

# Macro steel fiber effect on water permeability of concrete under coupled freeze-thaw cycles and compressive loading

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## ABSTRACT

The durability and damage mechanisms of concrete in cold regions are influenced by multiple coupled factors, including freeze-thaw (FT) cycles, mechanical loading, and moisture penetration. Water permeability directly plays a decisive role in durability, as water acts as the primary medium for aggressive agents to penetrate the matrix. This study investigates the water permeability of plain concrete (PC) and steel fiber reinforced concrete (SFRC) under compressive stress, both with and without exposure to FT cycles. The results show that the evolution of permeability with stress can be divided into three stages: a slight decrease, a slight increase, and a sharp increase. FT cycles substantially elevate permeability; for PC, the initial permeability rises from  $2.99 \times 10^{-11}$  to  $1.88 \times 10^{-6}$  m/s, while the ultimate permeability increases  $7.15 \times 10^{-9}$  to  $3.18 \times 10^{-5}$  m/s after 100 FT cycles. Although steel fibers increase the initial permeability at 0 FT cycles (e.g., SFRC60 is 137% higher than PC), their beneficial effect becomes increasingly evident as the number of FT cycles increases. After 100 FT cycles, the initial and ultimate permeability of SFRC60 decrease by 71.6% and 97%, respectively, compared with those of PC. Moreover, under high stress levels (stress level  $> 0.65$ , where stress level is defined as the ratio of applied compressive stress to the peak compressive stress of each specimen), SFRC consistently exhibits lower permeability than PC, with the difference becoming more evident as the number of FT cycles increases. These findings demonstrate that steel fibers significantly enhance the frost resistance and overall durability of concrete under the combined actions of compressive stress and FT cycling.

## 1. Introduction

Concrete structures in cold regions are frequently exposed to severe environmental conditions, among which freeze-thaw (FT) cycles are one of the most damaging factors affecting long-term durability [1]. Repeated freezing and thawing of pore water cause volumetric expansion, which progressively leads to deterioration of the cementitious matrix and the interfacial transition zone [2,3]. This degradation not only compromises mechanical strength but also modifies the pore structure, facilitates crack initiation and propagation, and markedly increases water permeability [4–6]. Water permeability is closely related to the FT-induced deterioration of concrete and thus provides a direct indicator of damage extent. Since water governs numerous durability-related processes [7–12], including chloride ingress, sulfate attack, and reinforcement corrosion, understanding how FT cycles influence the water permeability of concrete is therefore crucial for

durability evaluation and service life estimation.

Concrete in service is rarely subjected to a single environmental action. Structural members usually bear sustained loads [13–17] while also being exposed to environmental effects such as water penetration and FT cycles [1,2,18–20]. These coupled actions are particularly relevant for tunnel segments in cold regions [21–27], which are simultaneously subjected to water penetration, FT damage, and long-term compressive stress. As illustrated in Fig. 1, water penetration occurs at the inner surface of tunnel linings (Fig. 1a), while ice accumulation is formed on the lining due to the seepage and freezing (Fig. 1b). Meanwhile, the cross section of tunnel segments endures compressive stress transferred from the surrounding ground pressure. The interaction among these factors creates a complex degradation process that accelerates cracking and increases permeability [28–30].

The effect of compressive stress on the transport properties of concrete depends strongly on stress level. Previous studies [16,32] report

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that the impact of compressive stress on concrete permeability changes with stress level: micro-cracks may close and permeability decreases at low stress, but once the stress becomes high enough, cracks propagate and permeability rises. The threshold beyond which permeability rises sharply varies with material properties and test conditions [15,16,32–36]. Meanwhile, FT cycles enlarge pore structures, promote cracking, and thus increase permeability [1,17,37]. However, most existing studies [15,16,32–36] examine mechanical loading and FT damage independently, and the combined action of compressive stress and FT cycles under service conditions remains insufficiently understood.

Fiber provides a promising approach to mitigating such deterioration [4–6,38–40]. Macro steel fibers have been widely recognized for their ability to bridge cracks, redistribute stresses, and improve toughness. By bridging cracks, steel fibers improve the post-cracking performance of concrete and enhance its resistance to environmental degradation [41,42]. Numerous studies confirm that the steel fibers improve FT resistance by reducing mass loss, slowing stiffness degradation, and maintaining matrix integrity [43–45]. Steel fibers may influence the permeability of cementitious composites in different ways over time. Before concrete cracking, the presence of fibers introduces additional fiber-matrix interfaces, which can modify pore connectivity and slightly increase water permeability [46–48]. With the progression of FT cycles and sustained compressive stress, the effect of fibers would be more related to crack control. By bridging and restraining cracks, steel fibers may help limit crack width and reduce the formation of continuous seepage paths, thereby potentially slowing the increase in permeability under coupled actions.

Despite these advances, most existing studies focus either on the influence of FT cycles on durability indicators, or on the effect of compressive stress on transport properties. Only limited research [1,17,37] addresses their coupled action, and even fewer consider the potential role of steel fibers under such conditions. For instance, Zeng et al. [1] investigated steel fiber reinforced concrete subjected to FT cycles combined with splitting tensile loading, while Bao et al. [17] examined the effect of compressive stress and FT cycles on the permeability of plain concrete. However, systematic and quantitative investigations into how steel fibers influence the overall permeability evolution of concrete under coupled FT cycles and sustained compressive stress are still lacking. In practice, structural members in cold regions, such as tunnel linings, are simultaneously subjected to water penetration, FT action, and long-term compressive stress [24–27,49–52]. Steel fibers are commonly used in tunnel primary linings and precast segments [53–58]. Therefore, a comprehensive investigation into the permeability behavior of steel fiber reinforced concrete under coupled FT cycles and compressive loading is still needed.

The present study therefore aims to investigate the effect of steel fibers on the water permeability of concrete subjected to compressive stress and FT cycles. Experimental tests are conducted on plain concrete (PC) and steel fiber reinforced concrete (SFRC) with varying fiber dosages and numbers of FT cycles. The relative dynamic elastic modulus

(RDEM) and mass loss are measured to assess FT-induced damage. Permeability tests are performed under different compressive stress levels. Axial compressive stress is applied with a range from 0 to the peak compressive stress of the specimen. During each permeability measurement, the applied compressive stress is maintained constant. By analyzing the variation of permeability with respect to fiber content, stress level, and degree of FT damage, this study provides new insight into the mechanisms by which steel fibers influence crack development and transport properties under combined environmental and mechanical actions.

## 2. Experiments

### 2.1. Material properties

Table 1 provides the basic mix design for concrete as follows: P-O 42.5 R cement 390 kg/m<sup>3</sup>; fly ash 150 kg/m<sup>3</sup>; fine aggregate (0–5 mm) 820 kg/m<sup>3</sup>; coarse aggregate (5–20 mm) 850 kg/m<sup>3</sup>; water 273 kg/m<sup>3</sup>; polycarboxylate superplasticizer 4.0 kg/m<sup>3</sup>. Macro hooked-end steel fibers (RC-65/35-BN, Fig. 2) are used, with a length of 35 mm, diameter of 0.55 mm, aspect ratio of 65, tensile strength of 1200 N/mm<sup>2</sup>, elastic modulus of 200 GPa, and approximately 14500 pieces/kg. Four fiber dosages are used: 0 kg/m<sup>3</sup>, 20 kg/m<sup>3</sup>, 40 kg/m<sup>3</sup>, and 60 kg/m<sup>3</sup>, corresponding to PC, SF20, SF40, and SF60, respectively. The compressive strength at 28 days is tested using 150 mm concrete cubes cured under standard conditions.

Table 2 summarizes the air content and compressive strength of different mixtures. Their air content is quantified in compliance with ASTM C231 [59]. The incorporation of steel fibers increases the air content of concrete. The air contents of PC, SF20, SF40, and SF60 are 1.9%, 2.5%, 2.9%, and 3.1%, respectively. The air content increased moderately with increasing fiber content, from 1.9% for PC to 3.1% for SF60. Such an increase may be attributed to additional fiber-matrix interfaces and possible entrapped air introduced during mixing. The compressive strength of specimens ranges from 42.6 MPa to 44.5 MPa, corresponding to a variation of less than 4.3%. This observation indicates that the influence of steel fibers on compressive strength is relatively minor.

**Table 1**

Concrete base mixture proportion (kg/m<sup>3</sup>).

| Components             | Content |
|------------------------|---------|
| Portland 42.5 R Cement | 390     |
| Fly Ash                | 150     |
| Fine Aggregate         | 820     |
| Coarse Aggregate       | 850     |
| Water                  | 273     |
| Superplasticizer       | 4.0     |

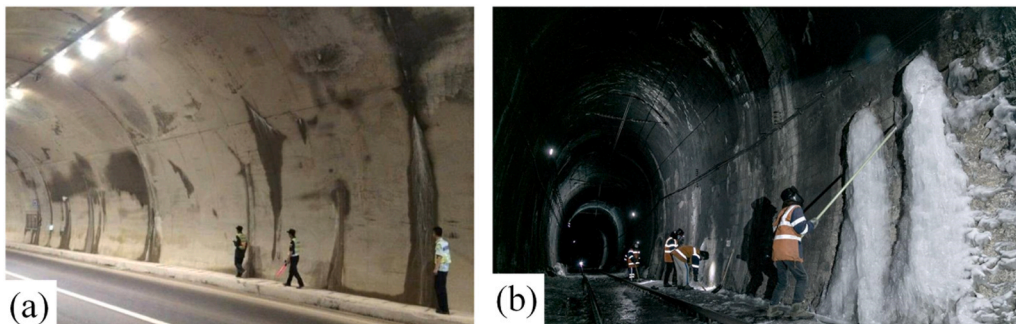


**Fig. 1.** (a) Water penetration and (b) ice accumulation on tunnel lining [31].

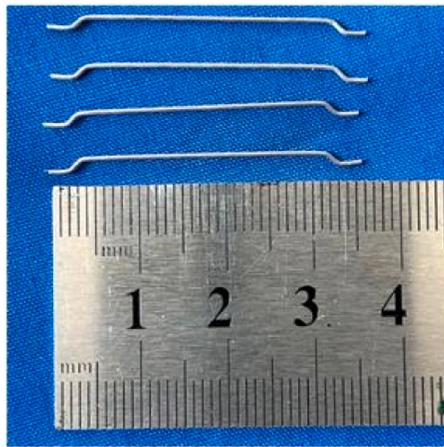


Fig. 2. Steel fibers.

Table 2

Air content and compressive strength of concrete.

| Fiber content (kg/m <sup>3</sup> ) | Specimen ID | Air content (%) | Compressive strength (MPa) |
|------------------------------------|-------------|-----------------|----------------------------|
| 0                                  | PC          | 1.9             | 44.5                       |
| 20                                 | SF20        | 2.5             | 44.3                       |
| 40                                 | SF40        | 2.9             | 43.5                       |
| 60                                 | SF60        | 3.1             | 42.6                       |

## 2.2. Specimen preparation

A forced mixer is used for mixing. Cylinder specimens with 200 mm height and 100 mm diameter are prepared for compressive strength tests, cubes (150 mm × 150 mm × 150 mm), and prisms (100 mm × 100 mm × 400 mm) are cast for the rapid FT test. For the permeability test, hollow cylinders (200 mm in height, inner diameter 50 mm, outer diameter 100 mm) are prepared, as shown in Fig. 3. Six hollow cylinders are obtained from larger hardened concrete slabs for each mixture.

## 2.3. Rapid FT test

Rapid FT test is conducted in compliance with GB/T 50082–2009 [60] and ASTM C666/C666M-15 [61]. The RDEM and mass-loss rate are used to evaluate and compare the concrete damage caused by FT. The prismatic specimens are stored in water for 4 days before FT cycles. The temperature-time curves of the center and the surface of the specimens are displayed in Fig. 4. At the specimen center, the temperature is controlled within a range from 6 °C to −18 °C. At the specimen surface,

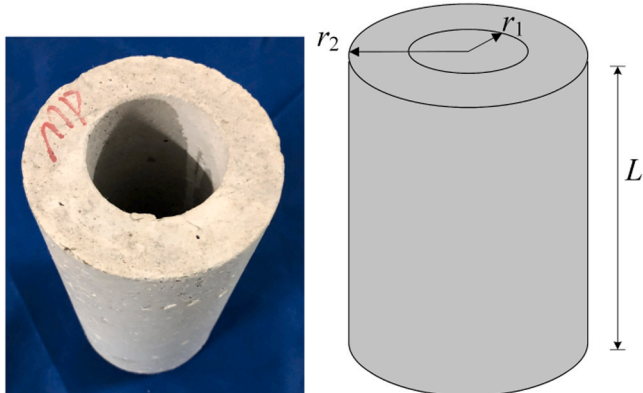


Fig. 3. Hollow cylinder specimen.

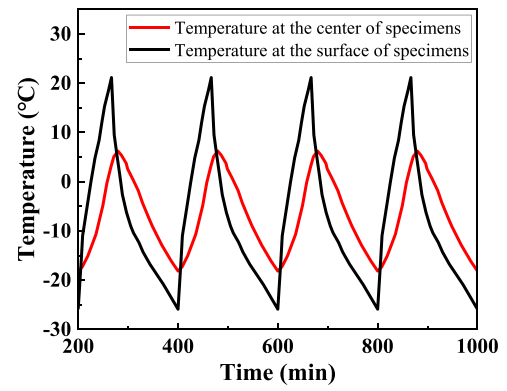


Fig. 4. Comparison between temperature-time curves of the center and the surface of the specimens.

the temperature is controlled within a range from 21 °C to −25 °C. Each FT cycle lasted about 200 min, which complies with the 2–4 h requirement specified in the relevant standards [60,61]. The 200-minute cycle adopted in this study complies with this requirement. It should be noted that the rapid FT method is an accelerated durability test designed to evaluate frost resistance under controlled laboratory conditions rather than to reproduce the exact duration of natural freezing events.

The specimens are removed for testing every 25 cycles. For each group, three 150 mm cube specimens are tested to measure the compressive strength before and after various FT cycles in accordance with GB/T 50082–2009 [60]. The integrity should first be checked to ensure the continuation of the test. Subsequently, the fundamental transverse frequency (FTF) of the prism specimens is measured using the resonance method. Prior to each test, the spalling products on the surface of the specimens are washed off and the surface moisture is wiped dry. The RDEM can be calculated by Eq. (1) [62,63].

$$E_k = (f_k/f)^2 \times 100 \quad (1)$$

where  $E_k$  is the RDEM after  $k$  cycles of FT;  $f$  is the initial FTF;  $f_k$  is the FTF after  $k$  cycles of FT.

Meanwhile, the mass of the specimens is subsequently measured via an electronic scale. The mass-loss rate can be calculated by Eq. (2) [62] below.

$$\Delta M_k = \frac{M - M_k}{M} \times 100 \quad (2)$$

where  $\Delta M_k$  is the mass-loss rate, percent;  $M$  is the initial mass;  $M_k$  is the mass after  $k$  cycles of FT.

## 2.4. Water permeability test

Based on the methods in Section 2.3, 0, 25, 50, and 100 FT cycles are conducted on the hollow cylinder specimens considering the degree of frost damage. A testing system is assembled to monitor the water permeability of hollow concrete cylinders under axial compression load. The testing system can provide constant water pressure and monitor the flow rate of the out flowed water in real time. As presented in Fig. 5 and Fig. 6, the testing system primarily comprises the following components: (a) universal testing machine; (b) compression load cell; (c) air vent; (d) water pressure gauge; (e) permeability test vessel; (f) water inlet; (g) water outlet; (h) electronic scale; (i) water pump. The electronic scale records the mass of the outflowed water and, together with other sensors [1], is connected to the IMC data acquisition system. The permeability test vessel transfers the axial compression load to the specimen while maintaining a watertight seal during testing.

After FT cycles, the specimens would be damaged, resulting in uneven surfaces. To avoid water leakage on the contact surfaces of the

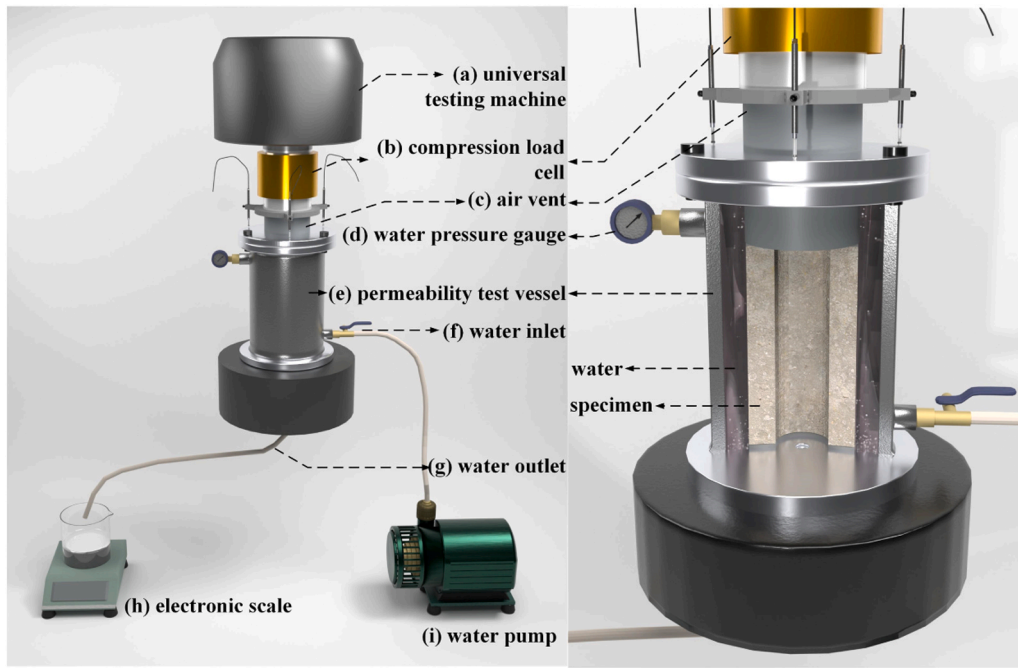


Fig. 5. Schematic of water permeability test system.



Fig. 6. Permeability test vessel.

specimens and vessels, the upper and lower surfaces of these specimens are coated with epoxy resin and smoothed. Moreover, two rubber rings are placed where the specimens and vessels are in contact to ensure their tight connection. Prior to the test, the specimens are treated with vacuum water retention to guarantee the accuracy of the test results. Pre-loading is carried out to ensure that the contact surfaces of the specimens are watertight and that a constant water pressure can be obtained. The specimens are then progressively loaded to different stress levels. Each stress level lasted for a sufficient time to achieve a steady-state flow to obtain the flow rate of the out-flowed water. A constant water pressure of 0.6 MPa is applied for all permeability tests, regardless of freeze–thaw cycles or stress levels. The target pressure is gradually increased to 0.6 MPa within approximately 3 min (corresponding to a loading rate of about 0.2 MPa/min) and then maintained constant during the permeability measurement to ensure stable hydraulic conditions. Steady flow is considered to be achieved when the variation in measured flow rate is less than 5% over a continuous period of 30 min. The water pressure inside the hollow cylinder specimen  $p_d$  is equal to atmospheric pressure (100.3 kPa). Following Darcy's law [6,36], the permeability coefficient is given in Eq. (3):

$$K = \frac{\rho g Q \ln \frac{r_2}{r_1}}{2\pi L(p_u - p_d)} \quad (3)$$

where  $K$  is the permeability coefficient;  $\rho$  denotes water density;  $g$  represents gravitational acceleration;  $Q$  represents the flow rate;  $r_1$  and  $r_2$  are the inner and outer radii of the specimen (see Fig. 3);  $L$  is the specimen thickness in the direction of flow.

It should be noted that FT cycles are conducted prior to permeability testing under compressive loading, representing a sequential loading scheme. In practical engineering, tunnel linings may experience simultaneous FT action and sustained loads. The adopted approach allows clearer identification of FT-induced damage and its interaction with compressive stress under controlled conditions. Nevertheless, differences may exist under fully simultaneous loading, which should be further investigated in future studies.

### 3. Results and discussion

#### 3.1. Mass-loss rate, RDEM, and compressive strength under different FT cycles

Fig. 7 compares the comparison of surface morphology of prism specimens after 0, 50, 100, and 200 FT cycles. With the increasing number of FT cycles, surface deterioration becomes progressively more severe. After 50 cycles, only slight surface peeling is observed. After 100 cycles, visible flaking and localized spalling appear, and the coarse aggregates begin to be exposed. After 200 cycles, extensive surface damage occurs, with large areas of mortar loss and noticeable exposure of both coarse aggregates and steel fibers. In comparison with the PC specimens, the SF specimens exhibit relatively denser and more intact surfaces, indicating that steel fibers can effectively restrain surface cracking and mitigate material spalling during FT deterioration.

Fig. 8(a) illustrates the mass-loss rates of PC and SFRC specimens over 200 FT cycles. During the initial 50 FT cycles, the mass-loss rates of all specimens remain below 1%. After approximately 75 cycles, the mass-loss rates of PC, SF20, and SF40 increase sharply, whereas the increase observed for SF60 is relatively moderate, with the mass-loss rate of PC reaching about 2%. After 200 FT cycles, the mass-loss rates

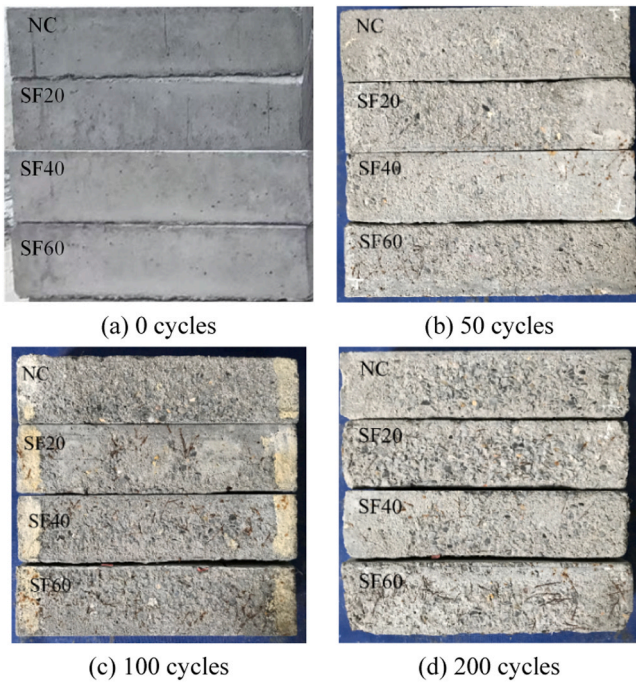


Fig. 7. Surface morphology of specimens at different FT cycles.

of PC, SF20, SF40, and SF60 are 6.37%, 5.23%, 5.01%, and 3.57%, respectively. Relative to PC, the mass-loss rates of SF20, SF40, and SF60 are reduced by 17.9%, 21.4%, and 44.0%, respectively. As stated in GB/T 50082–2009 [60], a specimen is considered to have failed in terms of surface deterioration when the mass-loss rate exceeds 5%. Based on this criterion, only the SF60 specimens do not reach the failure threshold

after 200 FT cycles.

Fig. 8(b) presents the variation of the RDEM with FT cycles for specimens with and without steel fibers. The RDEM values of all specimens decrease monotonically with increasing FT cycles, and a pronounced reduction is observed for PC after 50 FT cycles. After 200 FT cycles, the RDEM values of PC, SF20, SF40, and SF60 are 50.6%, 61.4%, 69.2%, and 76.8%, respectively. Relative to PC, the RDEM values of SF20, SF40, and SF60 increase by 21.3%, 36.7%, and 51.8%, respectively, demonstrating that the steel fibers effectively mitigate stiffness degradation. As stated in GB/T 50082–2009 [60], a specimen is considered to have failed when its RDEM reaches 60%. Therefore, only the PC specimens have failed after 200 FT cycles. This indicates that even the low fiber dosage of 20 kg/m<sup>3</sup> can effectively prevent FT failure within 200 FT cycles. Different failure criteria in GB/T 50082–2009 [60] may lead to different assessments of FT deterioration. The mass-loss rate mainly reflects surface damage, whereas RDEM represents the overall internal degradation of concrete. Therefore, RDEM is adopted as the primary FT failure criterion in this study, with mass loss serving as a supplementary indicator. Based on the RDEM criterion, steel fibers significantly enhance the FT resistance, and this effect increases with fiber dosage, consistent with previous studies [64,65].

Fig. 8(c) presents the variation of compressive strength with FT cycles for PC and SFRC cube specimens. The compressive strength of all specimens decreases progressively with increasing FT cycles. Compared with PC, the SFRC specimens exhibit a slower reduction rate, and the difference becomes more pronounced at higher fiber dosages. After 200 FT cycles, the compressive strengths of PC, SF20, SF40, and SF60 are 13.6 MPa, 20.7 MPa, 27.9 MPa, and 31.0 MPa, respectively. Relative to PC, the residual strengths of SF20, SF40, and SF60 increase by 51.5%, 105.0%, and 127.6%, respectively. These results demonstrate that steel fibers effectively mitigate FT-induced strength degradation, and the enhancement becomes more significant with increasing fiber dosage. This enhancement is due to two primary mechanisms: 1) the fibers bridge and constrain the propagation of cracks formed during FT

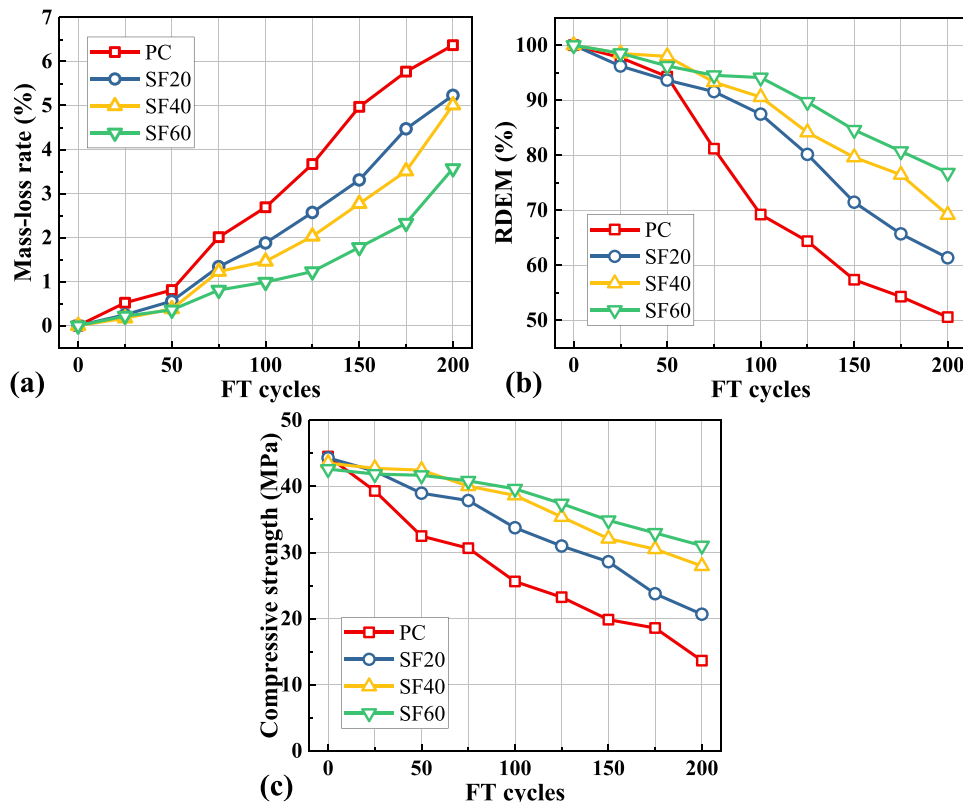


Fig. 8. (a) Mass-loss, (b) RDEM, and (c) compressive strength under different FT cycles.

cycling, thereby preserving the integrity of the cementitious matrix and delaying structural deterioration [64,66]; and 2) the incorporation of macro fibers slightly increases the air content of concrete because of the extra interfaces and the entrapped air introduced during mixing. A moderate increase in air content is known to enhance frost resistance, as the randomly distributed micro voids can accommodate the volumetric expansion of freezing water and relieve internal stresses [67]. Consequently, the synergistic action of these two mechanisms contributes to the better preservation of compressive performance in SFRC after FT cycles.

### 3.2. Peak compressive stress of hollow cylinder specimens under different FT cycles

Based on preliminary tests and previous investigations [1,4], hollow cylinder specimens can withstand up to 100 FT cycles in rapid FT tests. Accordingly, the subsequent sections focus on the impact of steel fibers on the various properties of hollow cylinder concrete specimens subjected to up to 100 FT cycles. Fig. 9 summarizes the peak compressive stress of hollow cylinder specimens subjected to various FT cycles. At 0 FT cycles, the influence of steel fibers on the peak compressive stress of specimens is negligible. The peak compressive stress of PC to SF60 specimens range from 33.1 MPa to 33.7 MPa, with variations within 2% compared with PC specimens. After 100 FT cycles, the peak compressive stress of PC, SF20, SF40, and SF60 specimens are 13.5 MPa, 15.1 MPa, 17.3 MPa, and 18.1 MPa, corresponding to reductions of 59.3%, 54.8%, 48.0%, and 46.3%, respectively. Relative to the PC specimens, the peak compressive stress of SF20, SF40, and SF60 increase by 11.7%, 27.9%, and 34.1%, respectively. The results indicate that steel fibers markedly enhance the residual compressive strength of concrete subjected to FT cycles, and this beneficial effect becomes increasingly significant as the number of FT cycles increases.

### 3.3. Evolution of permeability

#### 3.3.1. Evolution of permeability prior to FT cycles

The results in Fig. 10 demonstrate the permeability of PC, SF20, SF40, and SF60 prior to FT cycles under different stress levels. The blue line in Fig. 10 represents the evolution of permeability with stress levels (expressed in logarithmic form), while the red line represents the evolution of relative permeability with stress levels. The relative permeability denotes the ratio of the permeability to the initial permeability. The initial permeability refers to the permeability measured at the beginning of loading (stress level = 0). The variation rate in permeability with stress levels shows a staged behavior. As displayed in Fig. 10, the variation of permeability with stress level exhibits a three-stage behavior: I) a slight decrease stage, II) a slight increase stage, and III) a significant increase stage. In Stage I, the permeability decreases slightly and monotonically with increasing stress until it reaches

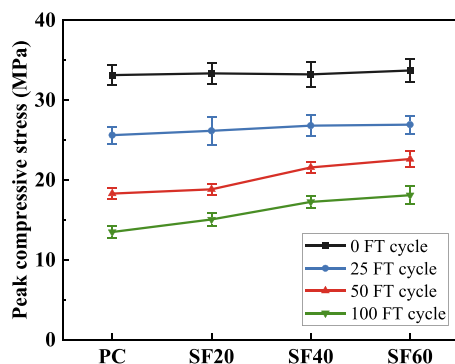


Fig. 9. Peak compressive stress of hollow cylinder specimens under different FT cycles.

a minimum value, which occurs at stress levels of 0.380, 0.405, 0.375, and 0.398 for PC, SF20, SF40, and SF60, respectively. These stress levels correspond to the end of the elastic stage (approximately 0.4 in stress level) of concrete under compression. At these stress levels, the permeability values of PC, SF20, SF40, and SF60 are  $1.79 \times 10^{-11}$  m/s,  $2.73 \times 10^{-11}$  m/s,  $3.32 \times 10^{-11}$  m/s, and  $3.34 \times 10^{-11}$  m/s respectively. Compared with the initial permeability, these values represent reductions of 40.1%, 34.3%, 34.4%, and 52.8%, respectively. This slight reduction in permeability is caused by the compaction of the existing permeability network composed of microcracks and pores under low compressive stress, which reduces the connectivity of flow paths [32].

In Stage II, as the stress increases beyond these critical levels, the permeability begins to increase slightly. This trend is associated with the gradual destabilization of the interfacial transition zone (ITZ) micro-crack system and the initiation of small cracks in the concrete matrix, leading to a minor enhancement in the connectivity of flow channels. At stress levels of 0.781, 0.808, 0.831, and 0.810, the permeability values of PC, SF20, SF40, and SF60 are  $3.56 \times 10^{-10}$  m/s,  $1.06 \times 10^{-10}$  m/s,  $9.69 \times 10^{-11}$  m/s, and  $5.80 \times 10^{-11}$  m/s, respectively, corresponding to increases of approximately 1090.7%, 288.7%, 191.6%, and 73.5% relative to the initial permeability.

In Stage III, once the stress level exceeds the threshold of approximately 0.8, the relative permeability curves increase significantly. This threshold marks the onset of rapid permeability growth, resulting from the propagation and interconnection of micro-cracks and macro-cracks, which form a continuous crack network and markedly enhance the permeability of concrete. At a stress level of 1.0, the permeability of PC, SF20, SF40, and SF60 reaches approximately 238, 88, 68, and 23 times their respective initial values.

Fig. 11 and Table 3 compare the permeability of PC, SF20, SF40, and SF60 under different stress levels. The steel fibers increase the initial permeability of concrete. The initial permeability values of PC, SF20, SF40, and SF60 are  $2.99 \times 10^{-11}$  m/s,  $4.20 \times 10^{-11}$  m/s,  $5.10 \times 10^{-11}$  m/s, and  $7.09 \times 10^{-11}$  m/s, respectively. Compared with PC, the initial permeability of SF20, SF40, and SF60 rises by 40.4%, 70.5%, and 137.1%, respectively. Similarly, the addition of steel fibers also increases the depth of water penetration, as displayed in Fig. 12. Tests conducted according to EN 12390-8:2019 [68] and GB/T 50082-2009 [60] indicate that the average depths of water penetration for PC, SF20, SF40, and SF60 are 9.4 mm, 40.0 mm, 49.6 mm, and 52.0 mm, respectively, as indicated by the orange dashed lines in Fig. 1. The increase in water penetration depth and initial permeability is mainly attributed to the ITZs introduced by the incorporation of steel fibers. X-ray computed tomography (CT) studies have demonstrated that the fiber-matrix interface generally exhibits higher local porosity than the cement matrix, and three-dimensional reconstructions indicate that these interfacial regions may form locally connected micro-pathways [46,48,69,70]. As shown in Fig. 13, steel fibers are embedded within the matrix. CT-based analyses suggest that the ITZ surrounding the fibers contains micro-voids and imperfect bonding zones [71], which may enhance local pore connectivity and contribute to the increased initial permeability observed in Fig. 12.

As illustrated in Fig. 11, with increasing stress levels, the development of macro-cracks is effectively restrained by steel fibers, thereby mitigating the increase in permeability. Once the stress level exceeds 0.65, the permeability of PC surpasses that of SFRC. For instance, at a stress level of 0.8, the permeability of PC, SF20, SF40, and SF60 is  $5.03 \times 10^{-10}$  m/s,  $8.76 \times 10^{-11}$  m/s,  $6.83 \times 10^{-11}$  m/s, and  $5.41 \times 10^{-11}$  m/s, respectively. At a stress level of 1.0 (ultimate compressive stress), these values (ultimate permeability) further increase to  $7.15 \times 10^{-9}$  m/s,  $4.54 \times 10^{-9}$  m/s,  $2.89 \times 10^{-9}$  m/s, and  $1.73 \times 10^{-9}$  m/s for PC, SF20, SF40, and SF60, respectively. These results indicate that when the stress level is greater than 0.65, a fiber dosage of 60 kg/m<sup>3</sup> provides the most effective reduction in concrete permeability. This behavior originates from two mechanisms. Steel fibers bridge cracks and transfer stress, thereby limiting the formation of

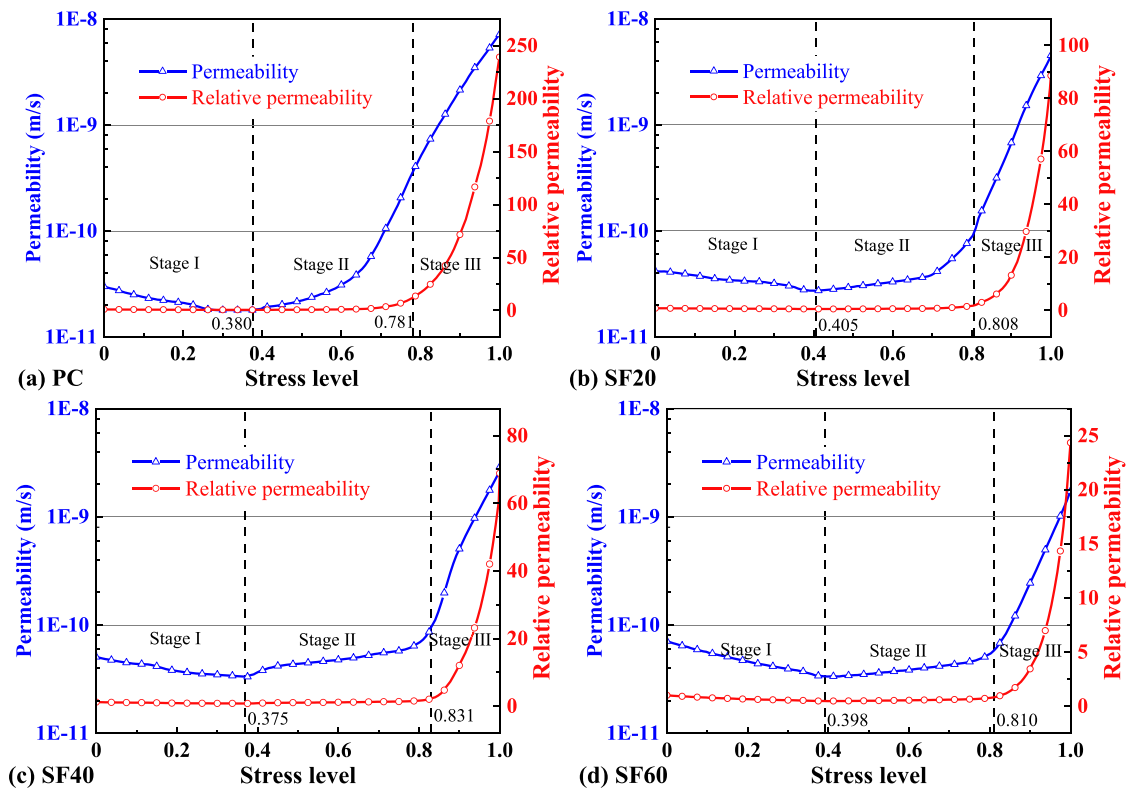


Fig. 10. Evolution of permeability with stress levels for (a) PC; (b) SF20; (c) SF40; and (d) SF60.

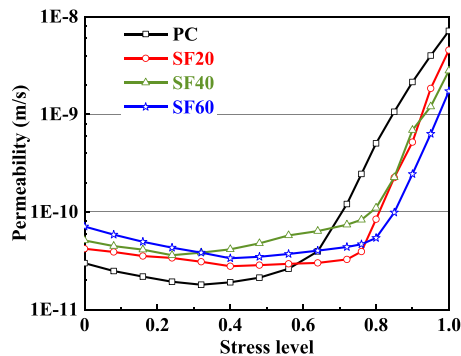


Fig. 11. Comparison of the permeability of concrete with four fiber dosages under different stress levels.

Table 3

Permeability of different concretes under various stress levels.

| Stress level | Permeability (m/s)     |                        |                        |                        |
|--------------|------------------------|------------------------|------------------------|------------------------|
|              | PC                     | SF20                   | SF40                   | SF60                   |
| 0            | $2.99 \times 10^{-11}$ | $4.20 \times 10^{-11}$ | $5.10 \times 10^{-11}$ | $7.09 \times 10^{-11}$ |
| 0.65         | $4.01 \times 10^{-11}$ | $3.05 \times 10^{-11}$ | $6.37 \times 10^{-11}$ | $4.01 \times 10^{-11}$ |
| 0.80         | $5.03 \times 10^{-10}$ | $8.76 \times 10^{-11}$ | $6.83 \times 10^{-11}$ | $5.41 \times 10^{-11}$ |
| 1.00         | $7.15 \times 10^{-9}$  | $4.54 \times 10^{-9}$  | $2.89 \times 10^{-9}$  | $1.73 \times 10^{-9}$  |

continuous flow channels. In addition, as depicted in Fig. 14, the incorporation of fibers enhances the roughness of crack surfaces, as also confirmed by previous studies [1,5,72]. As described in reference [5], the roughness ( $R_a$ ) of the cracked surface is calculated from Fig. 14(b) as the ratio of the actual surface area to the projected area. The  $R_a$  values for PC, SF20, SF40, and SF60 are 1.20, 1.47, 1.89, and 1.98, respectively. The increase of roughness not only extends the tortuous flow paths of

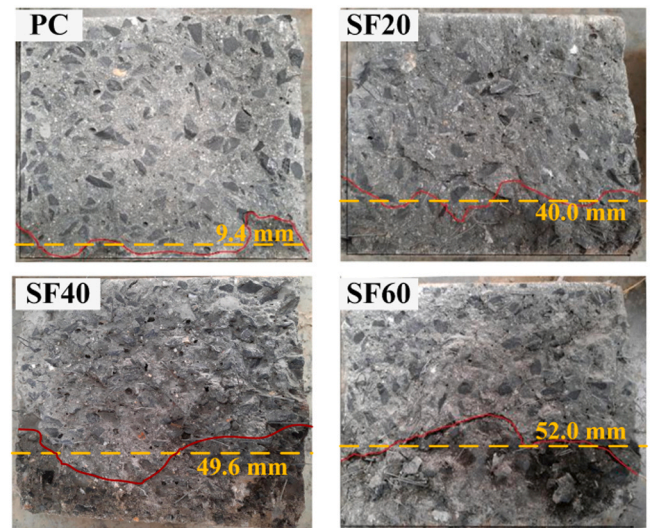


Fig. 12. Comparison of water penetration depths in concrete with different steel fiber dosages.

permeating water, but also increases the energy required for water penetration, thereby further reducing the permeability of cracked concrete. Consequently, concrete with higher steel fiber content exhibits lower permeability when subjected to high stress levels.

### 3.3.2. Evolution of permeability after FT cycles

Fig. 15 illustrates the comparison of permeability-stress level responses of PC and SFRC with different fiber contents. Table 4 lists the initial permeability and ultimate permeability of specimens, while Table 5 summarizes the critical stress levels of the specimens. The critical stress level is defined as the stress level at the boundary between

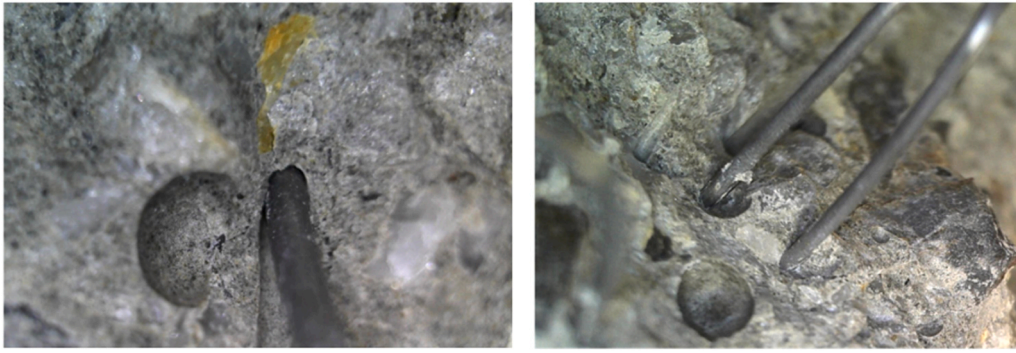
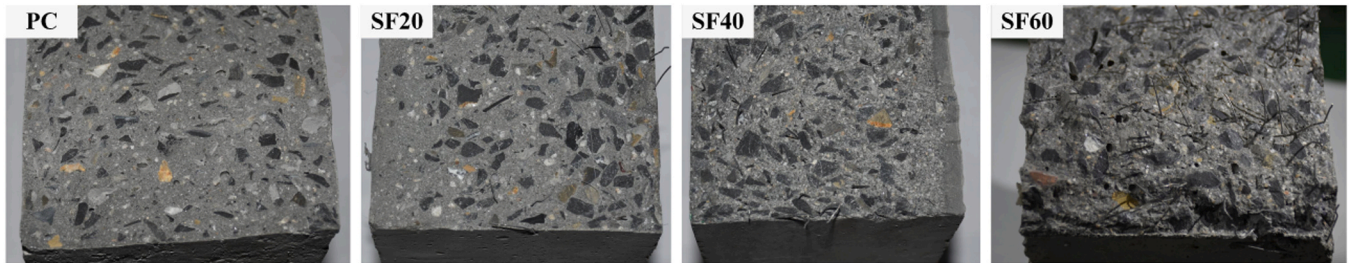
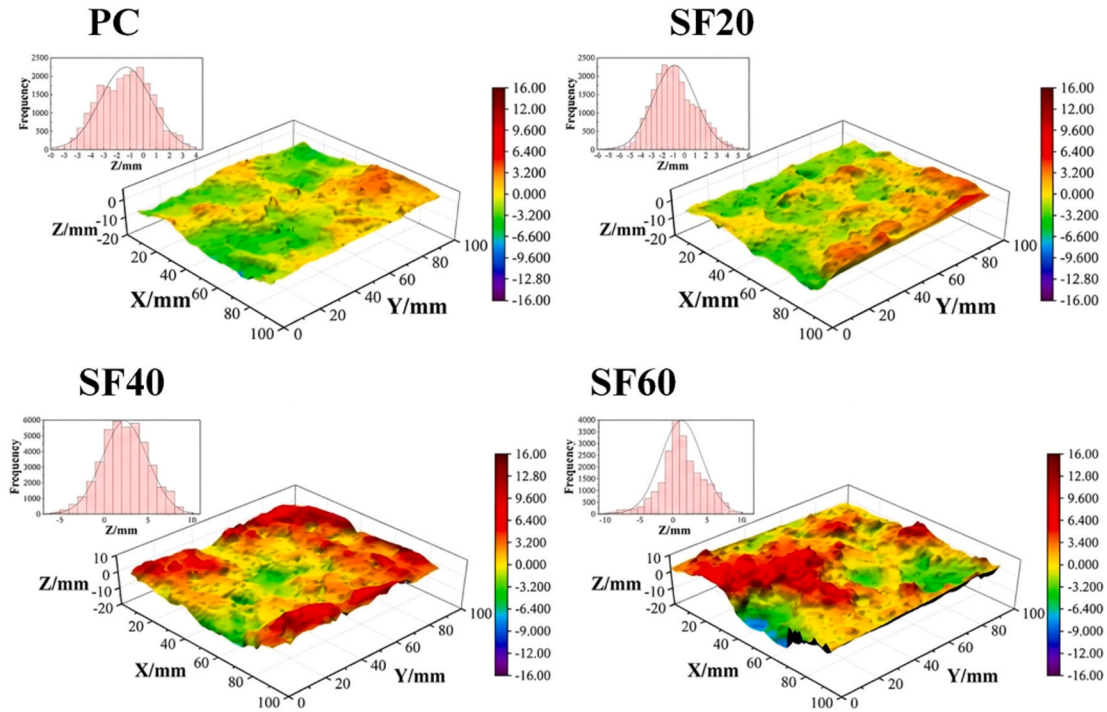


Fig. 13. Steel fibers embedded in the concrete matrix.



(a) photographs of crack surfaces



(b) 3D reconstructed surface topography of crack surfaces [5]

Fig. 14. Comparison of crack surface morphology and 3D topography in concrete with different steel fiber dosages.

Stage I and Stage II.

The results presented in Fig. 15, Table 4, and Table 5, reveal several important trends. The permeability decreases initially until the critical stress level and then increases with rising compressive stress levels. The slight decrease in permeability is caused by the compaction of the pore structure and closure of some micro-pores and micro-cracks by compressive stress in the elastic stage [32]. The critical stress level for

concrete without FT cycles is approximately 0.40. With an increasing number of FT cycles, this level shifts upward, reaching 0.574, 0.695, 0.710, and 0.731 for PC, SF20, SF40, and SF60 after 100 cycles, respectively. This shift occurs because FT-induced damage generates additional cracks and interconnected pores in the matrix, so higher external stress is required to activate further crack propagation and establish continuous transport paths.

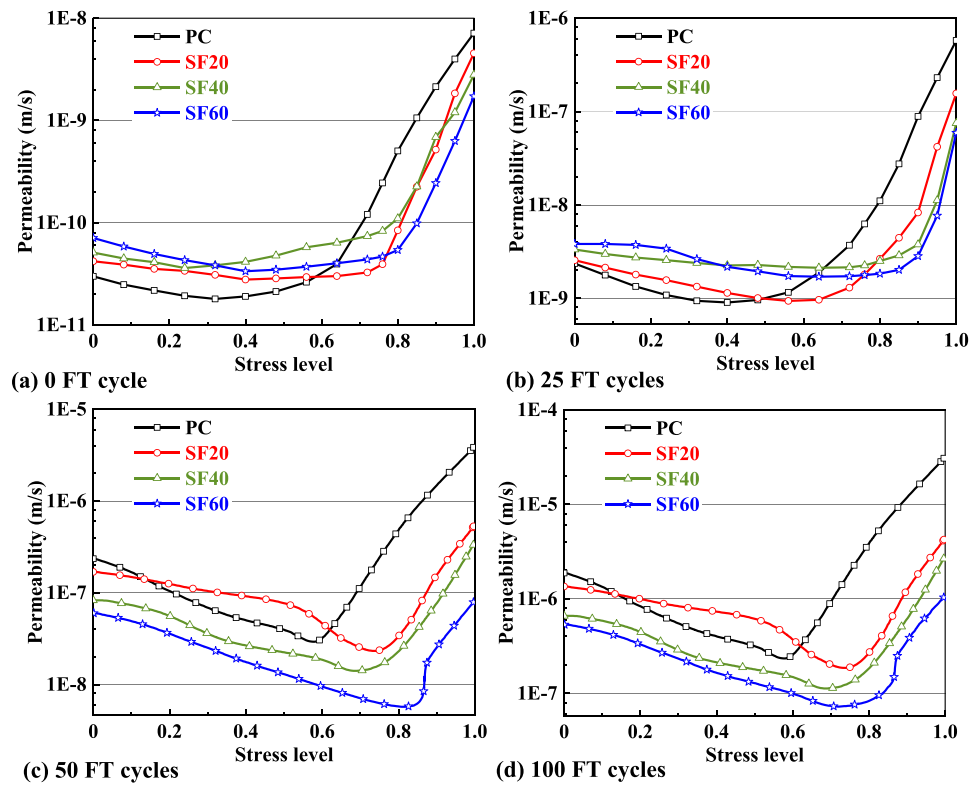


Fig. 15. Comparison of permeability-stress level responses of PC and SFRC with different fiber dosages.

Table 4

Initial and ultimate permeability of PC and SFRC specimens under various FT cycles.

| Number of FT cycles | Initial permeability/Ultimate permeability (m/s)  |                                                   |                                                   |                                                   |
|---------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
|                     | PC                                                | SF20                                              | SF40                                              | SF60                                              |
| 0                   | $2.99 \times 10^{-11}$ /<br>$7.15 \times 10^{-9}$ | $4.20 \times 10^{-11}$ /<br>$4.54 \times 10^{-9}$ | $5.10 \times 10^{-11}$ /<br>$2.79 \times 10^{-9}$ | $7.09 \times 10^{-11}$ /<br>$1.73 \times 10^{-9}$ |
| 25                  | $2.36 \times 10^{-9}$ /<br>$5.78 \times 10^{-7}$  | $2.56 \times 10^{-9}$ /<br>$1.57 \times 10^{-7}$  | $3.34 \times 10^{-9}$ /<br>$7.51 \times 10^{-8}$  | $3.82 \times 10^{-9}$ /<br>$5.92 \times 10^{-8}$  |
| 50                  | $2.35 \times 10^{-7}$ /<br>$3.97 \times 10^{-6}$  | $1.69 \times 10^{-7}$ /<br>$5.49 \times 10^{-7}$  | $8.27 \times 10^{-7}$ /<br>$3.52 \times 10^{-7}$  | $5.98 \times 10^{-8}$ /<br>$8.21 \times 10^{-8}$  |
| 100                 | $1.88 \times 10^{-6}$ /<br>$3.18 \times 10^{-5}$  | $1.35 \times 10^{-6}$ /<br>$4.40 \times 10^{-6}$  | $6.61 \times 10^{-7}$ /<br>$2.81 \times 10^{-6}$  | $5.33 \times 10^{-7}$ /<br>$1.04 \times 10^{-6}$  |

Table 5

Critical stress levels of PC and SFRC specimens with different fiber dosages under various FT cycles.

| Number of FT cycles | Stress levels |       |       |       |
|---------------------|---------------|-------|-------|-------|
|                     | PC            | SF20  | SF40  | SF60  |
| 0                   | 0.380         | 0.405 | 0.375 | 0.398 |
| 25                  | 0.401         | 0.635 | 0.635 | 0.675 |
| 50                  | 0.576         | 0.731 | 0.721 | 0.807 |
| 100                 | 0.574         | 0.695 | 0.710 | 0.731 |

Both the initial and ultimate permeability of all specimens increase markedly with FT cycles. At 0 cycles, the initial permeability of PC is only  $2.99 \times 10^{-11}$  m/s, while after 100 cycles it rises to  $1.88 \times 10^{-6}$  m/s, representing an increase of about five orders of magnitude. A similar trend is observed for the ultimate permeability, which rises from  $7.15 \times 10^{-9}$  m/s to  $3.18 \times 10^{-5}$  m/s. These indicate that severe FT damage strongly alters the pore structure and connectivity of concrete.

Meanwhile, the incorporation of steel fibers significantly modifies

both the initial and ultimate permeability after FT cycles. As FT cycles increase, the influence of fibers on the initial permeability reverses, changing from an increase to a reduction in initial permeability. After 100 FT cycles, the initial permeability of PC reaches  $1.88 \times 10^{-6}$  m/s, whereas that of SF20, SF40, and SF60 decreases by 28.2%, 64.5%, and 71.6%, respectively. Similarly, FRC specimens exhibit much lower ultimate permeability than PC specimens after the same number of FT cycles. After 50 cycles, the ultimate permeability of SF60 is  $8.21 \times 10^{-8}$  m/s, which is only about 5% of that of PC. After 100 cycles, SF60 exhibits the lowest permeability at all stress levels among the tested specimens. The ultimate permeability decreases from  $3.18 \times 10^{-5}$  m/s (PC) down to  $1.04 \times 10^{-6}$  m/s (SF60), corresponding to a drop of nearly 97.0%. Although fiber incorporation introduces additional interfaces that may locally increase connected porosity, the fibers effectively mitigate FT-induced microstructural damage, thereby limiting the formation of continuous pore networks within the cement matrix under the couple actions of FT cycles and compressive stress.

#### 3.4. Macroscopic and microscopic analysis of concrete damage after FT cycles

Fig. 16. illustrates that, in contrast to the specimens without FT cycling shown in Fig. 3, hollow cylinder specimens subjected to repeated FT cycles exhibit evident surface flaking, which results from the progressive expansion of the cement paste during freezing. This surface deterioration, together with internal cracking [73,74], reduces both the mechanical properties and impermeability of the matrix. Corrosion is observed on steel fibers exposed at the spalled surfaces, indicating the susceptibility of unprotected fibers to the aggressive FT environment. In contrast, steel fibers embedded in the concrete remain uncorroded [75], as the surrounding cementitious matrix provides effective protection. These internal fibers continue to effectively bridge cracks and maintain mechanical performance, which contributes to the durability and service life of concrete in harsh environments.

Fig. 17 depicts scanning electron microscope (SEM) images of the



Fig. 16. Concrete flaking of hollow cylinder specimen after FT cycles.

micro-structural evolution of the matrix before and after FT exposure, as well as the ITZ between steel fiber and matrix. In Fig. 17(a), the matrix without FT cycles exhibits a relatively continuous and compact micro-structure, and the cement paste remains largely preserved. In Fig. 17(b), the concrete matrix subjected to 100 FT cycles shows a significantly roughened micro-structure. Several micro-cracks and localized flaking debris can be observed. Such defects indicate apparent FT-induced deterioration and may create easier pathways for water to enter the matrix. Fig. 17(c) depicts the ITZ between the steel fiber and the matrix after FT cycling. A partial debonding at the interface is observed. Several micro-cracks are present around the ITZ, reflecting local degradation of the fiber-matrix interface. Nevertheless, the hooked end of the steel fiber remains embedded in the surrounding matrix (see Fig. 18), and the associated mechanical anchorage is still effective in restraining crack propagation. Consequently, the steel fiber mitigates FT-induced damage and helps limit the FT-induced increase in the permeability of the matrix.

#### 4. Conclusions

Based on the above findings, the main conclusions can be drawn:

- 1) The water permeability of concrete exhibits a three-stage evolution with increasing stress levels, with two turning points at 0.4 and 0.8: a slight decrease at low stress levels up to 0.4, a gradual increase at

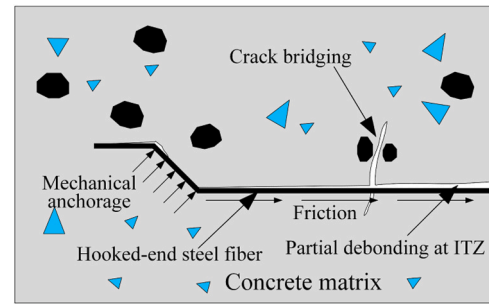


Fig. 18. Schematic of crack-bridging mechanism for hooked-end steel fiber after FT cycling.

intermediate stress levels, and a sharp increase beyond 0.8. Steel fibers effectively delay permeability escalation at high stress levels by restraining macro-crack development.

- 2) FT cycles significantly increase the permeability of concrete under different stress levels. Both the initial permeability and the ultimate permeability rise strongly with the numbers of FT cycles, reaching increases of several orders of magnitude after severe FT damage.
- 3) The influence of steel fibers on permeability exhibits a distinct “double-edged” characteristic under coupled FT and compressive loading conditions. Prior to FT cycles, steel fibers slightly increase the initial permeability of concrete, however, after sufficient FT exposure ( $\geq 50$  FT cycles), FRC shows significantly lower initial permeability than plain concrete. This finding highlights the distinct role of steel fibers in regulating permeability evolution under realistic coupled deterioration conditions.
- 4) Under the coupled effects of FT cycling and compressive loading, steel fibers substantially reduce concrete permeability at high stress levels. Among the tested mixtures, concrete with a fiber dosage of  $60 \text{ kg/m}^3$  consistently exhibits the lowest ultimate permeability.

In summary, this study provides a systematic and quantitative insight into the permeability evolution of steel fiber reinforced concrete under coupled FT and compressive stress conditions, offering improved understanding of its performance in realistic cold-region engineering environments.

#### CRediT authorship contribution statement

**Yining Ding:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Fernando Pacheco-Torgal:** Writing – review &

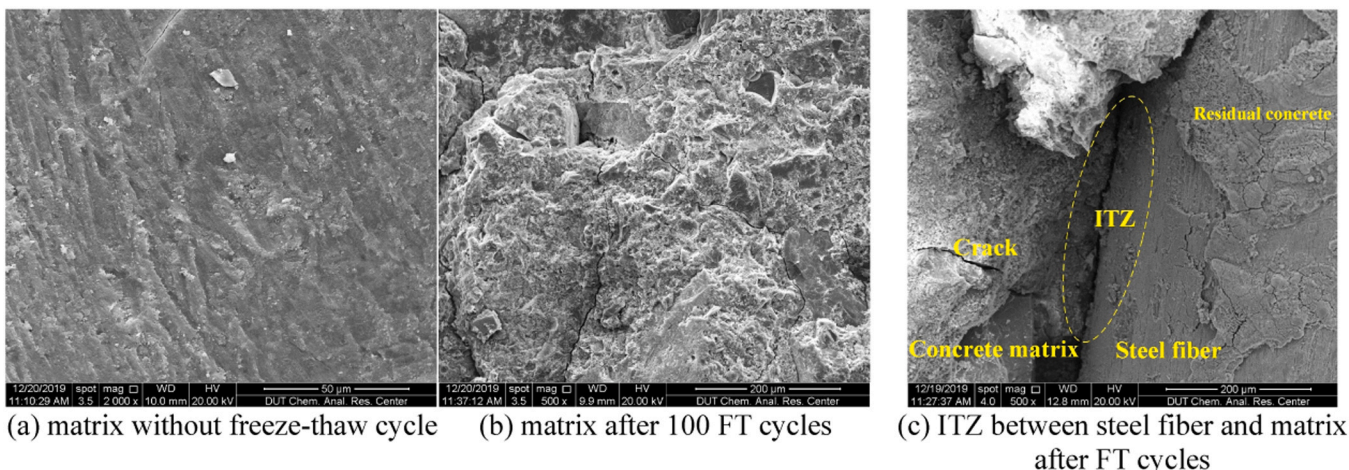


Fig. 17. SEM images of the microstructural evolution under FT cycling.

editing, Validation, Methodology. **Wei Guo:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

## Declaration of Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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## Data Availability

Data will be made available on request.

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