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Frost resistance and mesoscopic structure analysis of polystyrene granular concrete based on CT technology

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In order to reduce the energy consumption in the building, in this paper, silica fume (SF) was used to partially replace cement in the production of granular polystyrene concrete, the effect of SF content on the strength and frost resistance of polystyrene granular concrete was investigated, and the evolution of pores and destruction of granular polystyrene concrete before and after freeze-thaw cycles at an acceptable level were analyzed using CT technology. The results showed that that the introduction of SF significantly increased the number of 0-0.5 mm diameter pores in polystyrene granular concrete, reduced the number of macropores and total porosity, optimized the pore structure, increased the matrix strength and improved the microstructure. With an SF content of no more than 20%, the strength and frost resistance of polystyrene concrete can be increased. With the SF content of 10-15%, the improvement in frost resistance of polystyrene concrete is more satisfactory.

Keywords: polystyrene granular concrete; silica fume; mechanical properties; frost resistance; CT technique; mesoscopic analysis

Аналіз морозостійкості та мезоскопічної структури полістиролбетону на основі КТ-технології. *Zhouping Yu , Haoting Li , Jianyu Yang, Weijun Yang*

З метою зменшення споживання енергії будівлями, у цій статті для часткового заміни цементу для приготування полістиролбетону використано кремнеземний пил (SF), досліджено вплив вмісту SF на міцність та морозостійкість полістиролбетону, а також проаналізовано еволюцію пор та пошкодження полістиролбетону до та після циклів заморожування та відтавання на прийнятному рівні за допомогою КТ-технології. Результати показали, що додавання SF значно збільшило кількість пор діаметром 0-0,5 мм у полістирольному гранульованому бетоні, зменшило кількість макропор та загальну пористість, оптимізувало структуру пор, підвищило міцність матриці та покращило мікроструктуру. Коли коефіцієнт заміщення SF не перевищує 20%, це може покращити міцність та морозостійкість полістирольдегідного бетону. Коли коефіцієнт заміщення SF становить 10-15%, покращення морозостійкості полістирольдегідного бетону є більш задовільним.

1. Introduction

Polystyrene granular concrete is a lightweight porous material, which has attracted attention due to the fact that polystyrene granules are particularly light and contain 95% closed pores in volume, which provides them with excellent thermal properties, energy and vibration absorption, etc. [1, 2]. Therefore, polystyrene granular concrete can be used in walls, roofs, roads, railway track beds, floating marine structures, protection works and support works [3-5]. Freeze-thaw action is the main

cause of deterioration of the internal structure of concrete in cold regions [6]. Freezing and thawing action will cause micro-cracks, extended macro-cracks and even damage inside the concrete, affecting the safety and service life of the engineering structure [7]. Polystyrene particles have good deformability, which allows for effective mitigation of damage caused by freezing and thawing [8-10]. Therefore, polystyrene particle concrete can be used in cold regions.

Supplementary cementitious materials can improve mechanical properties of concrete and its durability to a certain extent, while reducing the amount of cement, which also leads to energy savings and reduction of carbon emissions [11]. Silica fume is a commonly used auxiliary cementitious material consisting of finely powdered silica as an inorganic material with good volcanic ash activity [12]. Silica fume can consume the reaction heat of cement during its hydration process, reduce the concrete temperature, and improve the early strength and elastic modulus of concrete [13]. The durability of concrete can be improved by avoiding early cracking and temperature stress caused by high-temperature hydration reactions [14]. In addition, mixing an appropriate amount of silica fume in concrete can improve the bond strength. It can also improve the mechanical properties and durability performance [15].

Freeze resistance is an important indicator of the durability performance of concrete in cold regions and an important factor in determining the service life of concrete structures [7]. Saikia et al. [16] and Kan et al. [10] found that mixing polystyrene particles in concrete can improve the freezing performance. Assaad et al. [17] showed that the freezing performance of polystyrene particles in concrete is enhanced with an increase in the number of polystyrene particles, and the freezing performance of concrete made using small-size polystyrene particles is more desirable [18]. Ferrandez et al. [9] found that the freeze resistance of concrete made using high quality plastic admixtures was more satisfactory. This is explained by the fact that polystyrene particles can partially absorb the freezing force during ice crystallization, thereby reducing mortar damage and enhancing durability. At the same time, Yuan et al. [19] found that preparation of UHPC-encapsulated polystyrene particles using SF can substantially improve the frost resistance and service life of polystyrene particle concrete.

The mesoscopic-scale structure of concrete directly affects the macroscopic properties, and polystyrene granular concrete mainly consists of aggregates, mortar matrix, interfacial transition zones, and initial defects (pores and voids) at the mesoscopic scale [20]. It has been found that the compressive strength of concrete decreases with increasing porosity [21, 22] and that permeability is related to the structure, number and distribution of pores [23]. For additional studies, piezoelectric, nitrogen adsorption and computed tomography (abbreviated CT) are usually used.

For additional studies, the piezo mercury, nitrogen adsorption, and computed tomography imaging technology (abbreviated CT) are commonly used. The CT technology allows testing inside a sample without damaging it, obtaining 2D and 3D images of the internal structure of concrete for detailed study of the internal microstructure and damage, as well as conducting qualitative and quantitative analysis of damage [24]. Since the presence of polystyrene particles directly affects the accuracy of the test data of the pressed mercury method and nitrogen adsorption method, the CT technique is the preferred method for composites to observe the distribution of aggregates, mortar, modified polystyrene particles, and interfaces inside the specimen under the conditions of initial damage and microcracking, as well as the changes in porosity, damage, and cracks.

In this study, polystyrene granular concrete by replacing 0-20% of cement with SF of equal mass was prepared. Using computed tomography technology, the mechanism of damage development of polystyrene concrete containing SF under the action of freeze-thaw cycle at an acceptable level was analyzed to ensure the use and promotion of polystyrene concrete in a region with severe cold. It has practical significance for the application and promotion of polystyrene concrete in cold regions.

2 Raw materials and proportion design

2.1 Material

In this test, P·O 42.5 silicate cement and silica fume (SF) with an activity index of 85% were used, and the compositions are shown in Table 1. The average particle sizes of cement and SF measured by a laser particle size analyzer are 19.87 μm and 4.33 μm, respectively. The grading curves are presented in Fig. 1.

Table 1. Chemical compositions of cement and SF (wt/%).

Compound details	SO_3	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O	otherwise
cement	5.35	26.18	4.34	10.42	44.13	2.23	1.38	0.54	5.43
SF	--	96.74	0.08	0.32	0.11	0.10	--	0.99	--

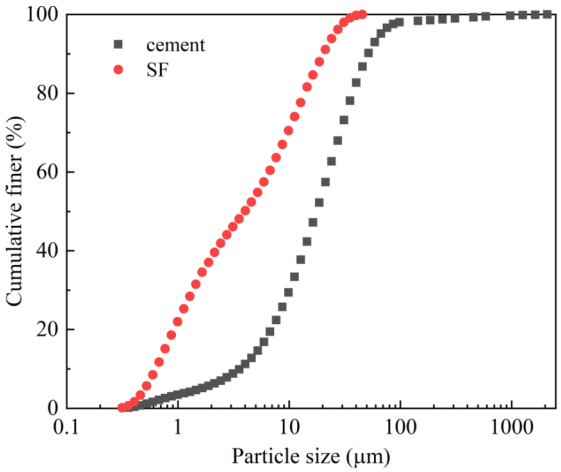

Fig. 1. Grading curves of cement and SF.

Fig. 2. Modified polystyrene particles.

The fine aggregates were river sand with a fineness modulus of 2.34, which is classified as medium sand. The coarse aggregate was continuously graded gravel with a 1~20mm particle size.

In this study, an EIA modifier was prepared by mixing a silane coupling agent, a polyethylene-maleic anhydride copolymer concentrate, and a modifier in a ratio of 1:5. Under high temperature and pressure conditions, the molecular structure of polystyrene particles was activated through a misting adhesion process, optimizing and coupling the organic-inorganic interface to achieve stable bonding with inorganic materials such as cement and gypsum. Using the EIA modifier, polystyrene particles with a particle size of 3~5 mm and a density of 8.4 kg/m^3 were modified to produce light blue modified polystyrene granules, as shown in Fig. 2. The modified polystyrene granules can be mixed into construction mortar while maintaining excellent flowability, without problems such as delamination, segregation or void formation.

The mixing water is tap water. A highly efficient polycarboxylate agent with a solid content of 20% and a water reduction rate of 35% was selected as the water-reducing agent.

2.2 Concrete proportioning and specimen preparation

Five different SF substitution degrees of 0%, 5%, 10%, 15% and 20% were designed to prepare polystyrene granular concrete with equal mass replacement of cement to study the effect of SF on the durability of polystyrene granular concrete. The weight-based mix ratios of the polystyrene granular concrete components are shown in Table 2, where the water-cement ratio is 0.36, the amount of cementitious material is 500 kg/m^3, and the unit of the amount of each component is kg. Polystyrene granular concrete was prepared according to the relevant fabrication process described in [25], with a slump of 160~180mm. The polystyrene concrete was demoulded for 24 hours after casting and placed in a standard curing box at 20±2°C and 95% relative humidity for 28 days.

2.3 Test methods

2.3.1 Mechanical property tests

Compressive and splitting tensile strength tests were carried out on polystyrene granular concrete specimens with sizes of 100 mm ×100 mm ×100 mm cured for 28d according to the protocol GB/ T50081-2019. The compressive strength testing was conducted using a 60-tonne servo-hydraulic testing machine with a loading rate of 5 kN/s. The splitting tensile strength was tested using a TTG (Tensile Strength Testing Machine). A TYE-100 servo-hydraulic testing machine performed the splitting tensile strength test with a loading rate of 2 kN/s.

2.3.2 Frost resistance tests

According to the testing requirements of the slow freezing method specified in GB/T 50082-2009, the a 100mm×100mm×100mm polystyrene granular concrete specimen aged for 28 days was subjected to freeze-thaw test. The water-saturated specimen is placed in a fully automatic freeze-thaw box, and the freeze-thaw cycle is carried out in air-freezing and water-soluble. The freeze-thaw cycle process is as follows: after freezing at -18° for 8 hours, water with a temperature of 20° is injected for thawing for 4 hours and then drained. The damage indexes (mass loss rate and strength loss rate) were tested for 25, 50, 100 and 150 freeze-thaw cycles. The strength loss rate mainly reflects the degree of loss of strength of concrete after freeze-thaw cycles and is calculated according to equation (1). The mass loss rate mainly reflects the ability of concrete to resist spalling after freeze-thaw cycles and is calculated according to equation (2).

$$\Delta f_c = \frac{f_{c0} - f_{cn}}{f_{c0}} \times 100 \quad (1)$$

In the formula: Δf_c is the rate of loss of compressive strength (%) of concrete specimens after N freeze-thaw cycles with an accuracy of 0.1;

f_{c0} is the measured compressive strength of concrete specimens of the control group (MPa), with an accuracy of 0.1 MPa;

f_{cn} is the measured compressive strength of a group of concrete specimens after N freeze-thaw cycles (MPa) with an accuracy of 0.1 MPa.

$$\Delta W_{\mathrm{ni}} = \frac{W_{0i} - W_{ni}}{W_{0i}} \times 100 \quad (2)$$

In the formula: ΔW_{ni} is the mass loss (%) of concrete specimens after N freeze-thaw cycles, accurate to 0.01;

ΔW_{0i} is the mass of the i-th concrete specimen before the freeze-thaw test (g);

ΔW_{ni} is the mass of the i-th concrete specimen after N freeze-thaw cycles (g).

2.3.3 CT scanning test

The CT scanning test was carried out using a YXLON CT Compact type high-precision industrial CT, an X-ray CT system with a resolution of 66ms, an image of 3072 × 3072 × 234, a thickness of 0.5mm per layer, and 1440 images.

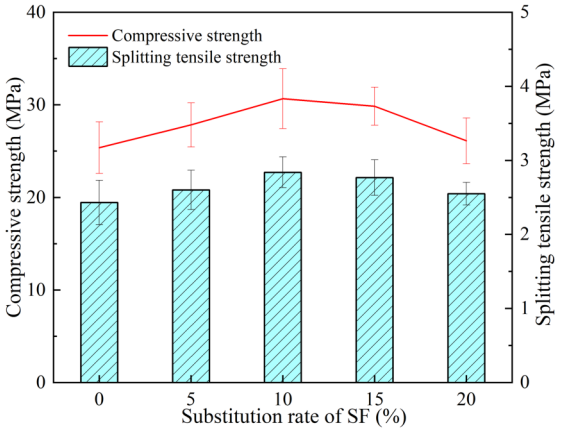

Fig. 3. Effect of SF on the strength of polystyrene granular concrete

3 Results and Discussion

3.1 Mechanical Properties

Fig. 3 shows the effect of the SF substitution rate on the strength of polystyrene granular concrete after 28 days age. The variation trends of the effect of SF substitution rate on compressive strength and split tensile strength of polystyrene granular concrete are similar. The strength of polystyrene granular concrete showed an increasing and then decreasing trend with the increase of the SF substitution degree, and the compressive strength of polystyrene granular concrete containing SF was higher than that of the control group. This phenomenon indicates that SF positively improves the strength and optimizes the mechanical properties of polystyrene granular concrete when the SF substitution degree is within 20%. This is mainly due to the large porosity of polystyrene granular concrete, while the fine SF particles act as microfillers [26, 27]. When the replacement degree of SF was 10%, the strength of polystyrene granular concrete reached its maximum value, and its compressive strength and split tensile strength increased by 20.89% and 16.84%, respectively, compared with the control group. The compressive strength and splitting tensile strength of polystyrene concrete increased by 17.68% and 13.91%, respectively, compared with that of the control group when the substitution degree of SF was 15%. It is further shown that the replacement of 10%-15% of cement with SF of equal mass significantly improves the strength of polystyrene concrete; especially when the replacement degree is 10%, the effect is more satisfactory. This is because SF is an active siliceous mineral admixture with very high silica content and fine particle

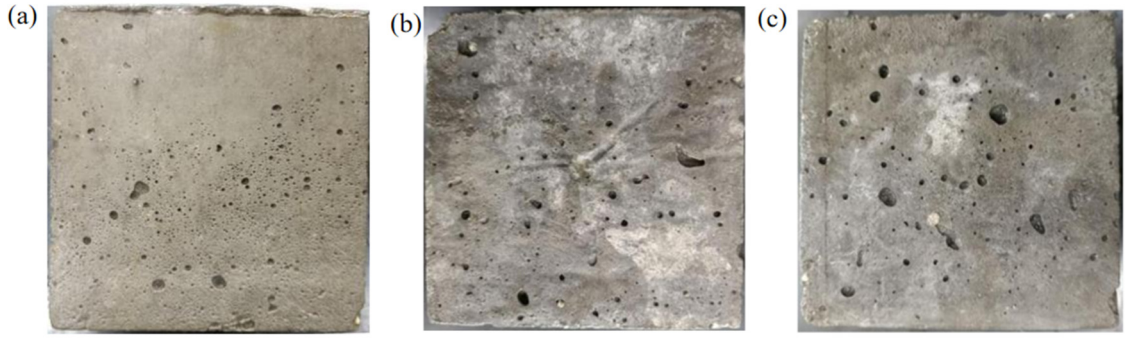

Fig. 4. Morphology of polystyrene granular concrete at 150 freeze-thaw cycles (a) EPSC, (b) EPSC+10SF, (c) EPSC+20SF.

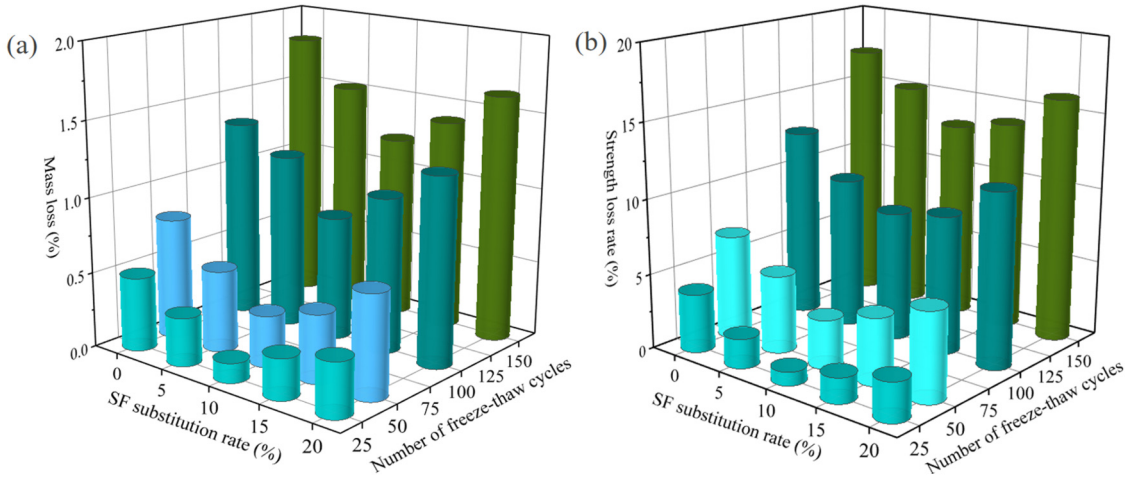

Fig.5. Effect of SF on damage indices of polystyrene granular concrete under freeze-thaw cycles (a) mass loss level, (b) strength loss level.

size, which reduces porosity and improves the compaction of the cement matrix structure through a secondary hydration reaction [28]. In addition, SF also has good adsorption properties, improves the dispersion of polystyrene particles in the cement paste, improves the adhesion at the interface between the polystyrene particles and the cement matrix, further improves the structure of the interfacial transition zone, and thus improves the strength of the polystyrene granular concrete [29].

3.2 Frost resistance

3.2.1 Appearance and morphology after freezing and thawing

The morphology of polystyrene granular concrete after 150 freeze-thaw cycles is shown in Fig.4. As can be seen from Fig. 4, the surface of the concrete specimen after 150 freeze-thaw cycles is flat but has many pores visible to the naked eye, and in some images, peeling of the concrete edges is observed. The erosion-prevention-sediment-control (EPSC) of polystyrene granulated concrete revealed some abrasion and spalling at corners, numerous pores and large pore sizes. Fig. 4(b, c) shows that the surface of polystyrene granular concrete containing SF is significantly denser and less porous, with a slight shedding of contours and higher integrity. The experimental results indicate that the addition of silica fume (SF) can effectively enhance the freeze-thaw resistance of expanded polystyrene granular concrete, which is consistent with the findings of the study [19].

3.2.2 Freeze-thaw damage indicators

As seen from Fig. 5, the freeze-thaw damage index of polystyrene granular concrete shows a tendency to decrease and then to increase with an increase in the degree of SF substitution. The lowest loss of quality and strength is exhibited by granulated polystyrene concrete with a SF substitution degree of 10%, followed by concrete with a SF substitution degree of 15%. The polystyrene concrete with a 20% SF substitution degree has the most significant loss of quality and strength of 1.63% and 16.24%, respectively after 150 freeze-thaw cycles. However, these losses are lower than the 5% and 25%

Table 2. Mixing ratios of polystyrene granular concrete (in weight)

Types of mixture	Cement	Sand	Gravel	Polystyrene granules	Water	Water-cement ratio	Water reducing agent	SF
EPSC	500	685	757	1.95	180	0.36	5	0
EPSC+5SF	475	685	757	1.95	180	0.36	5	25
EPSC+10SF	450	685	757	1.95	180	0.36	5	50
EPSC+15SF	425	685	757	1.95	180	0.36	5	75
EPSC+20SF	400	685	757	1.95	180	0.36	5	100

required by GB/T 50082-2009, and at the same time, they are lower than those of the control concrete by 9.94% and 5.8%, respectively. The quality and strength loss level of polystyrene granule concrete with SF substitution degree of 15% is close to that of polystyrene granule concrete with SF substitution degree of 10% after 150 freeze-thaw cycles, which is only 0.22% and 0.8% higher, respectively. This shows that when the SF substitution degree is within 20%, the equal mass substitution of cement can improve the frost resistance of polystyrene granular concrete, in which the SF substitution degree is more satisfactory when it is 10%~15%. The reasons for this are: firstly, the hydrophobicity of polystyrene particles has a positive protective effect on the frost resistance of concrete [10]. Secondly, the high compressibility of polystyrene particles can compensate for the effect of frost expansion force to reduce frost damage [9, 30]. Additionally, the micro aggregate effect and volcanic ash effect of SF particles optimize the pore structure, improve the strength of the cement matrix, hinder the transport and storage of water in the interior of the concrete, and at the same time have a positive effect on the resistance to freezing and expansion forces and inhibit the development of microcracks [31,32].

3.3 Mesoscopic analysis based on CT analysis

3.3.1 Qualitative analysis of two-dimensional cross-section layers

In this paper, the CT-scanned two-dimensional cross-section images of polystyrene granular concrete specimens at 5 mm from the upper surface were selected for analysis. In order to make each component of polystyrene granular concrete distinguishable in the processed CT image, after image processing by noise reduction, enhancement, segmentation, and edge detection, the gravel, polystyrene granules, mortar, and pores are colored and represented as white, color, gray and black respectively, as shown in Fig. 6. Control specimens of polystyrene particle concrete after 150 times of freezing and thawing showed obvious damage at the edges and corners with numerous large pores. On the other hand, the surface integrity of the polystyrene granular concrete containing SF is good, with no signs of aggregate exposure, cracks or holes. However, all of them have some slight abrasion and mortar detachment. The interfaces between the gravel and the cement matrix and between the polystyrene granules and the cement matrix are tightly bonded with clear boundaries. This is because freeze-thaw damage is a process that progresses from the outside in, and the edges, corners and surfaces of the specimen are the first to exhibit weakening, abrasion and even corner loss [33]. The number and size of pores in the two-dimensional cross-section diagrams of the polystyrene granular concrete specimens containing SF were significantly smaller than those of the control group, thus indicating that SF had a positive effect on the improvement of the frost resistance of polystyrene granular concrete. Secondly, many pores were distributed near the gravel, while fewer were near the interface between the polystyrene particles and the cement matrix. This is due to the fact that during the freeze-thaw cycle, the polystyrene particles are subjected to freezing and expansion forces, compressive deformation occurs which softens the effect of freezing and expansion forces and thus increases frost resistance [30]. Again, the interfacial bond between the polystyrene particles and the cement matrix is sufficient, and no interfacial cracks or detachment occurred during the freezing and expansion process. In addition, the gravel-cement matrix interface structure is a weak zone within the concrete, and its strength is much lower than that of the cement matrix and gravel [34]. The relatively loose area at the interface between gravel and cement matrix will produce new pores, or the volume of the original pores will increase and form large-diameter pores under the action of frost-expansion force. Fig. 6 (c, f) shows that

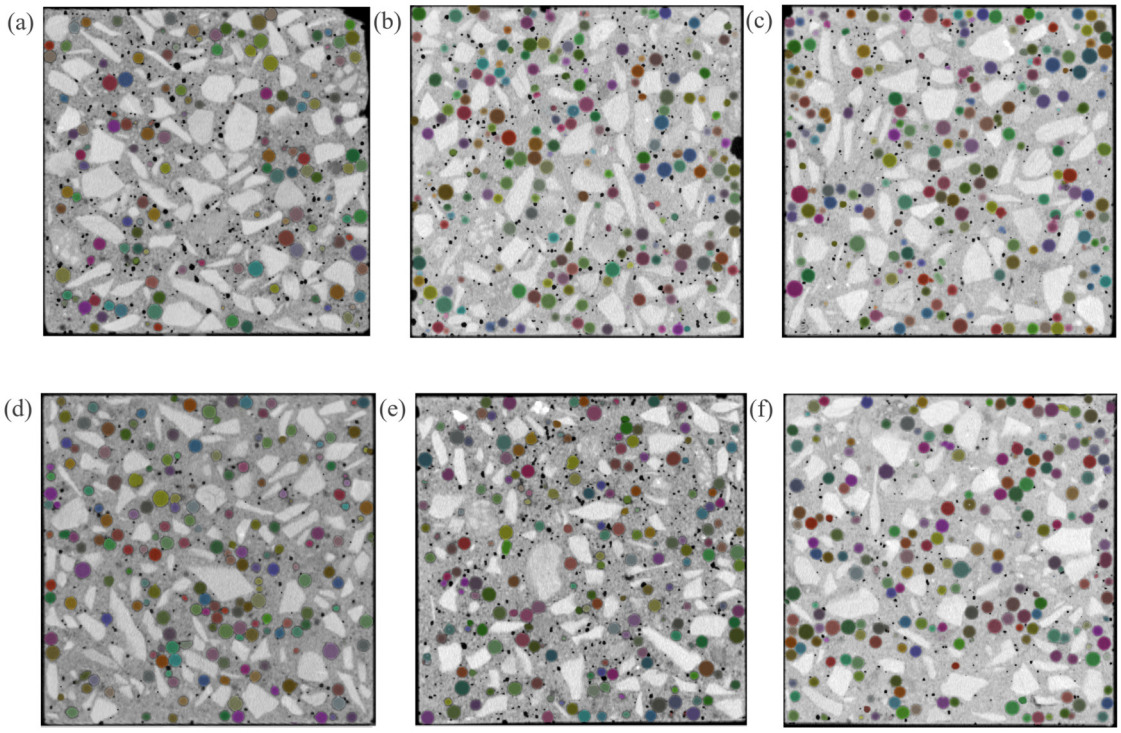

Fig. 6. 2D computed tomography scans of SF polystyrene granular concrete after 150 freeze-thaw cycles (a) EPSC-150, (b) EPSC+5SF-150, (c) EPSC+10SF-150, (d) EPSC+15SF-150, (e) EPSC+20SF-150, (f) EPSC+10SF-0.

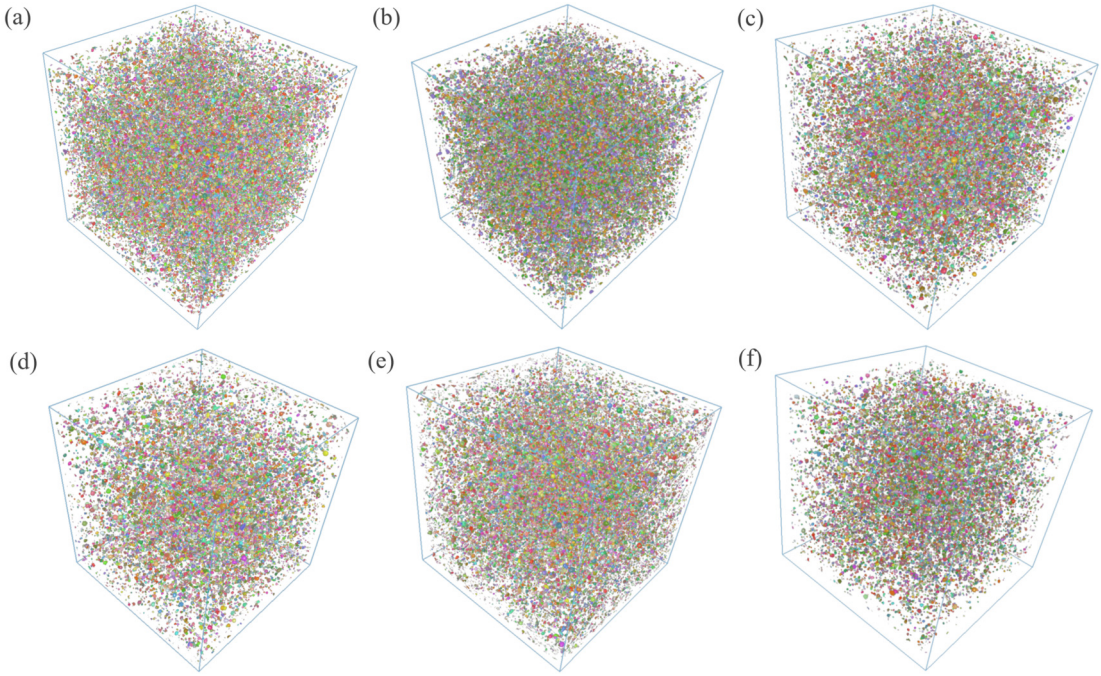

Fig. 7. 3D images of reconstructed pores obtained using computed tomography of polystyrene granular concrete with and without SF before and after freeze-thaw cycles (a) EPSC-150, (b) EPSC+5SF-150, (c) EPSC+10SF-150, (d) EPSC+15SF-150, (e) EPSC+20SF-150, and (f) EPSC+10SF-0.

the polystyrene granular concrete specimens with an SF substitution degree of 10% after 150 freeze-thaw cycles had obvious damage on the edges and corners. The number of pores increased, and the size of pores increased.

Table 3. Statistics of pore structure data of polystyrene granular concrete with SF.

Specimen number	EPSC +10SF-0	EPSC-150	EPSC+ 5SF-150	EPSC+ 10SF-150	EPSC+ 15SF-150	EPSC+ 20SF-150
Total volume of Specimen (mm^3)	971470	1006738	984932	1005430	980980	973843
Total pore volume (mm^3)	8452	16309	12016	10658	9025	13342
Porosity (%)	0.87	1.62	1.22	1.06	0.92	1.37
Total surface area of pores(mm^2)	50458	104203	77610	66614	51140	81754
maximum aperture (mm)	2.95	3.003	2.95	2.95	2.95	2.95
Minimum Hole Diameter (mm)	0.11	0.16	0.11	0.11	0.11	0.11
Average pore size (mm)	0.85	1.14	1.12	0.92	0.91	0.88

3.3.2 Qualitative analysis of degradation patterns in 3D models

A three-dimensional CT image of reconstructed polystyrene granular concrete pores after 150 freeze-thaw cycles is shown in Fig. 7. The pores of the polystyrene granular concrete specimen are dense in the central region due to the vibration effect. In contrast, the pores are sparse in the edge region, and the pore size is acceptable. A comparison of Fig. 7 (c, f) shows that polystyrene granular concrete with a degree of SF substitution of 10% has a denser pore structure and a significant increase in the number of pores after 150 freeze-thaw cycles. From Fig. 7 (a – e), it can be seen that SF incorporation significantly reduced the pores density inside the specimens after 150 freeze-thaw cycles of polystyrene granular concrete, and the number of pores and density showed a trend of decreasing and then increasing with the increase of SF substitution degree. Among them, the pores in Fig. 7(a) are the most intense, have a more elliptical shape and a larger diameter. This is followed by Fig. 7(e), in which the pores are denser, but there are more pores with small sizes. Meanwhile, the pore distribution of polystyrene granular concrete with 15% SF substitution in Fig. 7(d) after 150 freeze-thaw cycles is sparse, with the least number of pores.

This indicates that the appropriate amount of SF can optimize the internal pore structure of polystyrene granular concrete, reduce porosity, improve compactness, and positively improve frost resistance. While the excessive amount of SF substantially increases the pore number and their diameter in polystyrene granular concrete, which is unfavorable to the frost resistance performance.

3.3.3 Quantitative analysis of porosity and average pore size

Table 3 shows the pore characteristic parameters of polystyrene granular concrete before and after 150 freeze-thaw cycles. From Table 3 it is seen that the total pore volume and average pore diameter of polystyrene granular concrete after 150 freeze-thaw cycles have a trend of increasing and then decreasing with the increase of SF substitution degree. At the same time, the porosity and pore surface area showed a trend of decreasing and then increasing with the increase of the SF substitution degree. The average pore diameter of SF polystyrene granular concrete was lower than that of the control group. After 150 freeze-thaw cycles, the porosity, pore surface area, and minimum average pore diameter of polystyrene granular concrete with SF substitution degree of 15% were, respectively, 43.23%, 50.92%, and 22.81% lower than those of the control group. The maximum porosity and pore surface area values of polystyrene granular concrete with 20% SF substitution were 15.43% and 21.54% lower than in the control group. The porosity, pore surface area, and average pore diameter of polystyrene particle concrete with 10% SF substitution after 150 freeze-thaw cycles were 17.92%, 18.82%, and 3.41% higher than those in the initial state, respectively. The incorporation of SF reduced the number of pores and suppressed the pore size enlargement of polystyrene particle concrete after 150 freeze-thaw cycles. This indicates that replacing up to 20% of cement with SF in equal mass has a positive effect on the improvement of frost resistance of polystyrene particles.

3.3.4 Characteristics of pore size and number distribution of pores

As shown in Fig. 8, the pore number of polystyrene granular concrete after 150 freeze-thaw cycles shows a trend of increasing and

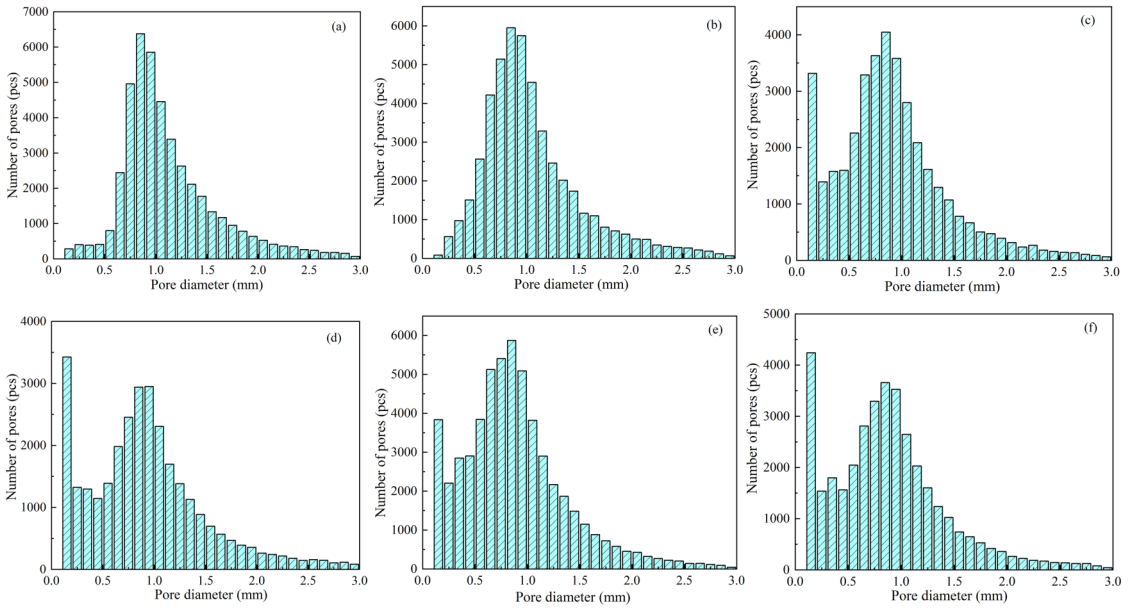

Fig. 8. Pore size versus number of pores in polystyrene granular concrete with SF before and after freeze-thaw cycles (a) EPSC-150, (b) EPSC+5SF-150, (c) EPSC+10SF-150, (d) EPSC+15SF-150, (e) EPSC+20SF-150, (f) EPSC+10SF-0.

then decreasing with the increase of pore diameter. However, with SF substitution degree of 10%, 15% and 20%, polystyrene granular concrete has a higher number of pores with a pore diameter of 0.1mm~0.2mm; at the same time, polystyrene granular concrete with 15% SF has the highest number of these pores, which accounted for 11.3% of the total number of pores. When the SF substitution degree was 5%, 10%, and 20%, the number of pores in the interval of 0.7mm~0.8mm is the highest, accounting for 12.4%, 10.6%, and 10.6% of the total, respectively. As shown in Fig. 9, with an increase in SF content, the number of pores in polystyrene granular concrete with a pore size of 0~1mm showed a trend of increasing and then decreasing. In contrast, the number of pores with a pore size of 1~3mm decreased and then increased. Polystyrene granular concrete with SF has the highest number of pores in the range of 0.6mm~1mm and the lowest number of pores in the range of 2mm~3mm. At a degree of SF substitution of 15%, the number of pores in the range of 0~0.5 mm is the maximum, and 1.6~3 mm is the minimum value in the corresponding pore size zone, and the percentage content of the number of pores is 21.4% and 32.7%, respectively; followed by the polystyrene concrete with SF substitution rate of 10%. This indicates that the addition of SF significantly increased the number of 0–0.5 mm pores, while simultaneously decreasing the number of 0.6–3 mm pores. Microaggregations of SF particles and the effect of volcanic ash filled large pores, turning them into small pores, and optimized the pore structure. This conclusion is consistent with the findings of the literature [35, 36]. Based on the macroscopic indices and reconstructed pore maps obtained by CT and related data, it is concluded that the SF replacement degree of 10% to 15% is the ideal range for improving the freeze-thaw performance of polystyrene granular concrete.

From Fig. 8 (c, f) it is seen that the pore number and pore diameter of polystyrene granular concrete specimens with a 10% SF substitution degree have similar trends before and after freezing and thawing. The number of pores with diameters of 0~0.5mm decreased by 3.84%, the number of pores with diameters of 0.6~1mm increased by 2.91%, and the number of pores with diameters of 1~1mm increased by 2.91% after 150 cycles of freeze-thaw of polystyrene granular concrete with SF substitution degree of 10%. At the same time, the number of pores with 1~3mm changed very little. This shows that after 150 freeze-thaw cycles, not only micropores are formed in polystyrene concrete, but also, under the action of freezing and expansion force, the pore size in the range of 0~0.5 mm gradually increases to pores of 0.6~1 mm. The reason for this is that the micro-aggregation effect of SF and the effect of volcanic ash to a certain extent reduced the

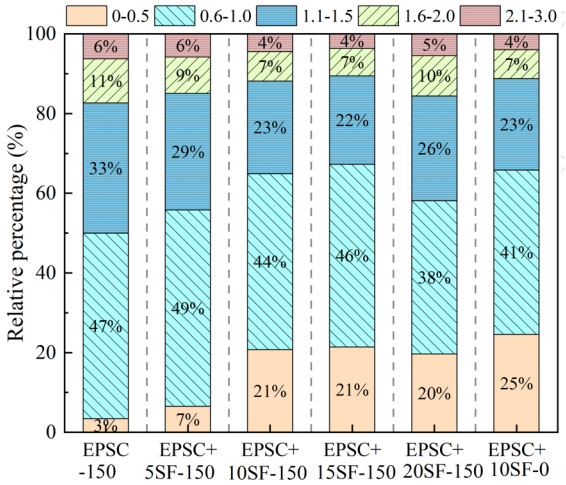

Fig. 9. Stacked histogram of pore size versus percentage number of pores for polystyrene granular concrete with SF

pore size, filled part of the pores, optimized the pore structure and improved the compactness and strength of the cement matrix. However, the micropores gradually increased under the continuous action of the freezing and expansion force during the freeze-thaw cycle.

3.3.5 Damage analysis

Damage-sensitive zones, which are dense areas of concrete microcracks generation and expansion, are presented as dark low-density bands after CT image processing, as shown in Fig. 10. The CT 3D images show damage-sensitive zones in of EPSC, EPSC+5SF and EPSC+20SF after 150 freeze-thaw cycles of polystyrene granular concrete. Two low-density crack bands were visible in EPSC+5SF and EPSC+20SF specimens as damage zones formed by developing internal pores and microcracks in the concrete during freeze-thaw cycles. However, the damage zones were smaller than those in the EPSC polystyrene granular concrete specimens without SF. The damage-sensitive zones were not found in the polystyrene granular concrete specimens with 10% and 15% SF after 150 freeze-thaw cycles. The damage-sensitive zone is consistent with the pattern of macroscopic mechanical properties and freeze-thaw damage index of polystyrene particle concrete. The specimens with high matrix strength, dense structure and suitable polystyrene granular concrete pore structure have less freeze-thaw damage.

5 Conclusion

This paper investigated the effect of SF on the mechanical properties and frost resistance of polystyrene granular concrete. The evolution of the pores and damage of polystyrene granular concrete before and after freeze-thaw cycles was analyzed at a fine-grained level by using the CT technique. The freeze-thaw damage was analyzed qualitatively and quantitatively. The main conclusions drawn are as follows:

- When the SF substitution degree is not more than 20%, mechanical properties and frost resistance of polystyrene granular concrete can be improved.
- When the SF substitution rate is 10%~15%, the improvement of frost resistance of polystyrene granular concrete is more satisfactory, providing a theoretical basis for selecting SF content in polystyrene granular concrete applied in cold environments.
- After 150 freezing and thawing cycles, polystyrene granular concrete with 15% SF has the most minor porosity and average pore diameter, and the number of tiny pores via pores is high.
- SF admixture significantly increased the number of pores of polystyrene granular concrete with 0~0.5mm pore size, reduced the large pore size pores and porosity, and optimized the pore structure.

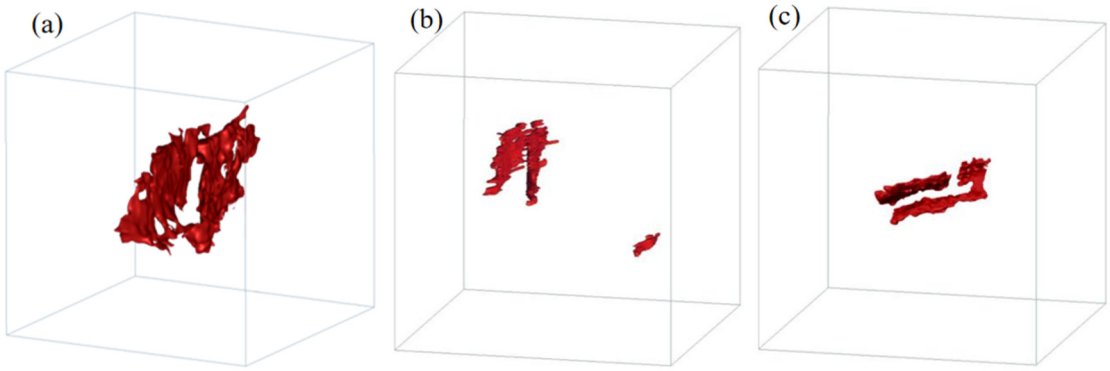

Fig. 10. Damage diagram of polystyrene granular concrete after 150 freeze-thaw cycles (a) EPSC-150, (b) EPSC+5SF-150, (c) EPSC+20SF-150

• Freeze and thaw action transformed SF polystyrene granular concrete pore size from 0~0.5mm to 0.6~1mm.

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