XVI International Conference on Durability of Building Materials and Components
DBMC 2023, China
K.F. Li and D.P. Fang (Eds)

Freeze-thaw Damage Mechanism and Cracking Behaviour of Perforated Plateau Concrete Structure

Jianghong Mao[1], Kun Fang[1], Lin Mi[1] and Hongtao Jia[1]

[1]College of Architecture & Environment, Sichuan University, Chengdu 610065, P.R. China

jhmao@scu.edu.cn (Jianghong Mao), 2019141470178@stu.scu.edu.cn (Kun Fang), 837238123@qq.com (Lin Mi), 906319074@qq.com (Hongtao Jia)

Abstract. *The harsh environment and poor quality of building materials used in plateau concrete projects adversely affect the ability of such structures to withstand the damaging impact of freeze-thaw. A fast-freezing test with a single variable control was carried out and the process of microstructural changes in the plateau concrete was traced. The results also showed that the plateau curing environment led to an increase in width and porosity of the interface transition zone (ITZ), and that clay content in building materials significantly impacted the microstructure of paste. The frost resistance of plateau concrete was found to be far lower than that of plain concrete. Perforated concrete structures are common in engineering, and concrete members can easily experience frost cracking in cold regions. This study conducts frost heave tests on perforated concrete, aiming at the problem of the frost heave cracking risk of perforated concrete structures in cold regions. The cracking characteristics of concrete with holes under freeze-thaw cycles are mastered by performing rapid freeze-thaw tests on concrete with holes and observing the cracked section. Finally, hydrophobic filling materials were adopted to alleviate the frost heave stress on concrete.*

Keywords: *Plateau concrete; Perforated concrete; Frost resistance; Freeze-thaw damage; Cracking*

1 Introduction

More and more structures are being constructed in cold environments with engineering infrastructure development (Ma et al. 2017, Ortiz et al. 2005, Yu et al. 2017). For cold region engineering, freeze-thaw(F-T) damage is the primary durability problem (Xie et al. 2021). For the freeze-thaw damage to concrete materials, theoretical methods, such as the hydrostatic pressure theory (Powers et al. 1945) and the osmotic pressure theory (Powers et al. 1953), have been developed. It is certain that the internal expansion pressure generated by the internal, saturated water during freezing causes freeze-thaw damage to concrete (Hanjari et al. 2011). After freeze-thaw cycles, microcracks are generated inside the material, and irreversible residual expansion deformation is retained (Cai et al. 1998), causing cracks to form in concrete and develop gradually, thereby eventually resulting in damage to concrete.

It is worth noting that the frost heave cracking of concrete with holes in cold regions should be a concern because the volume expansion due to the water-ice phase transition is about 9% (Davidson et al. 1985). Sun et al. (2021) reported that longitudinal cracks were formed and developed in post-tensioned box girders along the prestressed channel distribution after several months of casting them in cold and high-altitude environments. Their study found that the primary reason for the longitudinal cracking of the concrete beams was that the prestressed duct was not dense, leading to bleeding, followed by repeated water-freezing expansion. In another work, Zi et al. (2012) found that some bolt holes of concrete railway sleepers cracked after two or three freeze-thaw cycles in the experiment, but some did not crack. The above shows that concrete with holes does not crack immediately during the freeze-thaw process and undergoes specific freeze-thaw cycles to destroy, indicating that examining the freeze-thaw process of concrete with holes, involving the freezing process of water in the holes and the development of damage to concrete, is complex. Although the above studies indicate a risk of frost heave cracking of concrete with holes, the existing research has not investigated the characteristics of damage to concrete under frost heave force.

Given the lack of research on the frost cracking of concrete with holes based on the above discussion, this paper conducts an experimental study on the freezing behavior of holes in concrete using temperature monitoring and analyzes the development characteristics of damage to concrete with holes under the action of frost heave force. Finally, the preventive and controlling measures for the frost heave cracking of concrete with holes based on eliminating the pressure in the holes are put forward, which provides a scientific basis for the design of engineering structures in cold regions.

2 Experimentation

2.1 Materials and Specimens

This work used P.O 42.5 cement, river sand with a fineness modulus of 2.6 as the fine aggregate, the coarse aggregate of class I gravel with a large/small stone ratio of 8:2, a PCA-1 polycarboxylate high-performance water reducer, and tap water. Table 1 lists the mix proportion of the prepared concrete.

Table 1. The mixture ratio of the prepared concrete.

Water-to-Cement ratio	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	Water reducer (kg/m^3)
0.5	330	785	1120	165	3.96

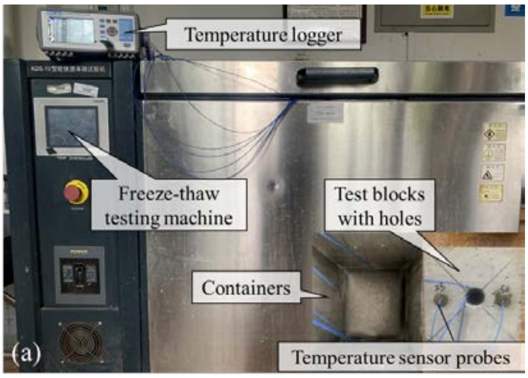
The concrete specimens had the dimensions 150 mm × 150 mm × 150 mm. After the concrete was cured for 28 days, the middle position of the testing block was drilled by a water drill; the diameter of the drilled hole was 27 mm.

2.2 Testing Methods

2.2.1 Freeze-thaw cycle test

Tests I and II examined the frost heave and frost crack prevention of concrete with holes. To this end, a KDS-10 freeze-thaw testing machine conducted the freeze-thaw cycles. Figure 2a illustrates the testing device for tests I and II.

Figure 2b delineates the testing temperature profile. The initial temperature was 12 °C, and the freezing temperature was -18 °C. The temperature declined at a rate of 0.3 °C/min from the initial temperature during 100 min, and the holding time was 120 min; thus, the total freezing time was 220 min. The heating rate was set at 1 °C/min, so it took 30 min to rise from -18 to 12 °C; the maintaining period was 90 min, and the total melting time equaled 120 min. In addition, the test used the same Yili EX3008 multichannel temperature recorder for temperature monitoring.



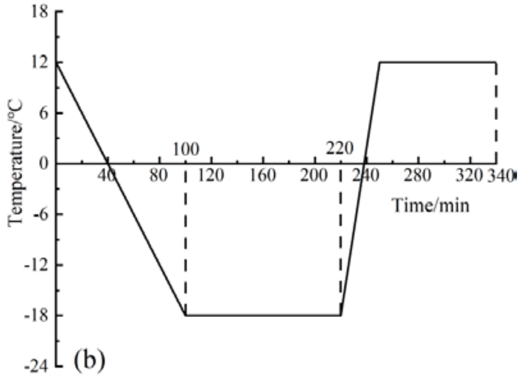


Figure 2. The layout of freeze-thaw test: (a) The testing device for tests I and II; (b) the testing temperature profile.

2.2.2 Crack observation

To further investigate the cracking behavior of concrete with holes, we extracted cylinders with a diameter of 100 mm and height of 10 mm from the middle and surface of the testing blocks along the direction of the holes, as shown in Figure 3. This work treated the cracks on the concrete surface using the dye impregnation method (Zhou et al. 2012) and observed and counted the distribution and number of cracks utilizing an Olympus GX51 inverted metallographic microscope (Olympus Corporation, Japan) and MG10085-1A crack width meter (Tuodayiqi, China). We first ground the surface of the specimens with 120, 240, 400, 600, 1000, 1500, and 2000 mesh sandpaper respectively and ground the surface continuously to eliminate the possible secondary cracking of the sawed specimen and obtain a fine and smooth surface. The crack was then treated with carbon black: ultrafine particles of carbon black with a diameter of about 20 nm were mixed with tap water and uniformly applied on the polished surface. After washing the surface, there were residual particles of carbon black in the cracks, contrasting well with the concrete matrix.

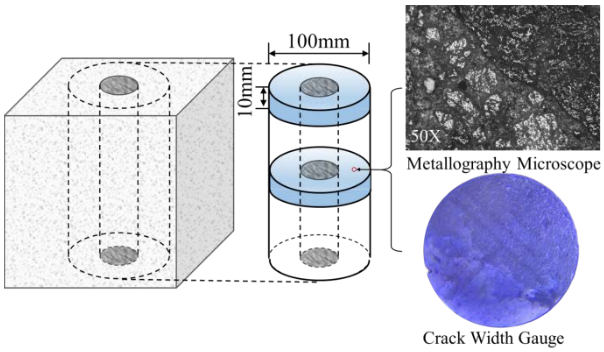


Figure 3. Preparing the testing blocks for crack observation and the crack observation results.

3 Experimental Results and Analysis

3.1 Development of Damage to Perforated Concrete

As shown in Figure 4, NF1-1 and NF1-2 are the blocks cut off the testing block without freeze-thaw, and F2-1 and F2-2 are the blocks cut off the cracked testing block after seven freeze-thaw cycles.

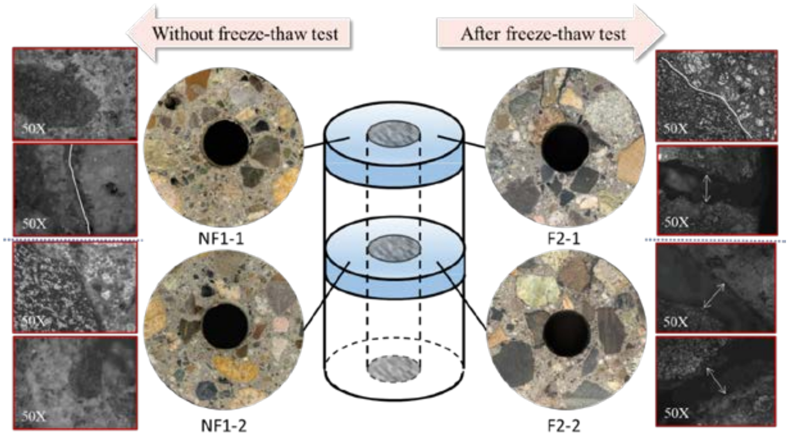


Figure 1. A holistic diagram of the crack around the hole in the concrete with hole.

The overall morphology of the specimen section in Figure 4. demonstrates that the concrete surface after the freeze-thaw test shows more apparent primary cracks compared to the concrete not undergoing freeze-thaw cycles. The microscopic observation of the cut surface shows that the interface between the aggregate and the matrix of unfrozen-thawed specimens NF1-1 and NF1-2 is clear, and small cracks appear at some locations, mainly from the initial defects in the concrete, such as cracks and air holes (Chen et al. 2021, Trawiński et al. 2018). In contrast, the cracks in the interface between the aggregate and the matrix are more evident in specimens F2-1 and F2-2, and more apparent cracks appear at the edge of hole F2-2. It is worth noting that specimen F2-1 has only one apparent primary crack, while specimen F2-2 has other obvious cracks in addition to the primary crack.

Further, the number of cracks in each section is counted and measured by a crack width gauge. The positions of 14.5, 22.5, 32.5, and 47.5 mm from the center of the circle are used to observe and count the cracks on the circle path. It should be noted that due to the limitation of the range of the crack width gauge, the statistical results do not cover fine cracks with a width smaller than 0.005 mm. Figure 5 depicts the results.

Figure 5a demonstrates that the crack width is uniform for the NF1-1 and NF1-2 sections, and the maximum crack width does not exceed 0.02 mm. For sections F2-1 and F2-2, the maximum crack width at 14.5 and 22.5 mm from the center of the circle is noticeably higher than that at the farther positions. The maximum crack width at a position of 14.5 mm from the center of the circle for the two cuts is 0.2 and 0.3 mm respectively. Similar laws can also be obtained for the average width and the number of cracks in Figure 5b: The average crack width of the specimen experiencing the freeze-thaw cycles is higher than that of specimens NF1-1 and NF1-2, and the number of cracks in specimens F2-1 and F2-2 after the freeze-thaw cycles is significantly more than that in specimens NF1-1 and NF1-2 not undergoing the freeze-thaw cycles. The closer the testing block is to the hole wall, the more the number of cracks becomes. The maximum width and the number of cracks in testing block F2-2 are also more than those in testing block F2-1. In addition, there are primary tensile cracks in sections F2-1 and F2-2. The cracks are wide, and there are cracks with different widths in the transition zone after the frost heave. Therefore, the error bar range of the average crack width in Figure 5b is broad.

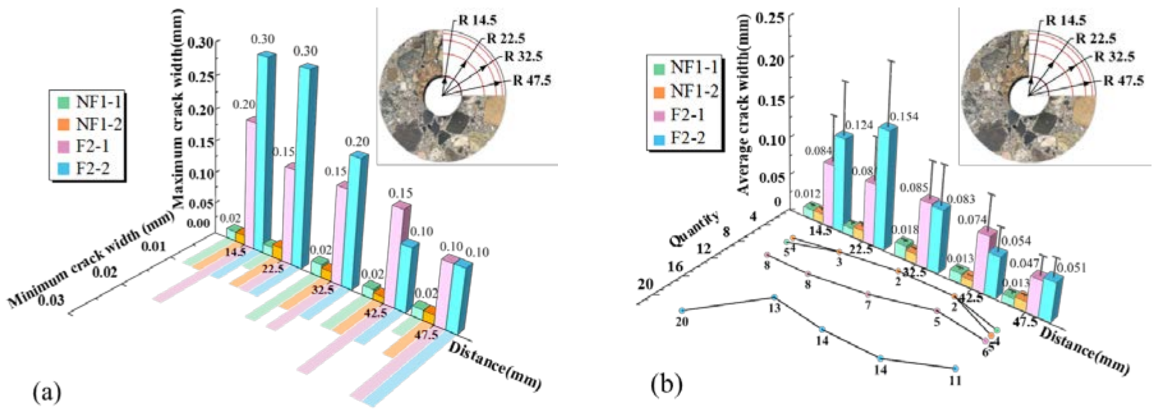


Figure 2. The statistical results of the cracks: (a) the maximum and minimum crack widths; (b) the average crack width and the number of cracks.

3.2 Effect of Preventive Measures

Aiming at the problem of freeze-thaw cracking of concrete with holes, we propose measures to prevent cracking by filling a polyurethane foaming agent in concrete holes. In order to study whether this method benefits antifreezing concrete with holes, a polyurethane foaming agent tube with a diameter of about 23 mm is prefabricated and inserted into the concrete hole. Figure 6 illustrates the test results.

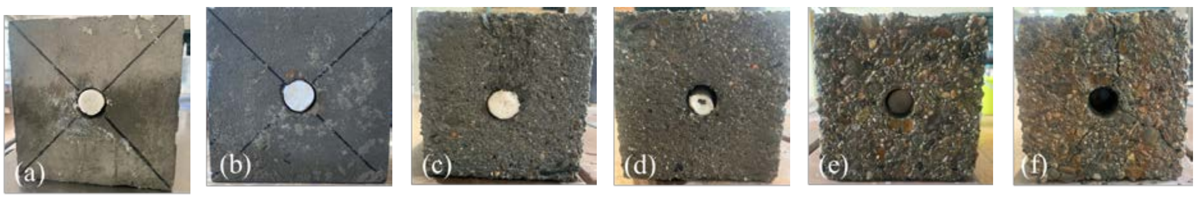


Figure 3. The freeze-thaw test on the concrete with holes under preventive measures: (a) 0 F-T cycles; (b) 25 F-T cycles; (c) 50 F-T cycles; (d) 75 F-T cycles; (e) 100 F-T cycles; (f) 150 F-T cycles.

Figure 6 shows that different from the previous test, the first phenomenon of the testing block is not its cracking but the freeze-thaw damage to its surface. According to Figure 6c, the original smooth surface of the cement mortar gradually roughens with an increase in the number of freeze-thaw cycles. The fine aggregate is exposed, and part of the surface is peeled off until the entire surface of the testing piece is loose and separated, indicating that the coarse aggregate and part of the edge angle separate. The final testing block is shown in Figure 6f. After 150 freeze-thaw cycles, the specimen is subjected to frost heave cracking.

4 Discussion

4.1 Analyzing Cracking Behavior of Porous Concrete

Regarding the previous crack observation results and analysis, we can propose the cracking mechanism of concrete with holes, as depicted in Figure 7.

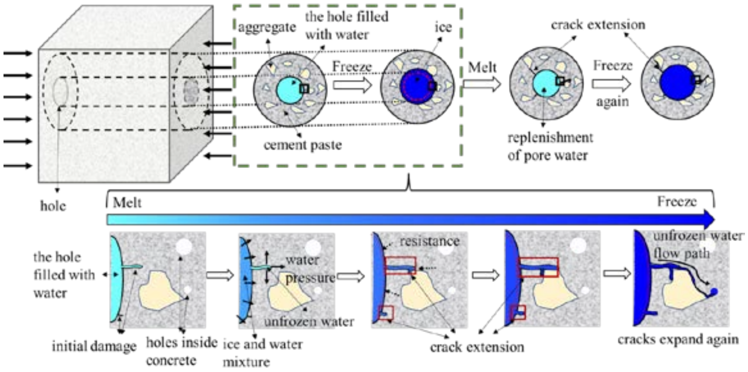


Figure 7. The cracking mechanism of perforated concrete.

According to Figure 7, considering that some initial defects appear in concrete due to improper pouring, these defects are manifested in some small holes and microcracks inside it; thus, there are small holes and microcracks around the large hole. Since the deformation modulus of the concrete skeleton is much higher than that of ice and water (about 10 times), the compression of the ice-water system cannot be ignored in the actual freezing process of the hole. Due to the presence of large amounts of water in the prefabricated holes, the unfrozen water is mainly in the unfrozen area during the freezing process, so there is sufficient unfrozen water to migrate. During many freeze-thaw cycles (Hasan et al. 2004), an additional water supply is essential for damage accumulation; otherwise, the damage may terminate immediately after several cycles (Sicat et al. 2013, Sicat et al. 2014).

It should be noted that hydrostatic pressure is generated during the migration of unfrozen water, and under the action of continuous low temperatures, the seepage of unfrozen water freezes in the micropores to produce expansion force, expanding the crack again. When water freezes in connected pores, the state change processes of the water, ice, and concrete skeleton system are quite different from those in closed pores, which are mainly reflected in the seepage of unfrozen water under pressure. Generally, the seepage of water offsets most of the phase-change expansion. In addition, during the icing process, water pressure is generated, including hydrostatic pressure and icing expansion force. When the water in the prefabricated hole freezes and reaches a particular degree (less than the stick-slip force generated by the ice jam), the unfrozen water flows through the microholes and microcracks in the hole wall under the action of water pressure, offsetting most of the phase-change expansion. When the ice melts, the pore is filled with water again due to the sufficient water outside.

Furthermore, previous scholars have pointed out that microcracks penetrate the concrete in this process, but it takes a long time. In contrast, the specimens in this test all crack after about seven freeze-thaw cycles, indicating that the damaging effect is profound under water pressure. Additionally, the interfacial transition zone is weak in concrete, and its mechanical properties, diffusion, and impermeability are weaker than those of the matrix (Guan et al. 2021). Cracks are more likely to form in the cross-sectional transition zone, which is consistent with the previous crack distribution mainly located between the aggregate and the matrix.

4.2 Effectiveness Analysis of Preventive Measures

A polyurethane foaming agent can be a preventive measure for concrete with holes and has a beneficial effect. Figure 8 depicts the principle of using a polyurethane foaming agent to fill concrete holes.

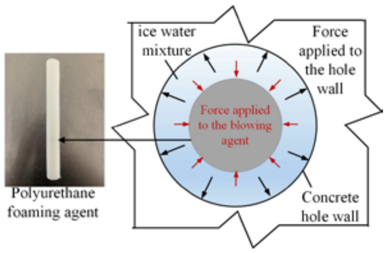


Figure 8. The polyurethane foaming agent and its prevention principle.

On the one hand, this measure reduces the water in the hole, thereby reducing the pressure generated by the unfrozen water. On the other hand, the foaming agent has a soft texture and good elasticity, which can offset part of the expansion force generated by the freezing of the water so as to prevent the rapid cracking of the concrete with holes in the freeze-thaw environment. This work concludes that inserting polyurethane rods in the holes can play a protective role. Indeed, the specimens with a foaming agent are eventually frozen and cracked at the late stages of the freeze-thaw test (150 freeze-thaw cycles) since the damage to the polyurethane foaming agent leads to the deterioration of its controlling effect, and the tensile strength of concrete decreases with freeze-thaw cycles.

The foaming agent at the two ends of the hole is significantly reduced or even broken after 75 freeze-thaw cycles. Figure 8d and 8e demonstrates the damage to the foaming agent, where a “necking” fracture can be seen. In the natural state, the foaming agent can isolate most water. However, due to many pores inside the foaming agent, some unfrozen water is squeezed into the foaming agent during the external freezing process, freezing the internal water with a temperature reduction. After repeated freeze-thaw cycles, there are also durability problems. Hence, further requirements can be proposed for the filling material of the hole, that is, a flexible hydrophobic material without many pores, such as rubbers and silicone rubber. On the one hand, the deformation of this type of flexible hydrophobic material can offset part of the frost heave force caused by water freezing expansion. On the other hand, the internal pores of these materials are tiny, so their durability is excellent in the process of repeated freeze-thaw cycles.

5 Conclusions

- The concrete hole wall was subjected to a force far exceeding the tensile strength of concrete during the freezing process of water in the hole. However, the concrete was destroyed after a specific number of freeze-thaw cycles. The main reason for this behavior is that concrete is an elastic-plastic material, and the expansion of cracks and the seepage of water release some of the force, so the cracking of concrete eventually delays. This phenomenon indicates that more attention should be paid to perforated concrete in cold-region engineering since sudden damage may occur to the concrete after damage accumulation.
- By inserting a prefabricated polyurethane foaming agent, the surface layer of the concrete separated in the early stages, but no frost heave cracking occurred. However, the concrete still cracked in the end due to the durability problem of the material after multiple freeze-thaw cycles. Thus, flexible hydrophobic materials are required: low water absorption is required to reduce the freeze-thaw damage to the filling material, and the material needs sufficient deformability to eliminate some frost heave force.

References

Cai, H. (1998). *Prediction model of concrete freeze-thaw durability*. Beijing: Tsinghua University, 20-21(in Chinese).

Chen, X., Li, J., Huang, S., Cui, H., Liu, P. and Sun, Q. (2021). *An automatic concrete crack-detection method fusing point clouds and images based on improved otsu's algorithm*. Sensors, 21(5), 1581.

Davidson, G. P. and Nye, J. F. (1985). *A photoelastic study of ice pressure in rock cracks*. Cold regions science and technology, 11(2), 141-153.

Guan, X.M. and Yang,L. (2021). *Concrete Materials Science.* Beijing: Chemical Industry Publishing, 7-18(in Chinese).

Hanjari, K. Z., Utgenannt, P. and Lundgren, K. (2011). *Experimental study of the material and bond properties of frost-damaged concrete.* Cement and Concrete Research, 41(3), 244-254.

Hasan, M., Okuyama, H., Sato, Y. and Ueda, T. (2004). *Stress-strain model of concrete damaged by freezing and thawing cycles*. Journal of Advanced Concrete Technology, 2(1), 89-99.

Ma, Z., Zhao, T. and Yang, J. (2017). *Fracture behavior of concrete exposed to the freeze-thaw environment.* Journal of Materials in Civil Engineering, 29(8), 04017071.

Ortiz, J., Aguado, A., Agulló, L. and Garcia, T. (2005). *Influence of environmental temperatures on the concrete compressive strength: Simulation of hot and cold weather conditions*. Cement and concrete research, 35(10), 1970-1979.

Powers, T. C. (1945). *A working hypothesis for further studies of frost resistance of concrete*. In Journal Proceedings, 41(1): 245-272.

Powers, T. C. and Helmuth, R. A. (1953). Theory of volume changes in hardened portland-cement paste during freezing. In Highway research board proceedings, 32.

Sicat, E., Gong, F., Ueda, T. and Zhang, D. (2014). *Experimental investigation of the deformational behavior of the interfacial transition zone (ITZ) in concrete during freezing and thawing cycles*. Construction and Building Materials, 65, 122-131.

Sicat, E., Gong, F., Zhang, D. and Ueda, T. (2013). *Change of the coefficient of thermal expansion of mortar due to damage by freeze thaw cycles*. Journal of Advanced Concrete Technology, 11(12), 333-346.

Sun, B.L., Yang, Y.Q., Yan, M. (2021). *Cause analysis, verification and treatment of longitudinal cracks in post-tensioned box girders in cold and high-altitude environments*. Bridge Construction, 51(03):39-46(in Chinese).

Trawiński, W., Tejchman, J. and Bobiński, J. (2018). *A three-dimensional meso-scale modelling of concrete fracture, based on cohesive elements and X-ray μCT images*. Engineering fracture mechanics, 189, 27-50.

Xie, C., Cao, M., Yin, H., Guan, J. and Wang, L. (2021). *Effects of freeze-thaw damage on fracture properties and microstructure of hybrid fibers reinforced cementitious composites containing calcium carbonate whisker*.

Construction and Building Materials, 300, 123872.
Yu, H., Ma, H. and Yan, K. (2017). *An equation for determining freeze-thaw fatigue damage in concrete and a model for predicting the service life*. Construction and building materials, 137, 104-116.
Zhou, C., Li, K. and Pang, X. (2012). *Geometry of crack network and its impact on transport properties of concrete*. Cement and concrete research, 42(9), 1261-1272.
Zi, G., Lee, S. J., Jang, S. Y., Yang, S. C. and Kim, S. S. (2012). *Investigation of a concrete railway sleeper failed by ice expansion*. Engineering Failure Analysis, 26, 151-163.