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Effect of Steel Fibers on Frost Resistance of Phosphogypsum Concrete

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Abstract: Phosphogypsum concrete is a new kind of green and low-carbon building material, but its mechanical properties and frost resistance are worse than of standard concrete. In order to improve the durability of phosphogypsum concrete, a certain amount of steel fiber is considered. Using C40 phosphogypsum concrete as matrix, the effect of steel fiber on the freeze-thaw performance of phosphogypsum concrete was studied by adding different proportions of steel fiber. Through the orthogonal test of the antifreeze performance data of steel fiber and phosphogypsum concrete with different content ratio, it is concluded that the concrete with steel fiber content of 1.5% and phosphogypsum replacement rate of 60% has better antifreeze performance, and steel fiber can significantly reduce the freeze-thaw damage of phosphogypsum concrete. The test results show that the anti-cracking effect and anti-freezing property of phosphogypsum concrete are obviously enhanced when steel fiber is added to the concrete. The research results can provide reference for the application of steel fiber phosphogypsum concrete in construction projects in cold and frozen areas.

Keywords: durability; freeze-thaw cycle; phosphogypsum concrete; steel fiber reinforced concrete

1 INTRODUCTION

1.1 Current Status of Phosphogypsum Concrete Research

Phosphogypsum is a by-product of phosphoric acid production and is one of the largest producers of gypsum waste, with a large accumulation and low utilization rate, which has a certain impact and harm on the surrounding ecological environment [1-3]. Phosphogypsum has the same gelling property as cement after harmless pretreatment such as calcination and lime mixing. After pretreatment, solid waste phosphogypsum replaces part of cement to prepare concrete, which can not only eliminate a large amount of phosphogypsum inventory, but also reduce the production and use of cement [4-8], so as to achieve environmental protection and the purpose of turning waste into treasure. This provides a reference for the development and application of new low-carbon green building materials [9-10].

1.2 Fiber Concrete Freeze-Thaw Damage Mechanism

The freeze-thaw damage mechanism of fiber concrete is similar to that of plain concrete and can be explained by hydrostatic pressure theory and osmotic pressure theory. According to the theory of hydrostatic pressure, concrete is composed of solid particles of concrete, pores of concrete, water filled in the gap between particles and air inside concrete. Concrete solid particles and air inside concrete have no obvious effect on freeze-thaw damage of concrete. However, when concrete is in a cold environment, capillary water and free water inside concrete freeze at low temperature. The frost heave force generated after freezing causes micro cracks inside the concrete. With the repeated action of the freeze-thaw cycle of the concrete, the internal cracks are connected and developed to the surface of the concrete, which ultimately leads to the reduction of the strength of the concrete and the deterioration of its performance. Osmotic pressure theory suggests that when deicing salts are sprayed on concrete surfaces in winter, salt water will penetrate into the internal pores of concrete along with the melting snow water. When the temperature decreases again, the solution will enter the large pores from the small holes due to the concentration difference between the large pores and the small pores. During the process of the liquid passing through the pore wall, ruthenium osmotic pressure will be generated on the coagulation, which is the main reason for the freeze-thaw damage of concrete.

In the fiber concrete mixing admixture, such as air-entraining agent, maintenance and hardening of concrete paste will produce independent, closed air bubbles. As the bubble is not easy to absorb water saturation, for the pore water to provide a "decompression space", the compressed pore water is discharged into the bubble in the vicinity of the pore water to shorten the length of the process of pore water, reducing the hydrostatic pressure. During the freeze-thaw cycle of hardened concrete, the internal and external stresses and temperature differentials experienced by the structure cause a transition in the concrete matrix from its original dense state to a loose and porous state. This, combined with the simultaneous effects of hydrostatic pressure and osmotic pressure, initiates crack formation within the concrete structure. Over time, these internal pores and small cracks gradually expand, resulting in varying degrees of structural damage [11-13].

The three-dimensional chaotic distribution of fibers in a grid structure effectively restricts the expansion and spalling of the concrete surface layer. Cracks encountered by the fibers change direction, continuing to propagate along the fiber-substrate interface, thereby preventing the formation of through cracks in concrete. The bridging effect of fibers blocks interconnected pores within the matrix, enhancing bonding between fibers and paste, resulting in denser concrete structures. This also significantly reduces water's freedom of movement, thus decelerating further development of existing cracks and inhibiting new crack formation [14, 15]. The fiber can also improve the freeze-thaw cycle process of concrete surface spalling, reduce its quality loss rate [16]. At present, it is believed that fiber can significantly improve the frost resistance of concrete through the above process, but there are few studies on the frost damage mechanism of fiber concrete, so further discussion is needed.

1.3 Research Status of Freeze Resistance of Steel Fiber Phosphogypsum Concrete

Concrete is one of the main civil engineering materials, but the shortcomings of concrete materials such as self-weight, low tensile strength and brittle nature limit its wide application in the field of engineering, and the main factors affecting the durability of concrete are corrosion of reinforcing bars, freezing and physicochemical effects, and the freezing factor is an important reason affecting the durability of concrete structures [17-19]. The fiber, when distributed in a three-dimensional chaotic pattern within the cement matrix as a reinforcing material, has been extensively studied and proven to effectively mitigate the brittleness of concrete. This results in an enhancement of its tensile strength, thus highlighting its significant research value [20].

Steel fiber concrete, as an emerging construction material, has been widely used in engineering practice due to its excellent performance. Freezing and thawing cycles in cold regions lead to the reduction of concrete durability, which is ultimately manifested in the expansion and penetration of cracks [21, 22]. The concrete matrix itself is a multiphase-multicomponent-non-homogeneous brittle material with low tensile-to-compression ratio and small ultimate elongation, and the damage evolution during freeze-thaw cycling leads to earlier destruction of the structure.

The poor freeze-thaw resistance of phosphogypsum concrete leads to the limitation of its use in buildings in cold regions, and it is difficult to meet the requirements of lightweight, high strength and durability of engineering structures and buildings in cold regions. Incorporating steel fibers into the phosphogypsum concrete matrix is an effective way to improve the crack-resistant ability of concrete, which can have a significant crack-resistant effect on the concrete structure, thus strengthening the tensile strength of concrete [23-25]. Therefore, it is of great practical value to carry out research on the freeze-thaw performance of steel fiber phosphogypsum concrete [26-28].

2 MATERIALS AND METHODS

2.1 Test Materials

The cement is P·O42.5 grade cement. Tabs. 1 and2 list the chemical composition and physical and mechanical properties of the cement. The main component of phosphogypsum, $CaSO_4 \cdot 2H_2O$, has a water content of 10.0%-15.0%, the average particle size of fineness is 80 μm, and the pH value is about 1.9-5.3.

Table 1 Chemical composition analysis of cement

Chemical composition	CaO	SiO_2	SO_3	Al_2O_3	Fe_2O_3	MgO	K_2O	TiO_2	Na_2O
Content / %	69.08	23.14	4.98	4.60	3.07	1.85	0.75	0.58	0.30

Table 2 Physical and mechanical properties of cement

Compressive strength / MPa		Flexural strength / MPa		Stability	Heat loss / %	Surface area / m^2/kg
3d	28 d	3d	28 d	competent	3.28	363
33.5	60	6.4	9.7			

The sand is medium coarse sand with an apparent density of 2480 kg/$m^{3,}$ a bulk density of 1320 kg/$m^{3,}$ a mud content of 0.8% and a fineness modulus of 2.4. The concrete coarse aggregate is 5-20mm continuous graded gravel with good particle grading, apparent density of 2700 kg/m^3 and bulk density of 1430 kg/m^3. HYPCA polycarboxylic acid series high performance water reducing agent was used as admixture, the water reducing rate was 25.5%, the solid content was 10.9%, the flow of cement paste was 260 mm, the density was 1.03 g/cm^3. The shear steel fiber of circular section is selected, with a length of 35 mm, a diameter of 0.8 mm, a density of 1.15 g/cm, a tensile strength of 630MPa, and an elastic modulus of 9900 MPa. Water shall be experimental water that meets the requirements of the standard.

2.2 Pilot Program

When concrete is prepared into various buildings or structures, it needs to meet the requirements of serviceable life cycle of as short as 50 years and as long as 80-100 years, which is mainly due to the fact that the buildings are exposed to various natural environments and internal closed environments for a long period of time, and are subjected to the erosion from the atmosphere, water bodies, and so on [29, 30].

The durability test of concrete can simulate the reaction between concrete and internal cement caused by salt erosion and chloride ion penetration after being exposed to rainwater, rivers, or other water bodies. It can also replicate the thermal expansion and contraction of the internal volume of concrete due to freezing and thawing in cold winter conditions when temperatures drop below –20 °C.

The above conditions will have an impact on the service life of concrete, thus affecting the safety of buildings and human life and property, so the durability test is an important index for the qualified testing of concrete products. According to the requirements of GB/T50082-2009 "Standard of Test methods for long-term performance and durability of ordinary concrete" and relevant regulations, the following tests were carried out for the frost resistance of steel fiber phosphogypsum concrete.

(1) Preparation of test pieces

Prepare 100 mm according to the experimental design ratio × 100 × 400 mm steel fiber phosphogypsum concrete prism specimen. Steel fibers are added based on the grouping of modified phosphogypsum concrete, as shown in Tabs. 2 and 3. Among them, G0L0 was used as the blank control group, and five different amounts of phosphogypsum concrete that performed well in the single addition experiment were added with different percentages of steel fibers to explore the influence and role of SF on the workability and mechanical properties of concrete.

Before preparing the test piece, the raw materials should be pretreated: phosphogypsum is calcined at high temperature, mixed with lime for harmless treatment, then dried and screened; Determine the mud content of sand and dry and screen it; Cement screening to remove solidified hard lumps; Dry the stones naturally. Then use an electronic balance to weigh the amount of raw materials according to the ratio, and use a measuring cylinder to take water during the experiment.

Pour the preprocessed raw materials into the mixer in sequence. After mixing cement, sand, and coarse aggregate in a mixer, the steel fibers are evenly sprinkled and stirred for about 2 minutes. Finally, water is added to mix to ensure uniform distribution of the steel fibers. To avoid steel fiber agglomeration, manual stirring should be used, and the mixed mixture should be measured for slump to determine whether it meets the target design requirements. Pour the mixed slurry into the test mold and place it on a compaction table for compaction until there are no more bubbles on the surface of the test piece. After scraping it flat, let it sit and let it naturally solidify for 24 hours [31-34].

Table 3 Steel fiber mixed C40 phosphogypsum concrete mix

Group	Steel fibre / %	Phosphogypsum / %	Substrate usage / kg/m^3							
			Phosphogypsum	Cement	Sand	Stones	Fly ash	Mineral powder	Water reducing agent	Water
G0L0	0	0	0	232.44	35.11	1146.72	29.06	29.06	2.91	145.28
G1L1	0.5	15	34.87	197.57	35.11	1146.72	29.06	29.06	2.91	145.28
G2L1	1		34.87	197.57	35.11	1146.72	29.06	29.06	2.91	145.28
G3L1	1.5		34.87	197.57	35.11	1146.72	29.06	29.06	2.91	145.28
G4L1	2		34.87	197.57	35.11	1146.72	29.06	29.06	2.91	145.28
G1L2	0.5	30	69.73	162.71	35.11	1146.72	29.06	29.06	2.91	145.28
G2L2	1		69.73	162.71	35.11	1146.72	29.06	29.06	2.91	145.28
G3L2	1.5		69.73	162.71	35.11	1146.72	29.06	29.06	2.91	145.28
G4L2	2		69.73	162.71	35.11	1146.72	29.06	29.06	2.91	145.28
G1L3	0.5	45	104.60	127.84	35.11	1146.72	29.06	29.06	2.91	145.28
G2L3	1		104.60	127.84	35.11	1146.72	29.06	29.06	2.91	145.28
G3L3	1.5		104.60	127.84	35.11	1146.72	29.06	29.06	2.91	145.28
G4L3	2		104.60	127.84	35.11	1146.72	29.06	29.06	2.91	145.28
G1L4	0.5	60	139.46	92.98	35.11	1146.72	29.06	29.06	2.91	145.28
G2L4	1		139.46	92.98	35.11	1146.72	29.06	29.06	2.91	145.28
G3L4	1.5		139.46	92.98	35.11	1146.72	29.06	29.06	2.91	145.28
G4L4	2		139.46	92.98	35.11	1146.72	29.06	29.06	2.91	145.28
G1L5	0.5	75	174.33	58.11	35.11	1146.72	29.06	29.06	2.91	145.28
G2L5	1		174.33	58.11	35.11	1146.72	29.06	29.06	2.91	145.28
G3L5	1.5		174.33	58.11	35.11	1146.72	29.06	29.06	2.91	145.28
G4L5	2		174.33	58.11	35.11	1146.72	29.06	29.06	2.91	145.28

(2) Testing process

According to the GB/T50082-2009 "Long term Performance and Durability Test Methods for Ordinary Concrete" standard, the test block should be taken out in a timely manner 4 days before the concrete reaches the standard strength of 28 days. The sample should be soaked in water at a temperature of (20±3) °C for 4 days, and after taking out, the surface moisture of the test piece should be wiped off before conducting the frost resistance test [35-37].The fast freezing method is selected for the frost resistance test, and the testing equipment uses a TDR type non-metallic material fully automatic freeze-thaw testing machine and a high-precision electronic balance to test the initial dynamic elastic modulus and mass of the sample.

Adjust instrument parameters: 25 freeze-thaw cycles. The duration of each freeze-thaw cycle is 4 hours (3 hours of freezing and 1 hour of thawing), with 25 small cycles forming one large cycle. After completing a major cycle, take out the test block and wipe it dry. Observe the peeling condition on the surface of the test piece, test the mass loss and dynamic modulus of the sample. After testing, turn the test block around and place it in the test piece box before proceeding to the next major cycle [38].

In order to meet the test requirements, the test will be stopped when the concrete freeze-thaw reaches any of the following conditions: 1) the specified number of freeze-thaw cycles is reached; 2) The relative dynamic elastic modulus of the specimen decreased to 60%; 3) The quality loss rate reached 5%.

3 RESULTS AND DISCUSSION

3.1 Frost Resistance Test

The test was conducted using the fast-freezing method, to determine the proportion group of phosphogypsum concrete with different steel fiber admixtures, measure the cross-section dimensions and use a marker pen to make a good cross intersection marking on the test block to ensure that the measurement point of the dynamic modulus is consistent each time, and then start the first freeze-thaw cycle after determining the initial mass and the initial modulus of the dynamic elasticity [39, 40]. The initial values are shown in Tab. 4.

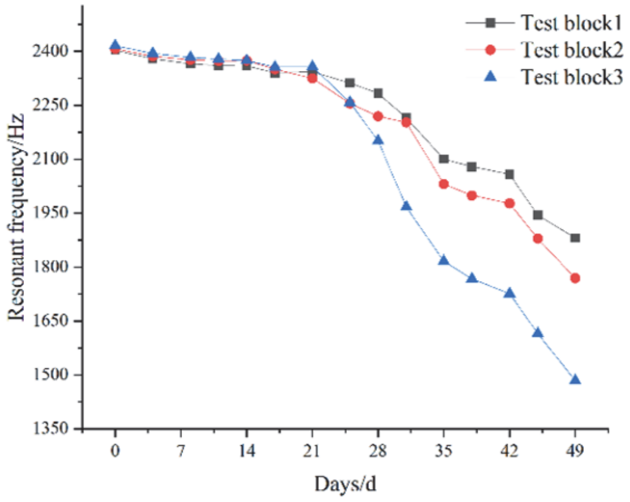
Table 4 Initial mass and resonant frequency of steel fiber mixed phosphogypsum concrete test block

Specimen group	serial number	length / mm (left, right)	cross-section / mm	weights / g	resonant frequency / Hz
G0L0	1	398, 398	99.7 × 100.8	9654	2416
	2	398, 398	100.1 × 100.4	9676	2403
	3	398, 398	99.6 × 100.6	9742	2427
G2L3	4	398, 398	100.8 × 99.4	9644	2396
	5	398, 398	100.3 × 99.9	9829	2412
	6	398, 398	99.5 × 101.3	9781	2400
G3L2	7	398, 399	98.7 × 100.5	9684	2450
	8	398, 398	100.0 × 100.5	9756	2438
	9	398, 398	100.2 × 100.2	9664	2430
G3L3	10	398, 398	100.2 × 100.4	9632	2422
	11	398, 398	100.5 × 99.4	9693	2442
	12	398, 398	99.8 × 99.8	9761	2454
G3L4	13	398, 398	99.9 × 100.6	9902	2403
	14	398, 398	100.7 × 100.9	9910	2407
	15	398, 398	99.6 × 100.7	9786	2416

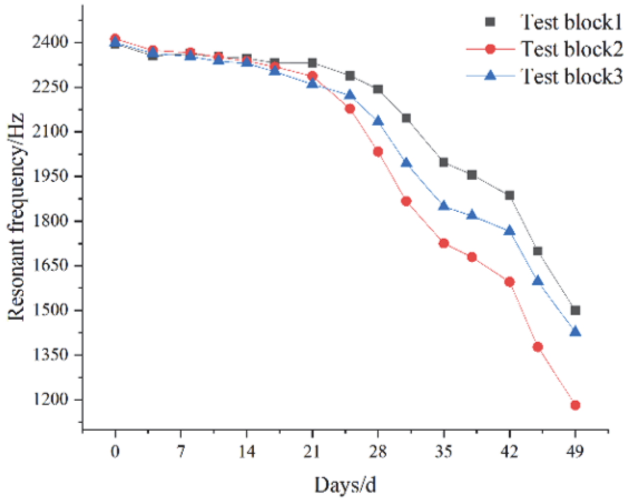
In the test process, a freeze-thaw cycle is freeze 4 h, thaw 1 h, when it reaches 25 freeze-thaw cycles, it is necessary to stop the test and remove the specimen from the instrument, to be measured after the loss of mass and after the reduction of the resonant frequency of the transverse fundamental frequency, and then simply deal with the surface of the specimen due to freezing produced by the crushing of fine aggregates and so on, to continue the next 25 cycles.

3.2 Characteristics of Freeze-Thaw Mass Loss Rate of Steel Fiber Phosphogypsum Concrete

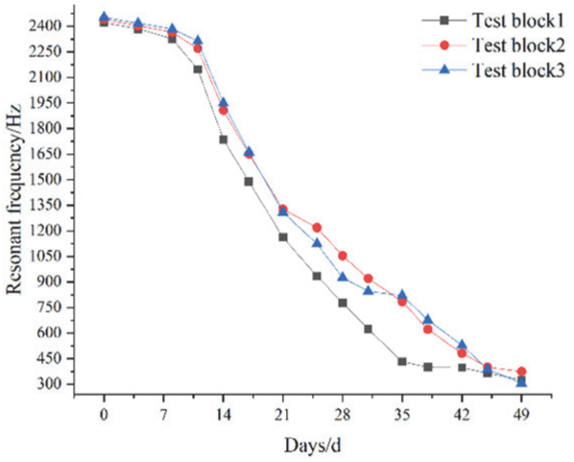
Concrete freezing quality loss rate and freeze-thaw cycle of concrete surface paste spalling related, with the increase in the number of freeze-thaw cycle, the concrete structure internal damage deterioration, internal cracks gradually extended to the concrete surface, the appearance of laminated spalling collapse, weight loss is increasing. The existing literature has demonstrated that the degradation of concrete during freeze-thaw cycles comprises two components: one is attributed to the spalling of surface paste, coarse and fine aggregates (absolute loss), while the other is associated with an initial weight gain resulting from internal micro-crack deterioration and water saturation in cracks (relative gain). However, in practical scenarios, the weight loss caused by freeze-thaw cycles exceeds the weight gain [41-44].



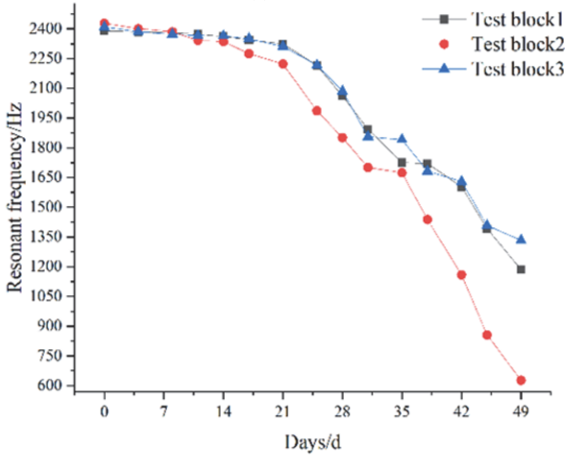
(a) G0L0



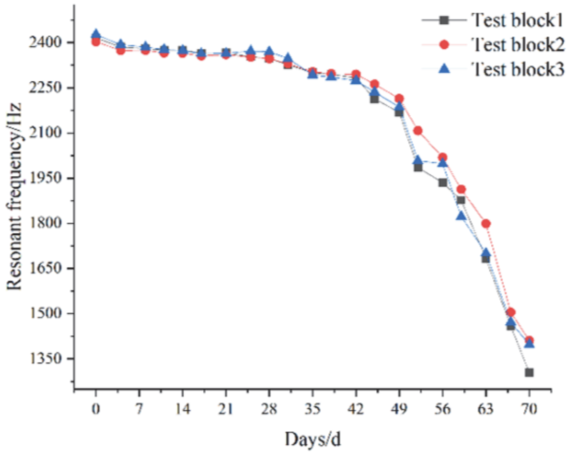
(b) G2L3



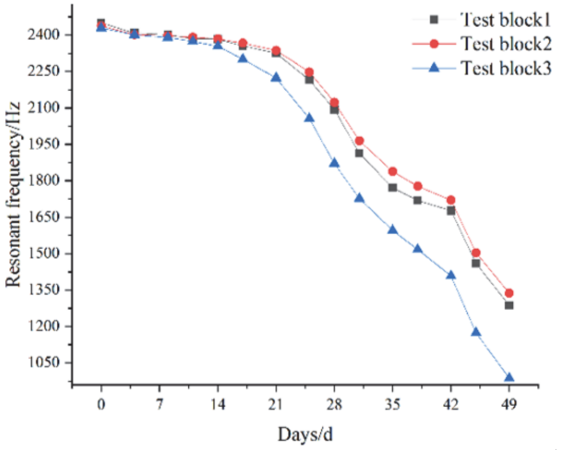
(c) G3L2



(d) G3L3



(e) G3L4



(f) G4L3

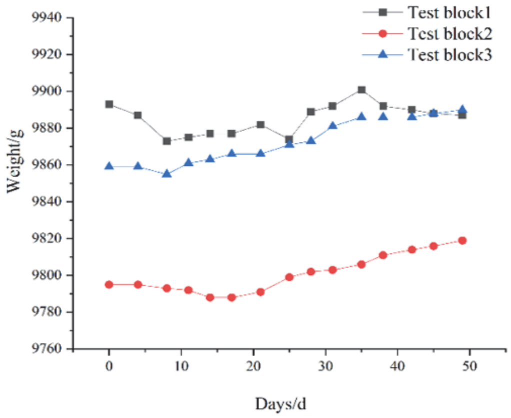
Figure 1 Weight variation diagram of concrete test block in antifreezing process

It can be concluded from the change of weight in Fig. 1 that the change of each group of specimen blocks basically maintains the trend of first slow and then fast. Observing the graphical changes of G3L2, G3L3 and G3L4, the mixing ratio of phosphogypsum is getting bigger and bigger with the fixed amount of steel fibers, and the frequency data are first slow and then fast, especially in the graph of G3L4, which is rapidly decreasing after 14 days from the beginning of the test, and the reason for this is considered to be probably due to the large mixing ratio of phosphogypsum which leads to the large proportion of water absorbed by the concrete in the process of freezing and thawing cycle, and the freezing and thawing, and repeated cycles lead to the repeated cycles resulting in volume changes and thus more pores on the surface and inside of the concrete, which ultimately led to impaired concrete quality. The increase in the phosphogypsum admixture content results in a larger reduction of concrete frost resistance, while the increase in steel fiber admixture content enhances the internal connection within concrete, as evident from the flexural test. Additionally, the inclusion of steel fibers improves frost resistance.

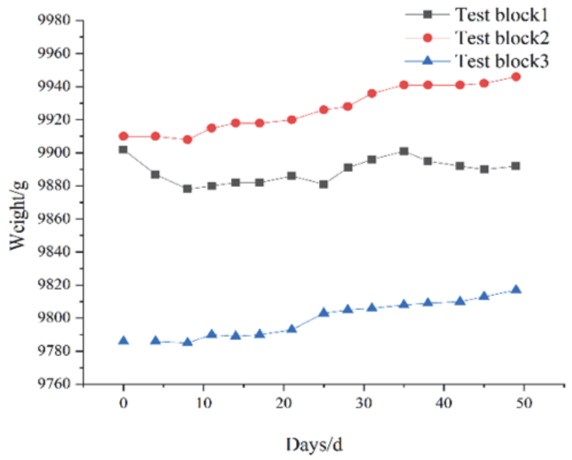
3.3 Characteristics of Freeze-Thaw Dynamic Modulus of Concrete

The rate of loss of concrete's dynamic modulus is another important parameter to reveal the physical-mechanical characteristics of steel-fiber phosphogypsum concrete [45, 46]. Concrete is a multiphase porous material composed of cement paste, aggregate, interfacial zone and pores, and the elastic modulus of concrete is closely related to the physico-mechanical state of coarse and fine aggregates of concrete, and aggregates and mortar with higher kinetic modulus can increase the kinetic modulus of concrete, while weak interfaces, and porosity inside the concrete will reduce the kinetic modulus of concrete [47-49]. Therefore, the freeze-thaw cycle effect has a significant effect on the kinetic modulus of phosphogypsum concrete with different steel fiber contents.

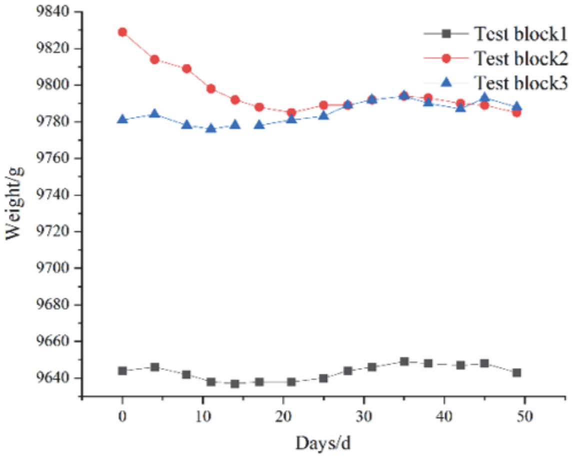
Fig. 2 shows the law of the influence of the volume rate of steel fiber phosphogypsum concrete on the loss rate of the dynamic modulus; with the increase of the number of freeze-thaw cycles, the loss rate of the dynamic modulus of steel fiber phosphogypsum concrete showed a decreasing tendency, indicating that the concrete freezing resistance has been improved.



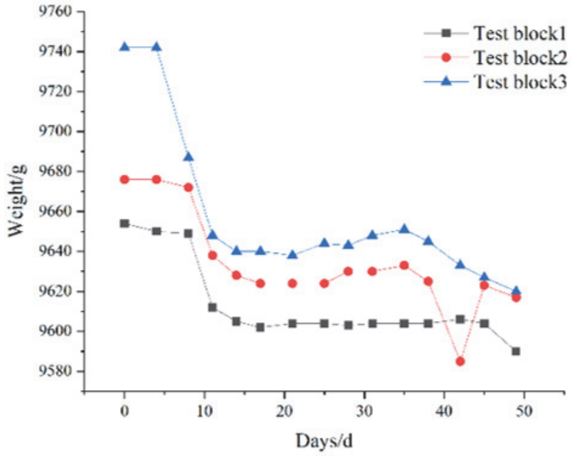
(a) G0L0



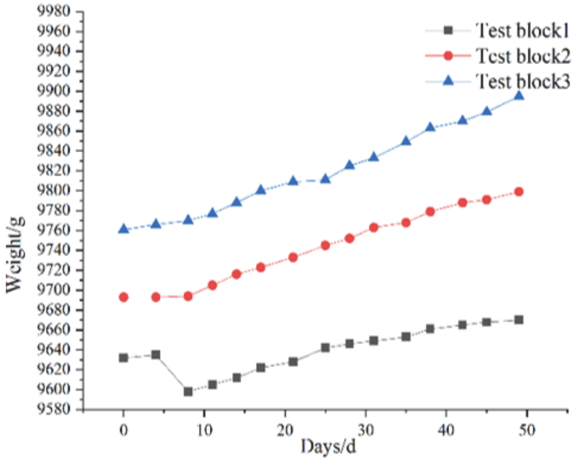
(b) G2L3



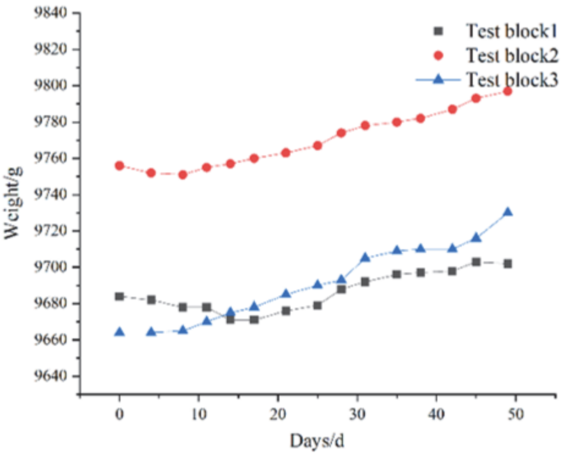
(c) G3L2



(d) G3L3



(e) G3L4



(f) G4L3

Figure 2 Resonance frequency changes of concrete test blocks in each group

Analysis of the reasons that the steel fiber admixture reduces the freeze-thaw destructive force that initiates cracks and promotes crack development, hinders crack development, and restricts the damage process of the concrete matrix, i.e., the admixture of steel fibers has a certain crack-blocking effect on the concrete, which inhibits the relative kinetic-elastic modulus damage of the concrete, and improves the freezing-resistant performance of the concrete.

As the volume rate of steel fiber continues to increase, there is a corresponding decrease in the relative dynamic modulus of the specimen. This can be attributed to the significant impact on the concrete paste, interface zone, and pores caused by an increasing number of freeze-thaw cycles. Consequently, a multitude of microcracks originate from the paste while both the number and size of pores gradually escalate with each subsequent freeze-thaw cycle. Eventually, pores start appearing in the interface zone [50, 51]. Subsequently, under the influence of freeze-thaw cycles, both concrete aggregate and paste begin to deteriorate as microcracks progressively propagate through them. This results in a loosening internal structure that ultimately leads to attenuation in concrete's dynamic modulus [52, 53].

This indicates that too high steel fiber admixture does not have a significant effect on the freeze-thaw damage resistance of concrete, but rather reduces the frost resistance of steel fiber phosphogypsum concrete. Therefore, when the steel fiber content is 0-1.5%, the frost damage resistance of phosphogypsum concrete increases.

3.4 Orthogonal Experimental Design

During the test, three influencing factors were selected, including the number of freeze-thaw cycles, steel fiber content and phosphogypsum substitution rate, and three levels were designed for each factor [54-56]. Orthogonal test factors and levels are shown in Table5.

A total of 27 samples were prepared, which were divided into 9 groups according to the proportion of different factors, and each group had 3 test blocks. The mass loss and relative dynamic elastic modulus of 3 parallel concrete specimens were measured for each specimen after 25 freezing and thawing times. In numerical processing, three average values were taken as the final result, and orthogonal analysis was performed [57-58]. The designed orthogonal design scheme is shown in Tab. 6.

Range analysis method, referred to as R method, also known as intuitive analysis method, can analyze the specific change rules of assessment indicators with various levels of various factors. It is characterized by convenient calculation, visual image and simplicity, and is the most widely used in the analysis of orthogonal test results, which consists of two parts: calculation and judgment [59, 60]. The calculation is as follows:

$$R_i = \max\left\{\bar{k}_{j1},\bar{k}_{j2},...,\bar{k}_{jm}\right\} - \min\left\{\bar{k}_{j1},\bar{k}_{j2},...,\bar{k}_{jm}\right\} \qquad (1)$$

Relevant parameters are shown in Tab. 5.

Table 5 Orthogonal test factors and levels

Level	Factor		
	Number of freeze-thaw cycles	Steel fiber dosage	Phosphogypsum replacement rate
1	75	1.0	30
2	150	1.5	45
3	225	2.0	60

Table 6 Orthogonal test design table

Test groups	factor				
	Number of freeze-thaw cycles	Steel fiber dosage/%	Phosphogypsum substitution rate/%	Mass loss rate/%	Relative dynamic modulus of elasticity/%
Z1	75	1.0	30	0.08	94
Z2	75	1.5	45	0.41	93
Z3	75	2.0	60	0.68	88
Z4	150	1.0	45	1.33	78
Z5	150	1.5	60	3.31	50
Z6	150	2.0	30	1.12	87
Z7	225	1.0	60	3.55	45
Z8	225	1.5	30	1.95	76
Z9	225	2.0	45	2.45	69
K_1	Sum of indicators assessed at the 1st level of factors A, B, C				
K_2	Sum of indicators assessed at the 2st level of factors A, B, C				
K_3	Sum of indicators assessed at the 3st level of factors A, B, C				
$\bar{k}_1$	Average value of K_1				
$\bar{k}_2$	Average value of K_2				
$\bar{k}_3$	Average value of K_3				
extremely poor	The difference between the maximum and minimum values in Average value of (K_1, K_2, K_3)				

3.5 Analysis of Orthogonal Test Results

The mass loss rate and relative dynamic elastic modulus of different specimens were measured after undergoing freeze-thaw cycles, with each group having varying steel fiber doping levels and phosphogypsum substitution rates (75 times, 150 times, 225 times). By calculating the influence of each factor at every level and obtaining their average values, the extreme R value was determined. Analyzing the relationship between R values allowed for an analysis of how these factors impacted the experimental data indexes, revealing their respective contribution rates.

Fig. 3 above shows the effect of each factor on the extreme difference of the rate of quality loss of PG/SF concrete, through the comparison of R. The larger the value, the greater the influence of this factor on the test index, which can be derived from the primary and secondary relationship of the influence of factors. From the above figure, it can be seen that the degree of influence of the three influencing factors on the quality loss is the number of freeze-thaw cycles > phosphogypsum substitution rate > steel fiber admixture. The number of freezing and thawing cycles has the greatest influence on the rate of mass loss, with a contribution rate of 54% followed by the phosphogypsum substitution rate, with a contribution rate of 35%; the steel fiber mixing amount has the least influence on the rate of mass loss between concrete groups, accounting for 11% of the total contribution rate.

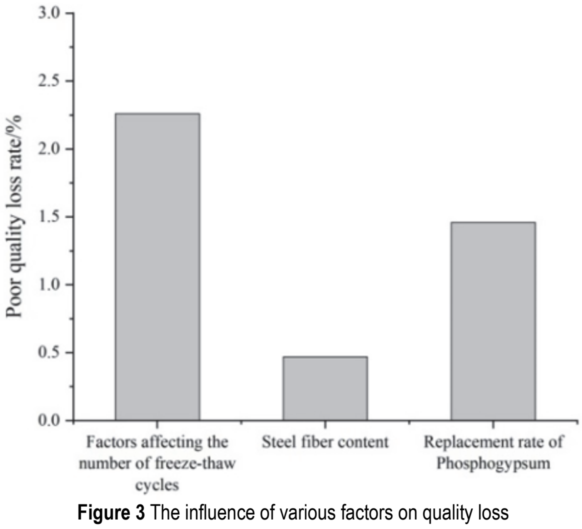


Figure 3 The influence of various factors on quality loss

This is because during the freeze-thaw cycle, cement dominates the internal structure of the concrete in the early stage, and as the ratio of phosphogypsum replacing cement gradually increases, the ettringite generated by the hydration reaction of phosphogypsum has not yet been finalized, which cannot fully support the interior of the concrete pores, thereby affecting the overall strength of the concrete. During the freeze-thaw cycle, concrete absorbs a large proportion of water, and after freezing, it melts and cycles repeatedly, resulting in volume changes and more pores on the surface and inside of the concrete, ultimately leading to damage to the quality of the concrete.

As the freeze-thaw cycle time increases, the water vapor in the freeze-thaw testing machine gradually penetrates into the interior through the fine pores on the surface of the concrete test block, providing conditions for the hydration reaction between phosphogypsum and cement and water, generating a large amount of hydrated calcium silicate and ettringite. The internal hydration reaction is completed, and the structure is dense and stable, achieving the best compressive strength. This in turn increases the strength of the interior of the concrete and plays a supporting role.

Therefore, during the freeze-thaw cycle, the duration and number of freeze-thaw cycles have the greatest impact, followed by the replacement rate of phosphogypsum and the amount of steel fiber added.

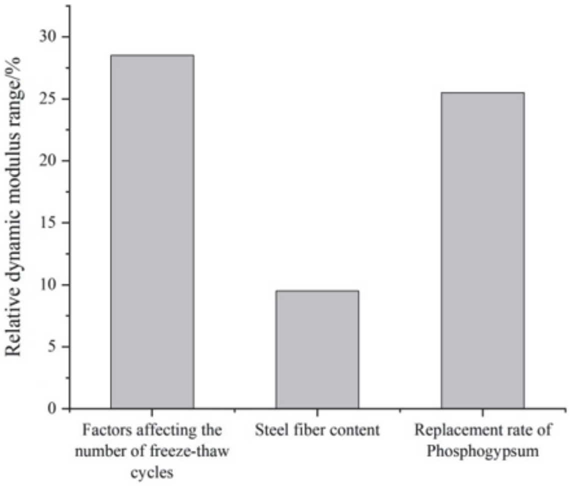


Figure 4 The influence of each factor on the relative dynamic elastic modulus

Fig. 4 above show the effect of each factor on the relative dynamic modulus of elasticity of PG/SF concrete. From the above figure, it can be seen that the degree of influence of the three influencing factors on the loss of quality is the number of freeze-thaw cycles > phosphogypsum substitution rate > steel fiber admixture. The influence of the number of freeze-thaw cycles on the rate of mass loss is closer to that of the phosphogypsum substitution rate, with contribution percentages of 46% and 40%, respectively; the steel fiber admixture has the smallest influence on the rate of mass loss, accounting for 14% of the total contribution.

Therefore, by adding steel fibers, concrete will also have better elastic modulus, reduce the quality loss of phosphogypsum concrete, significantly improve durability, and make the concrete to have better toughness and stronger frost resistance.

3.6 Brief Summary

(1) The frost resistance of concrete is very important for durability and affects its effective service life. In each group of concrete with different mixing ratios, it can be concluded from the change of transverse fundamental frequency that the frequency change of each group of specimens basically maintains the trend of slow and then fast; the transverse fundamental frequency of the blank control group G0L0 declined sharply after the test was conducted until the 49th day, and then it was lower than the required frequency value on the 70th day, and the phosphogypsum mixing ratio was getting bigger and

bigger in G3L2, G3L3 and G3L4, and the change of the frequency showed a stepwise change, which was characterized by slow and then fast, then slow and then sharp decline.

From the orthogonal test, it can be concluded that the size relationship of the factors affecting the frost resistance is the number of freeze-thaw cycles > phosphogypsum substitution rate > steel fiber admixture, in which the steel fiber admixture has the smallest effect on the frost resistance, and therefore the steel fiber has the highest contribution to the internal structural stability of phosphogypsum concrete.

(2) The appearance quality and internal structural damage of the steel fiber phosphogypsum concrete specimen decreased gradually with the increase of freeze-thaw cycles, and the appearance showed that the surface appeared with new sand and spalling phenomenon. The internal performance is that the porosity becomes higher and higher due to continuous freeze-thaw, which reduces the resonant frequency and causes the dynamic elastic modulus to decline.

(3) When the replacement rate of phosphogypsum is 60% in the concrete benchmark mix ratio, and the steel fiber content is 0-1.5%, the steel fiber significantly reduces the freeze-thaw damage of phosphogypsum concrete.

4 CONCLUSIONS

Through the research results, it can be concluded that improving the durability of phosphogypsum concrete with steel fibers is practical and feasible. It not only utilizes phosphogypsum as a resource, but also effectively reduces the surrounding ecological environment pollution caused by phosphogypsum, and develops new building materials to turn waste into treasure, realizing the recyclable utilization of solid waste. At the same time, adding steel fibers for compressive strength is better applied in cold engineering areas, effectively enhancing the frost resistance of concrete buildings, making concrete to have better toughness and longer service life. Therefore, under the reference mix ratio of concrete with a substitution rate of 60% for phosphogypsum, the addition of steel fibers ranging from 0 to 1.5% can effectively improve the frost resistance of C40 phosphogypsum concrete.

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