

INVESTIGATION OF THE FREEZE-THAW RESISTANCE OF ECO-POROUS CONCRETE CONTAINING FLY ASH

PREISKAVE ODPORNOSTI NA ZAMRZOVANJE IN ODTALJEVANJE EKOPOROZNIH BETONOV, KI VSEBUJEJO PEPEL

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Laboratory tests were conducted to evaluate the freeze-thaw resistance of eco-porous concrete containing fly ash. In order to address the freeze-thaw resistance of eco-porous concrete, the mass loss, compressive strength and relative dynamic modulus of elasticity (RDME) were obtained. Furthermore, based on the RDME, the freeze-thaw damage index (FTI) was provided to evaluate the internal damage. The results showed that the higher the amount of fly ash, the poorer is the frost resistance of porous concrete. The mass, compressive strength and RDME of specimens decreased with the increasing freeze-thaw cycles. The compressive strength decreased with an increase in fly ash, but the initial compressive strength is sufficient for requirements. Therefore, the content of fly ash should be controlled when producing eco-porous concrete and predicting its performance under freeze-thaw attacks with the explored method.

Keywords: eco-porous concrete, fly ash, freeze-thaw resistance, mass loss, relative dynamic modulus of elasticity (RDME), freeze-thaw damage index (FTI)

Avtorji prispevka so z laboratorijskimi preizkusi ugotavljali odpornost na zamrzovanje in odtaljevanje (FTR, angl.: Freeze-Thaw Resistance), s pepelom polnjenih ekoporoznih betonov. Da bi dobili podatke o odpornosti betona so določevali izgubo mase, tlačno trdnost in relativni dinamični modul elastičnosti (RDME). Na podlagi RDME so določili indeks poškodb med preizkusom zamrzovanja in odtaljevanja (FTI, angl.: Freeze-Thaw Damage index), ki je merilo notranjih poškodb betona po izvedenem preizkusu. Rezultati so pokazali, da večja kot je polnitev poroznega betona z elektrofiltrskim pepelom, slabša je njegova odpornost na zamrzovanje. Masa, tlačna trdnost in RDME preizkušancev so se zmanjševali z naraščajočim številom ciklov zamrzovanja in odtaljevanja. Tlačna trdnost poroznega betona se je precej zmanjšala s povečevanjem deleža elektrofiltrskega pepela, kljub temu, da so bile vrednosti začetne tlačne trdnosti betona znotraj predpisov. Zato je potrebno delež elektrofiltrskega pepela nadzorovati, ko se oblikuje nove, s pepelom polnjene, ekološke porozne betone in jih testirati oz. ovrednotiti z, v tem članku opisano, metodo zamrzovanja in odtaljevanja.

Ključne besede: ekoporozni beton, elektrofiltrski pepel, odpornost na zamrzovanje in odtaljevanje, izguba mase, relativni dinamični modul elastičnosti (RDME), indeks poškodb betona nastalih med preizkusom zamrzovanja in odtaljevanja (FTI)

1 INTRODUCTION

The concept of green concrete was first proposed by the Concrete Engineering Institute of Japan in 1990s.¹ Until now, green concrete has been used in parking lots, roadside slopes, shoulder partitions and other projects in Japan, the United States and other countries. Eco-porous concrete is a kind of green concrete, mainly formed with coarse aggregate, water, cement and admixtures. After filling in the pores with soil, nutrients and water-retaining materials, eco-porous concrete can meet the growing needs of plants. Compared with ordinary concrete, eco-porous concrete has the function of planting, water purification, noise reduction and reducing the heat-island effect.²⁻³

Due to the typical skeleton structure of porous concrete, environmental factors have an important influence on the service life of porous concrete, especially the freeze-thaw attacks. It is well known that the effect of materials (such as aggregates, cement, admixtures, etc.) on the freeze-thaw resistance should be explored, and the

degradation characteristics of concrete should be studied.⁴⁻⁸ Compared with permeable concrete, eco-porous concrete has a higher porosity and a larger pore size. There were few researches on the freeze-thaw resistance of eco-porous concrete.⁹⁻¹¹ Considering the cost and ecological benefit, the industrial, waste, residue fly ash is usually added to concrete.¹²⁻¹³ Based on the above, fly ash was added to eco-porous concrete in the study. Accordingly, the freeze-thaw resistance and evaluation of porous concrete were researched. The results have an important guiding significance for the evaluation of frost resistance and preparation of eco-porous concrete.

2 EXPERIMENTAL PART

2.1 Materials

The P.O. 42.5 cement was selected. The performance indexes of the cement is shown in **Table 1**. There is only coarse aggregate, no fine aggregate. The II grade fly ash was used.

Table 1: Performance indexes of cement

SSA m ² /kg	SO ₃ %	Stabi- lity qualifi- ed	IS min	FS min	3d FS MPa	3dCS MPa	28dFS MPa	28dCS MPa
354	2.4		155	200	5.6	25.3	8.9	53.0

Note: SSA = Specific surface area; IS = Initial setting; 3dFS = 3d flexural strength; 3dCS = 3d compressive strength; others similarly

2.2 Mixture design

The mix-design theory is similar to the filling theory of RCC.¹⁴ The design principles are: close packing of the coarse aggregate, the cementitious paste evenly distributed on the aggregate surface, a porosity of 20–30 % and the compressive strength after 28 d of 5–15 MPa as the control criteria. According to the findings of Y. P. Sheng and others,^{15–17} the primary mix proportion can be achieved.

Moreover, Y. Jing provided empirical data for the preparation of the vegetation-type eco-porous concrete.¹⁸ Based on the formula and empirical data, the test mix proportions are presented in **Table 2**. The "n value" represents 0, 1, 2, 3, 4, 5, respectively.

Table 2: Mix proportion of eco-porous concrete

Number	FLC/%	Grain size/mm	Cement/ kg/m ³	Water/ kg/m ³	Water-bin der ratio
Fn	10n	19–26.5	300	90	0.30

Note: FLC = Fly ash content

2.3 Specimen preparation

Fly ash was used to replace cement in the amounts of (0, 10, 20, 30, 40 and 50) %. Using the paste-coating-gravel method, cement, fly ash and 70 % of water were mixed in a mechanical mixer for 1 min, then the coarse aggregate was added, being mixed into the mixture for 1 min, and the remaining 30 % of the water was added by mixing the mixture for another minute. The specimen size for the compression test was (100 × 100 × 100) mm, and it was (100 × 100 × 400) mm for the transverse-fundamental-frequency test. After the mixing, a vibrating rod was used to ensure a good compaction and the specimens were demolded 24 h after being cast. Then, the specimens were cured in a standard curing room for 23 d, and soaked in water (20±2 °C) for another 4 d. Meanwhile, the water level was higher than the top surface of the specimens by 20–30 mm.

3 EXPERIMENTAL METHOD

In this study, the vacuum-sealing method, as specified in ASTM D7063, was adopted to determine the effective porosity of porous concrete.¹⁹ It is reported that this method can be effectively used for porous concrete due to its open-pore structure.^{20–21} Strength tests were

conducted on porous-concrete specimens by following the testing procedures specified in GB/T 50081-2002.²² Triplicate cubic specimens with a side length of 100 mm were used for the testing. Compressive-strength tests were performed on the specimens after 28 curing d.

Cyclic freeze-thaw tests were conducted to determine the freeze-thaw resistance of the porous-concrete mixtures, mainly referring to the Chinese specification GB/T50082-2009, in which specimens were subjected to repeated freeze-thaw cycles.²³ After 28 d of curing, we took the specimens out, wiping the surfaces with a cloth until there was no water on them. We numbered the specimens with the sides of (100 × 100 × 400) mm, weighed the initial mass M_0 , measured the lateral fundamental frequency f_0 and observed their appearance. We put the specimens with the dimensions of (100 × 100 × 400) mm and (100 × 100 × 100) mm into the box with wetting conditions; after 5 cycles of freezing and thawing, we measured the above criteria, until the RDME decreased to 60 % or the mass-loss rate reached 5 %.

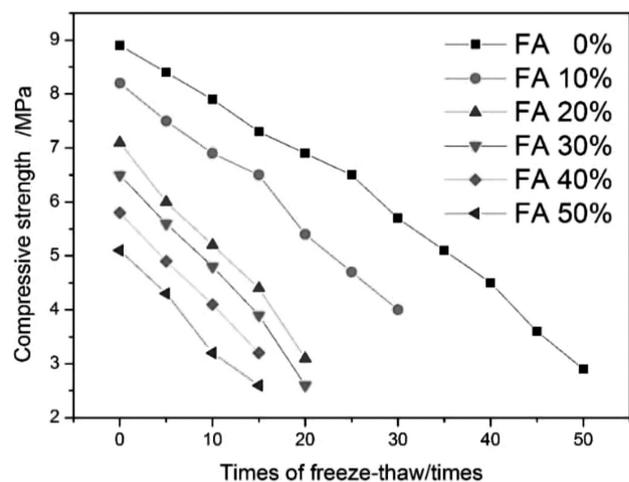
4 RESULTS AND DISCUSSION

4.1 Uniaxial compressive strength

The test results of the compressive strength obtained when the relative dynamic modulus of elasticity (RDME) of the eco-porous concrete was reduced to 60 % are shown in **Figure 1**.

It can be clearly observed from **Figure 1** that with an increase in the freeze-thaw cycle, the compressive strength decreased rapidly. The strength of the specimens without fly ash is larger than that of the specimens with fly ash. And with the increasing amount of fly ash, the compressive strength of the specimens significantly decreased.

The specimens damaged during the freeze-thaw attacks and compression tests can be seen in **Figures 2** and **4**. The bonding sites of the aggregate were broken

**Figure 1:** Relation between uniaxial compressive strengths and freeze-thaw times

and cracks developed along the bond interface. This indicated that the contact areas were still weak. Therefore, the cementitious paste had to be modified to improve the strength of porous concrete. It is well known that cementitious paste gradually degrades under the expansion stress of ice, and the bond strength of cementitious paste also decreases. In addition, the high porosity of specimens provided the condition for water freezing, leading to an aggravated degeneration. On the other hand, the fly ash decreased the strength of the cementitious paste between aggregate particles. The content of fly ash also had to be controlled. Finally, with the increasing freeze-thaw cycles, the RDME of the specimens decreased to 60 %.

4.2 Mass loss

The mass-loss rate and the appearance of the specimens after the reduction of the RDME of eco-porous concrete to 60 % are shown in **Table 3** and **Figure 4**, respectively.

The mass-loss rate for the eco-porous concrete without fly ash was lower than for the other types of eco-porous concrete from **Table 3**. With the increasing amount of fly ash, the mass-loss rate increased, but it was still less than 5 %.

Table 3: Mass-loss rate of eco-porous concrete

Fly-ash content (%)	0	10	20	30	40	50
Mass-loss rate (%)	0.06	0.09	0.11	0.12	0.16	0.19

There were no cracks on the surfaces of the specimens, and only slight damage appeared, mainly on the surface, as shown in **Figure 4**. With the increasing cycles, individually spalled aggregate particles could be observed from **Figure 2**.

A lower water-binder ratio and the paste-coating-gravel method improved the strength of the cementitious paste and the interface between the aggregate particles. Then, the interfacial transition zone of eco-porous concrete was strengthened. Accordingly, the freeze-thaw resistance of eco-porous concrete significantly increased.

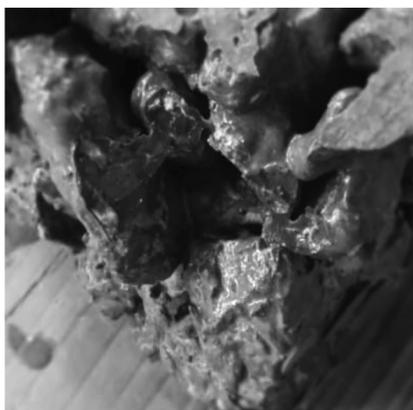


Figure 2: Freeze-thaw failure of a specimen



Figure 3: Compressive failure of a specimen

However, after the cement was replaced by fly ash, the activity, hydration degree and fluidity of the cementitious paste were reduced. Finally, the roughness and holes of the cementitious-paste surface increased. With the freeze-thaw attacks going on, the expansion stress from the holes caused the cementitious paste to peel off and fall off. Besides, with the increase in the fly ash, a small amount of particles appeared, but the mass-loss rate was still low.

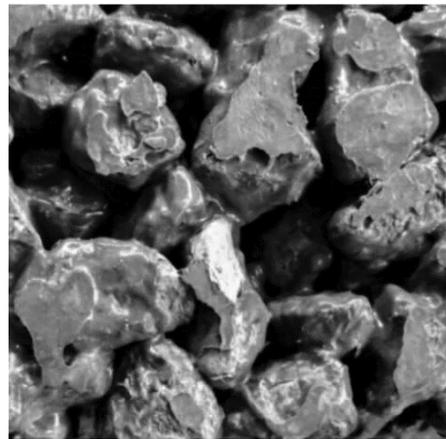
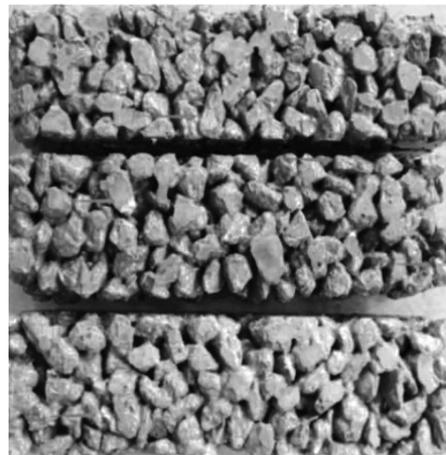


Figure 4: Appearance of the specimens

4.3 Relative dynamic modulus of elasticity (RDME)

4.3.1 Analysis of relative dynamic modulus of elasticity (RDME)

RDME curves for different fly-ash contents in eco-porous concrete are presented in **Figure 5**.

It can be clearly observed from **Figure 5** that with an increase in the number of freeze-thaw cycles, the RDME decreased rapidly. The RDME of the specimens without fly ash is larger than that of the specimens with fly ash. And with the increasing amount of fly ash, the RDME of the specimens significantly decreased.

When the RDME was reduced to 60 %, the eco-porous-concrete specimens did not produce cracks that could be seen from **Figure 4**. As we can see, the variation trend of the RDME is similar to the compressive strength. Accordingly, the RDME values also depend on the durability of cementitious paste, the content of fly ash and freeze-thaw cycles. Nevertheless, the RDME value has an important role when evaluating the internal damage.

4.3.2 Freeze-thaw damage index (FTI)

The change in the relative dynamic modulus of elasticity (RDME) is the macroscopic form of micro-damage (or internal damage). By establishing the relation between the RDME and freeze-thaw damage index, the damage degree of concrete during freeze-thaw attacks can be described. According to this, the formula is as follows:

$$D_F = (E_{RI} - E_{RF})/0.4 E_{RI} = 2.5(1 - E_{RF}) \quad (1)$$

where D_F is the freeze-thaw damage index, $0 \leq D_F \leq 1$; E_{RI} is the initial RDME, its value is 1.0; E_{RF} is the instantaneous RDME. Under the non-destruction condition, $E_{RI} = E_{RF} = 1$, $D_F = 0$; under the theoretical limit state of freeze-thaw damage, $E_{RF} = 0.6 E_{RI}$ and $D_F = 1$. When the RDME is included in formula (1), we find that the damage degree of specimens can be calculated using the freeze-thaw damage index. Furthermore, the

closer D_F is to 1, the greater the damage; the closer D_F is to 0, the smaller the damage.

The larger the amount of fly ash, the lower the relative dynamic modulus of elasticity (RDME) of the porous concrete, as can be seen from **Figure 5**. In addition, when the fly-ash amounts were 40 % and 50 %, the specimens were subjected to the freeze-thaw cycle five times. Therefore, the relation between the number of the freeze-thaw cycle and the freeze-thaw damage index was only studied when the fly ash amounts were (0, 10, 20 and 30) %. The fitting curve Equations (6), (7) and (8) are as follows:

$$0 \%: y = -6 \times 10^{-7} x^3 - 8 \times 10^{-5} x^2 - 0.001x + 0.9969 \quad R^2 = 0.9983 \quad (2)$$

$$10 \%: y = -0.0004x^2 - 0.0092x + 1.0183 \quad R^2 = 0.9821 \quad (3)$$

$$20 \%: y = -0.0003x^2 - 0.0205x + 1.019 \quad R^2 = 0.9789 \quad (4)$$

$$30 \%: y = -0.001x^2 - 0.0257x + 1.0138 \quad R^2 = 0.9824 \quad (5)$$

where y is the RDME and x is the number of freeze-thaw cycles. However, when the fly-ash content amounted to 30 %, the deviation between the calculated results and the experimental results was large. Therefore, the relation between the number of freeze-thaw cycles and the freeze-thaw index was not discussed when the fly-ash content exceeded 30 %. Next, we replaced the E_{RF} from Equation (1) with y from Equations (2), (3) and (4), respectively. Then, new Equations (6), (7) and (8) were obtained for the fly-ash contents of (0, 10 and 20) %, as follows:

$$0 \%: D_F = 1.5 \times 10^{-6} x^3 + 2 \times 10^{-4} x^2 + 2.5 \times 10^{-3} x + 7.75 \times 10^{-3} \quad (6)$$

$$10 \%: D_F = 10^{-3} x^2 + 0.023x - 0.04575 \quad (7)$$

$$20 \%: D_F = 7.5 \times 10^{-4} x^2 + 0.05125x - 0.0475 \quad (8)$$

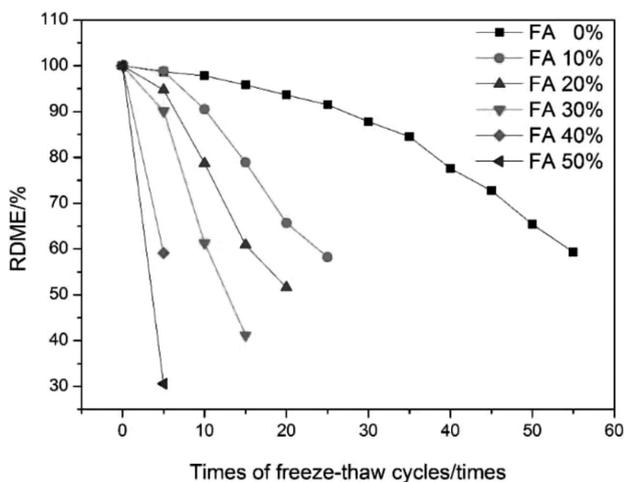


Figure 5: Relation between RDME and freeze-thaw cycles

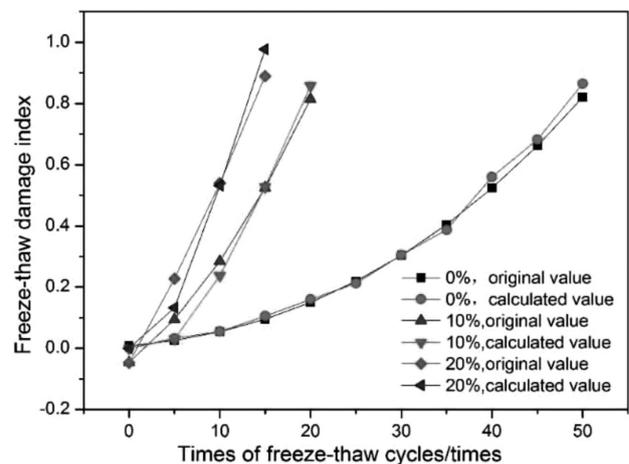


Figure 6: Relation between the calculated value and original value of freeze-thaw damage index

The freeze-thaw damage index D_F increases with the increase in the number of freeze-thaw cycles from Equations (6), (7) and (8). Furthermore, the freeze-thaw damage degree for the specimens can be calculated by assuming the number of freeze-thaw cycles. The relation between the original value and calculated value of the freeze-thaw damage index of eco-porous concrete is shown in **Figure 6**.

It can be clearly seen that the deviation of the calculated value from the original value is small. That is to say, the freeze-thaw damage index can be used to describe the damage degree of eco-porous concrete during the freeze-thaw attacks. Moreover, the relation between the number of freeze-thaw cycles and freeze-thaw index can, not only be used to estimate the damage degree, but also to predict the number of freeze-thaw cycles that eco-porous concrete can withstand.

5 CONCLUSIONS

The fly-ash content has an important influence on the frost resistance of eco-porous concrete. In order to make eco-porous concrete with sufficient ecological benefits and a certain frost resistance, the fly-ash content should not exceed the total amount of cementitious paste, which is 30 %.

On the basis of the relative dynamic modulus of elasticity (RDME), the freeze-thaw damage index D_F is defined, and the freeze-thaw damage degree of eco-porous concrete can be estimated by calculating the value of D_F . The relation between the freeze-thaw damage index D_F and the number of freeze-thaw cycles is obtained when fly-ash amounts account for 0, 10 and 20 %. The freeze-thaw damage index D_F can also be calculated by assuming the number of freeze-thaw cycles, through which we can obtain the freeze-thaw damage degree or evaluate the freeze-thaw resistance of eco-porous concrete.

When the relative dynamic modulus of elasticity (RDME) of eco-porous concrete decreased to 60 %, the number of freeze-thaw cycles was lower than that of compressive specimens. The relative dynamic modulus of elasticity (RDME) was selected to evaluate the frost resistance of eco-porous concrete. Therefore, the mass loss, appearance, and freeze-thaw damage can be used as the evaluation indexes for the frost resistance of eco-porous concrete.

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