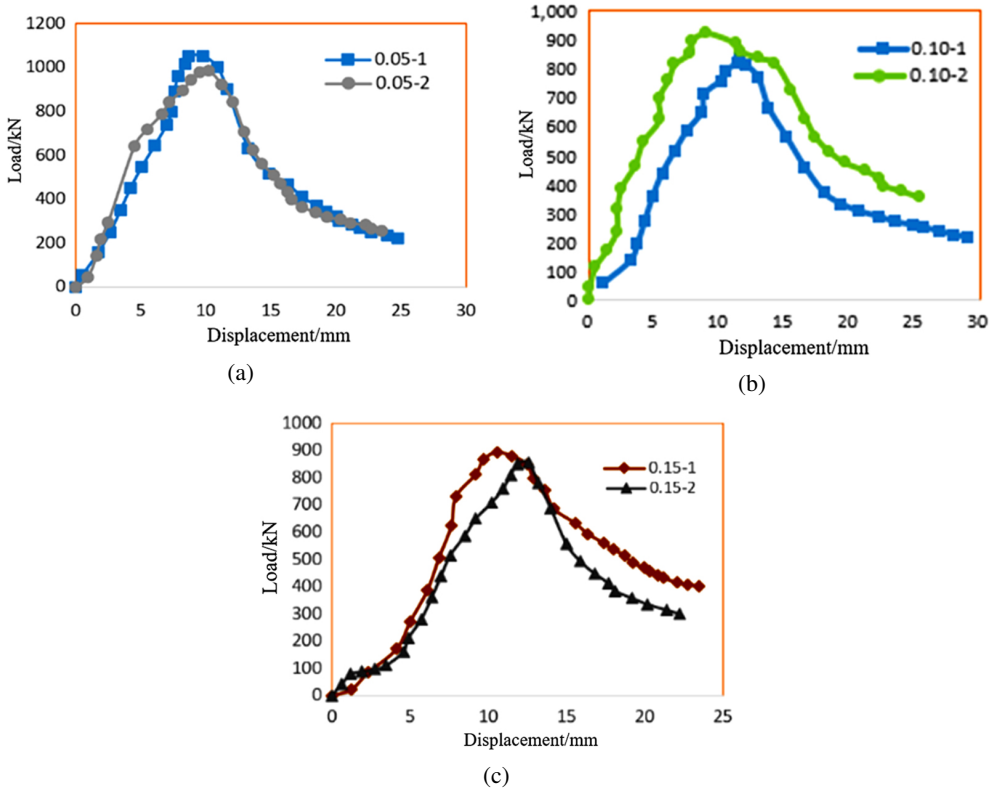


Fig. 4. Load-displacement curves ($\rho_v =$): (a) 0.05%, (b) 0.10%, (c) 0.15%

Manga's composite material theory, the mechanical properties of multiple composite materials depend on the weighted elastic superposition of the corresponding mechanical properties of multiple single materials. However, the elastic modulus of polypropylene fiber is only about one tenth of that of concrete, and the addition of polypropylene fiber will reduce the ultimate bearing capacity of concrete structures.

At the same time, it can be observed that the descending segment of the load displacement curve corresponding to the three groups of components is relatively gentle. After being subjected to freeze-thaw cycles, ordinary concrete will significantly increase the probability of structural penetration cracks, reduce the overall stiffness of the structure, and the frost heave effect will further develop micro cracks at the interface of coarse aggregates in concrete and inside mortar. The accumulation of such damage will lead to more obvious brittle failure of concrete when subjected to external loads, and the phenomenon of "spikes" in the load displacement curve will be severe [20,21]. Adding polypropylene fibers is essentially equivalent to adding "micro steel bars" to concrete materials, allowing the concrete to still have a certain tensile strength after cracking, increasing its structural deformation capacity, and making its ductile failure characteristics more obvious.

3.3. Analysis of compressive toughness

From an energy perspective, the product of load and displacement is the amount of energy absorbed by the specimen during loading, which is the area enclosed by the envelope line in the load curve. Referring to [22,23], the energy absorption corresponding to the cracking load, ultimate load, and failure load of the specimen is defined as follows:

1. The area from the coordinate origin of the load displacement curve to the envelope line of the corresponding load when the first crack appears is defined as CPE (Compressive pre-crack energy absorption);
2. The area within the envelope line of the load to ultimate load corresponding to the first crack appearing on the load displacement curve is defined as CCE (Compressive cracked energy absorption);
3. The sum of CPE and CCE is defined as CE_{max} (Compressive energy absorption);
4. The area enclosed by the load envelope after the ultimate load of the load displacement curve is defined as FCE (Failure compressive energy absorption);
5. The sum of CPE, CCE and FCE is CTE (Compressive total energy absorption);
6. CTE/CPE is defined as the compressive toughness index CTI (Compressive toughness index) of the test specimen;
7. Considering that the load displacement curve of the specimen will enter a rapid decline segment after reaching its peak, the failure displacement is defined as:

$$(3.1) \quad D_F = D_P \times 0.3 + D_P$$

where: D_F – the failure displacement, D_P – the peak displacement.

According to the above definitions, the CPE, CCE, CE_{max} , FCE, CTE, and CTI of three groups of specimens are calculated, and the results are shown in Table 3.

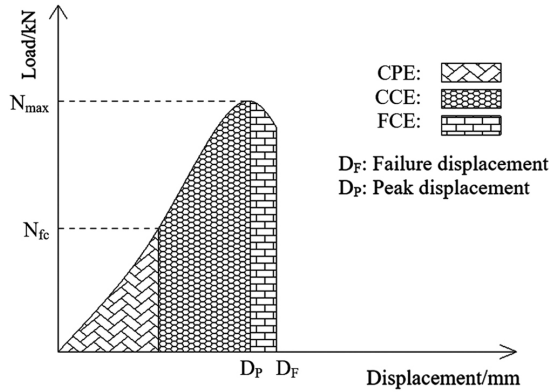


Fig. 5. Energy fractal diagram of load displacement curve

Table 3. Compressive performance test results of the specimens

Specimen No.	Cracking load /kN	Ultimate load/kN	Failure load/kN	CPE /kN·mm	CCE /kN·mm	CE _{max} /kN·mm	FCE /kN·mm	CTE /kN·mm	CTI /kN·mm
0.05-1	515.07	1056.24	910.17	1109.21	3198.70	4307.90	2632.38	6940.28	6.26
0.05-2	540.08	987.97	651.35	1137.05	4792.52	5929.58	2624.53	8554.11	7.52
0.10-1	350.31	829.35	684.57	634.54	5805.01	6439.54	1700.06	8139.60	12.83
0.10-2	451.80	925.24	837.54	806.24	4982.57	5788.80	2629.79	8418.60	10.44
0.15-1	360.56	896.29	730.82	714.55	3476.89	4191.44	2691.37	6882.81	9.63
0.15-2	420.74	861.02	496.26	1120.66	3784.24	4690.31	2483.93	7174.24	6.40

According to Table 3, the compressive total energy and compressive toughness index calculated for the specimens with a volume fraction of 0.10% polypropylene are both the highest. The average compressive total energy of the specimens with a content of 0.05% and 0.15% increased by 6.87% and 17.79% respectively, while the corresponding average compressive toughness index increased by 68.94% and 45.14%, respectively.

The main reason is that during the compression failure process of the specimens, the three-dimensional disorderly distribution of polypropylene fibers inhibits the development of cracks and effectively improves the ultimate deformation capacity of the concrete due to its high fracture elongation. At the same time, polypropylene fibers help the concrete absorb some energy during the crack resistance process, ultimately improving the compressive toughness of the component. Excessive addition of polypropylene fibers will lead to poor fluidity and workability of concrete, reduce the elastic modulus and compressive strength of components, and produce a “ball forming” effect that prevents fibers from being evenly distributed in the concrete. These will have adverse effects on the frost resistance, bearing capacity, and compressive toughness of polypropylene fiber reinforced concrete subjected to freeze-thaw cycles.

3.4. Ultimate bearing capacity analysis

Referring to the formula for the bearing capacity of reinforced concrete axial compression components, and considering the combined effects of freeze-thaw cycles and polypropylene fibers on concrete, the formula for calculating the axial compressive bearing capacity of polypropylene fiber reinforced concrete short columns after freeze-thaw cycles is obtained:

$$(3.2) \quad N_{\text{duk}} = 0.9\phi \left(f'_{dck} A_{de} + f'_{yk} A'_s \right)$$

where: N_{duk} – the standard value of the bearing capacity of polypropylene fiber reinforced concrete short columns after freeze-thaw cycles; ϕ – the stability coefficient of axial compression components, here taken as 1.0; A_{de} – equivalent cross-sectional area of components after freeze-thaw cycles, $A_{de} = A - \beta \times N$ [24, 25], where N is the number of freeze-thaw cycles; β is the coefficient of freeze-thaw cycle damage, and $\beta = 18$ after 200 freeze-thaw cycles. f'_{dck} – the standard value of axial compressive strength of polypropylene fiber reinforced concrete after freeze-thaw cycles, which can be obtained by calculating the conversion formula $f'_{dck} = 0.87 f'_{dcu,k}$ for the compressive strength and axial compressive strength of polypropylene fiber reinforced concrete cubes; $f'_{dcu,k}$ is the compressive strength of polypropylene fiber reinforced concrete cubes after freeze-thaw cycles, which is taken according to Table 4 when subjected to 200 freeze-thaw cycles. f'_{yk} – the standard yield strength value of longitudinal compressive steel bars. A'_s – the cross-sectional area of all longitudinally compressed steel bars.

Table 4. Compressive strength of cube after 200 freezing-thawing cycles

Fiber volume fraction ρ_v /%	Load /kN	Average load /kN	Compressive strength of cubes /MPa
0.05	732.58	668.97	29.73
0.05	647.68		
0.05	626.64		
0.10	565.15	624.89	27.77
0.10	680.09		
0.10	629.42		
0.15	648.76	573.82	25.50
0.15	557.47		
0.15	515.266		

The theoretical values of the axial compressive bearing capacity of polypropylene fiber reinforced concrete short columns after 200 freeze-thaw cycles calculated according to Eq. (3.1) are shown in Table 5. The corresponding measured values of the component bearing capacity test are also provided [26].

According to Table 5, the theoretical value of the bearing capacity of polypropylene fiber reinforced concrete short columns after 200 freeze-thaw cycles calculated according to Equation (3.1) is close to the experimental measured value. This formula can provide a reference for the design of polypropylene fiber reinforced concrete short column structures subjected to freeze-thaw effects.

Table 5. Tested values and theoretical values

Fiber volume fraction ρ_v /%	Measured value of load /kN	Measured value of load /kN	Theoretical value/measured value
0.05	1022.11	1010	0.988
0.10	877.30	949	1.082
0.15	878.66	890	1.013

4. Conclusions

1. When the number of freeze-thaw cycles is 200, the compressive strength of concrete and the ultimate bearing capacity of reinforced concrete short column specimens generally decrease with the increase of polypropylene fiber content, and this is mainly due to the lower strength and modulus of elasticity of polypropylene fibers themselves.
2. Proper polypropylene fibers can enhance the frost resistance of concrete structures, reduce surface damage to components, and improve the ductility and toughness of components. However, excessive polypropylene fiber content can have an adverse effect. Based on the test, it is recommended to add polypropylene fibers with a volume ratio of 0.08–0.12% to achieve better frost resistance performance of concrete.
3. Considering the freeze-thaw effect and polypropylene fiber content, a calculation formula for the ultimate bearing capacity of polypropylene fiber reinforced concrete short columns under axial compression after 200 freeze-thaw cycles is established. This can provide a reference for the engineering application of polypropylene fiber reinforced concrete structures in freeze-thaw areas.
4. Due to the characteristics of polypropylene fibers, the specimens in the study have enhanced frost resistance while sacrificing a certain load-bearing capacity. In the future, it may be considered to incorporate an appropriate proportion of hybrid fibers into the concrete to further expand its performance.
5. This paper mainly discusses the compressive bearing capacity and compressive toughness of polypropylene concrete after freeze-thaw action, without discussing its flexural and tensile properties. This could be considered as a future research direction.

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