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FREEZE-THAW DURABILITY OF CONCRETE: ICE FORMATION PROCESS IN PORES

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ABSTRACT

Freeze-thaw durability of concrete is of great importance to hydraulic structures in cold areas. Study of ice formation process in concrete pores is necessary to evaluate the damages in concrete caused by freezing. In this paper, freezing of pore solution in concrete exposed to a freeze-thaw cycle is studied by following the change of concrete electrical conductivity with freezing temperatures. Concretes were subjected to freeze-thaw cycles with temperature varying between −0°C and −20°C . In the freezing process, the changing rate of concrete electrical conductivity obviously decreases at about −10°C, indicating that more pore solution in concrete freezes above −10°C than below −10°C. According to Powers' static hydraulic pressure hypothesis, it is thought that frost damage mainly occurs between 0°C and −100°C. To ordinary concrete, frost damages below −10°C are negligible. © *1998 Elsevier Science Ltd*

Introduction

With the deterioration of existing structures, durability of concrete is of great concern (1). For hydraulic structures in cold areas, freeze-thaw durability of concrete is especially important.

Freeze-thaw durability of concrete has close relationship with its pore structure. The volume, radius, and size distribution of pores decide the freezing point of pore solution and the amount of ice formed in pores. Generally, within a certain temperature interval, more frozen concrete pore solution induces greater internal hydraulic pressure and, consequently, more severe frost damages. Thus the freezing point and the amount of frozen solution in pores reflect the frost durability of concrete. By knowing the ice content in the freezing process, it is possible to calculate the internal hydraulic pressure caused by ice formation; hence, frost deterioration of concrete can be evaluated and predicted. The results will help enable structure design and maintenance by taking into consideration the freeze-thaw durability of concrete. Therefore, in deciding the damages in concrete caused by freezing, study of ice formation process in concrete pores is critical.

The low temperature calorimeter is a useful tool in this field of study because the freezing point and the amount of frozen solution in pores can be directly measured and calculated by this method (2–5). But problems are also brought about by too small an amount of testing sample, such as:

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TABLE 1
Mix proportions of concrete.

Mix	w/c	Water content (kg/m^3)	Cement content (kg/m^3)	Sand content (kg/m^3)	Coarse aggregate content (kg/m^3)		Fly ash content (kg/m^3)	AEA* (%)	FDN† (%)	28-Day strength (MPa)
					Pebble	Gravel				
W6	0.6	200	333	636	369	861				31.19
W6A	0.6	200	333	579	337	786		0.02%		27.95
W4	0.45	200	444	555	360	840				37.45
W4A	0.45	200	444	515	328	765		0.02%		36.81
W3	0.3	150	400	716	322	752	100		1%	69.83
W3A	0.3	150	400	663	298	697	100	0.02%	1%	65.55

* AEA, anionic type of air entraining agent.
† FDN, naphthalene based superplasticizer.

1) Can experiments done on such small quantities of sample stand for the situation in practice? Are they comparable? 2) Small quantities of sample limit the application field of the technique. The method is often used to study paste, sometimes mortar, but seldom concrete. Jacobsen et al. have applied the method to concrete (4). Their specimens were concrete cylinders with diameter 14~15 mm and height 70 mm. Concrete is heterogeneous on a small scale. A concrete cylinder of that size casts doubt on the reliability and representation of the test results.

Because of the deficiencies of the low temperature calorimeter, ice formation process in concrete pores will be investigated in this paper by following the change of electrical conductivity of concrete during a freeze-thaw cycle. Concrete is conductive due to ions contained in concrete pore solution, such as Ca^{2+}, OH^-, Na^+, K^+ etc. Since ice can be regarded as nonconductor, when some amount of concrete pore solution freezes under negative temperatures, concrete electrical conductivity decreases because of the decreasing amount of conductive pore solution. Therefore, by studying the decreasing rate of concrete electrical conductivity, the amount of frozen pore solution at different temperatures within a freeze-thaw cycle, namely, ice formation process, can be evaluated. The major advantage of this experiment method is that it can be easily applied to concrete.

Procedure

The mix proportions of concrete prepared for test are listed in Table 1.

After 3 months' curing, the specimens were cut by the size of 100 × 100 × 30 mm. The 100 × 100 mm surfaces should be even and smooth so that they could contact electrodes well. To further eliminate the negative influence of interface, a piece of wet sponge was put between the surfaces of specimens and electrodes. The arrangement of a specimen and electrodes is plotted in Figure 1,

Specimens were stored in water until they reached constant weights. The saturated specimens were put in a refrigerator after their surfaces were dry. Temperature was gradually lowered and raised in the refrigerator between 0°C and −20°C to simulate a freeze-thaw cycle. The electrical conductivity of the specimens was measured after every 5°C interval during freezing and thawing processes.

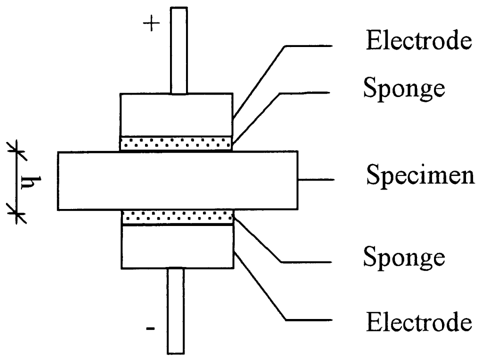

FIG. 1.
Test arrangement.

Results and Discussion

Figure 2 shows the relationship between temperature and the relative electrical conductivity of different mixtures. The relative electrical conductivity is defined as the ratio of the electrical conductivity under a certain temperature to the one at 0°C of the same specimen. Test results in Figure 2 indicate some similar behaviors of different mixtures.

Freezing processes do not coincide with thawing processes. To a certain mixture within a freeze-thaw cycle, the electrical conductivity in freezing process is always higher than that in thawing process under the same temperature. It indicates hysteresis of ice formation in freezing process. More ice exists in concrete in the thawing process. If the ice content in thawing process were taken to evaluate the damage caused by freezing in concrete, the damage would be overestimated. So ice formation in freezing process is of critical importance to study the freezing effect on concrete.

The electrical conductivity of concrete remains almost constant in thawing processes in spite of different mixtures. Two conclusions can be drawn from this result: 1) Ice content in concrete doesn't change when temperature rises. That is, once the pore solution freezes, it thaws little before the temperature rises approximately to 0°C. This conclusion agrees with the results of Bager and Sellevold's tests on cement paste (2). 2) The test result of constant electrical conductivity implies that the increment of electrical conductivity of pore solution due to temperature change can be neglected, at least within the temperature range the test covered, although generally, the electrical conductivity of solution increases with the rise of temperature. It can be assumed that the electrical conductivity of concrete pore solution does not change with temperature and keeps constant during test procedure. This assumption is important to the discussion below.

Because concrete is conductive due to its pore solution, it can be assumed that the resistance of concrete specimen R_c is equal to that of its unfrozen pore solution R_s. Because $R_c = \frac{h_c}{\sigma_c S_c}$ and $R_s = \frac{h_s}{\sigma_s S_s}$, the following formulation is obtained:

$$\frac{h_c}{\sigma_c S_c} = \frac{h_s}{\sigma_s S_s}$$

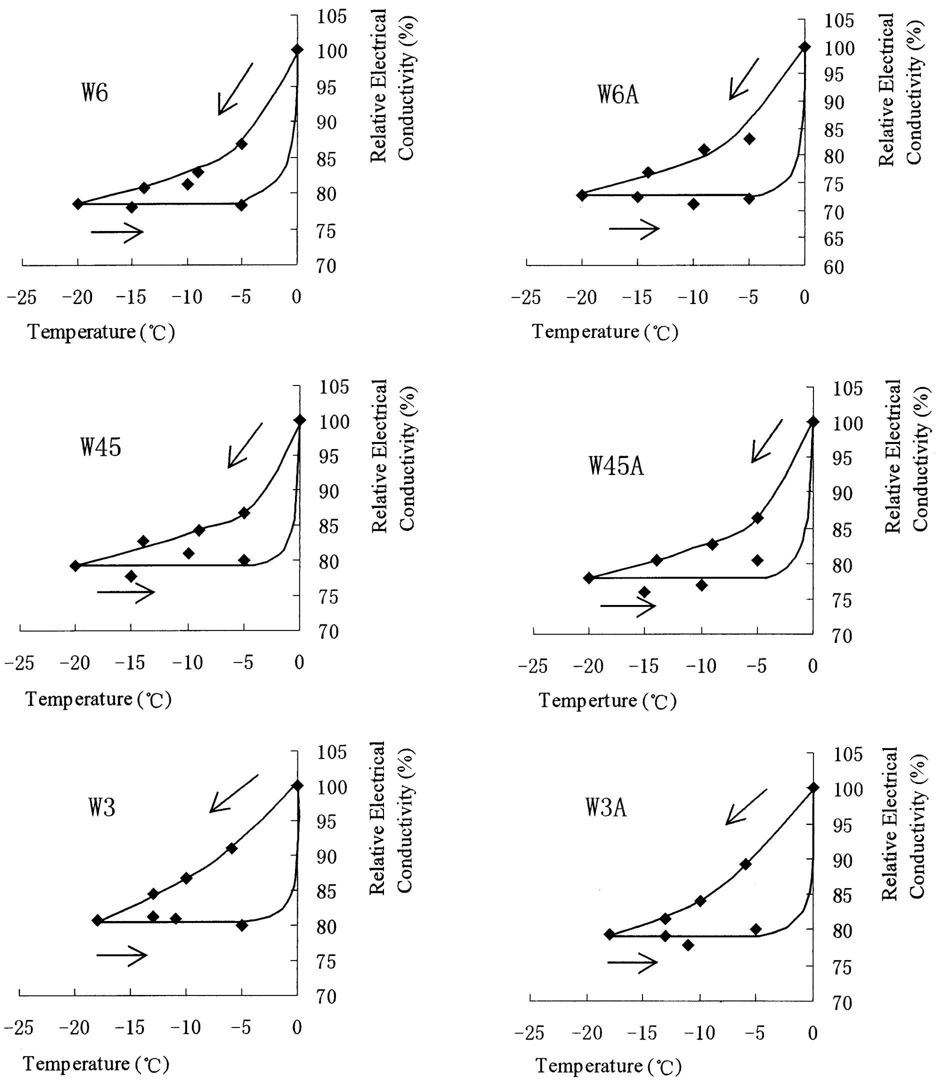

FIG. 2.
Relative electrical conductivity of different concrete mixtures vs. temperature.

where h_c is the length of concrete through which electrical current has passed; h_s is the effective length of pore solution through which electrical current has passed; S_c is the area of concrete through which electrical current has passed; S_s is the effective area of pore solution through which electrical current has passed; σ_c is the electrical conductivity of a concrete specimen; and σ_s is the electrical conductivity of pore solution.

Electrical current always takes the short path, even though it is conducted through pores that are often not perfectly aligned. So if it is hypothesized that h_c and h_s are all equal to h, then:

$$\sigma_c S_c = \sigma_s S_s$$

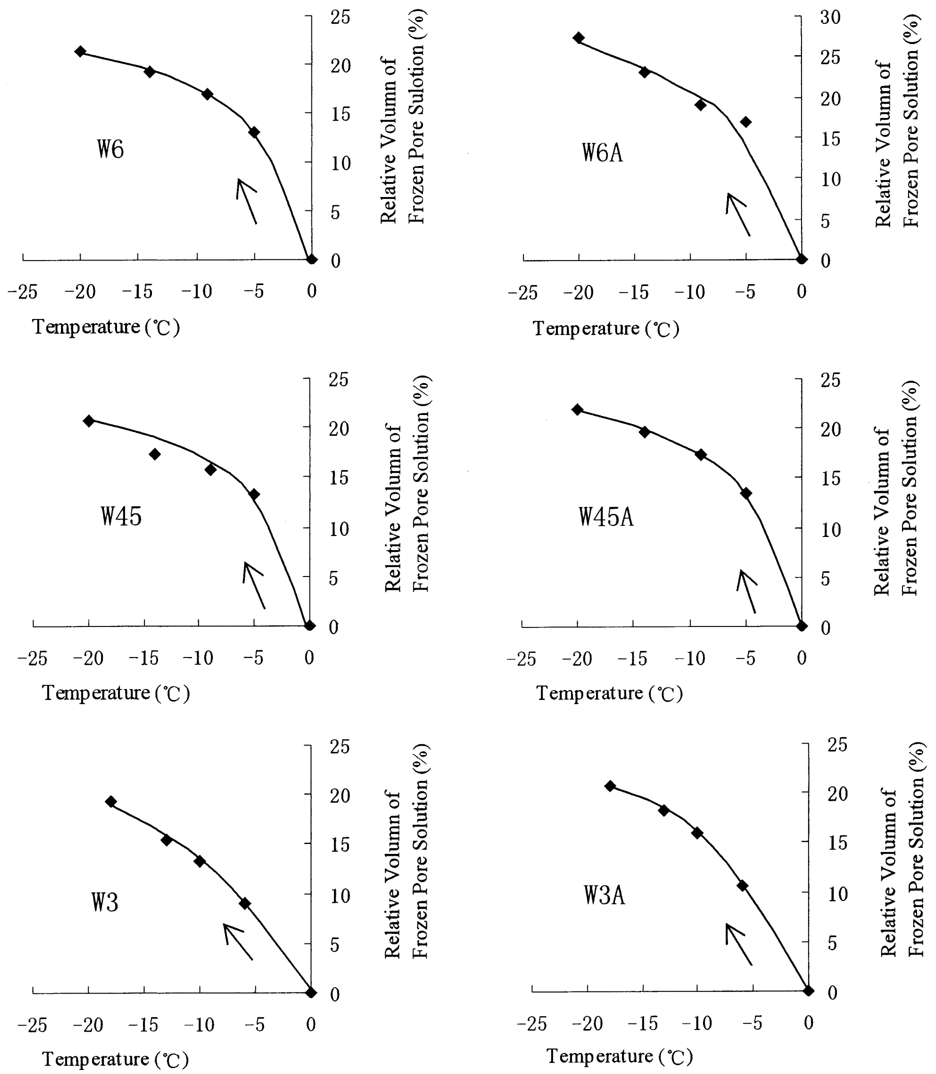

FIG. 3.
Relative volume of frozen pore solution of different concrete mixtures vs. temperature.

Multiplying the above equation by *h*, it is obtained that:

$$\sigma_c V_c = \sigma_s V_s$$

$$\sigma_c = \frac{\sigma_s}{V_c} V_s$$

where V_c is the volume of concrete conducting electricity, and V_s is the volume of unfrozen pore solution.

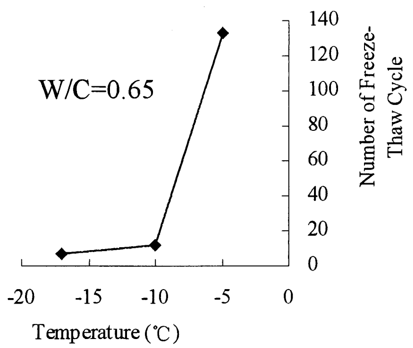

FIG. 4.
Freeze-thaw durability of concrete vs. the lowest temperature in freeze-thaw cycles.

Because V_c and σ_s are considered constant during test procedure, the percent change of the volume of unfrozen pore solution V_s is equal to the percent change of the electrical conductivity of the specimen σ_c. Hence, Figure 2 also illustrates the volume change of unfrozen pore solution at different temperatures. Because pore solution is composed of frozen and unfrozen parts, the volume change of frozen pore solution with temperature is known correspondingly.

Substituting the vertical coordinate in Figure 2 with the relative volume of frozen pore solution causes the ice formation process in concrete to be illustrated more obviously (Fig. 3). The tangential slope of every point on the curves in Figure 3 is the freezing rate under the relevant temperature.

As shown in Fig. 3, there is no obvious difference of freezing point and amount of ice formed between specimens, with or without air entraining agent. It can be concluded that the beneficial effect of air entraining does not lie in changing the behavior of pore solution, but mainly in improving the mechanical properties of concrete.

A common behavior of different mixtures is that there is a turning point of freezing rate at about −10°C. Pore solution freezes more quickly above −10°C than below −10°C. According to Powers' static hydraulic hypothesis (6), higher freezing rate leads to greater internal hydraulic pressure. Internal hydraulic pressure is a direct factor causing frost deterioration of concrete. So concrete suffers more destructive effects from freezing between 0°C and −10°C whether it is ordinary or high-strength concrete.

In the case of ordinary concrete, freezing rate decreases sharply below −10°C and the destructive effect is accordingly negligible. Studies by the Chinese Institute of Water Resources and Hydropower Research strengthen the conclusion (7). Their studies are concentrated on the effect of the lowest temperature in freeze-thaw cycles on the frost durability of ordinary concrete (Fig. 4). When the lowest temperature is −5°C, concrete of 0.65 w/c ratio can sustain 133 freeze-thaw cycles. When the temperature drops to −10°C, the number of freeze-thaw cycles that the same concrete sustains quickly reduces to 12. Upon a further lowering of the temperature to −17°C, the frost durability reduces slightly to 7 freeze-thaw cycles. The test results clearly show that damages mainly occur in the range from 0°C to −10°C and have limited increase below −10°C. A possible reason that may explain the phenomenon is that there is a concentrated distribution of solution in pores that have the most probable pore size and solution in these pores freezes above −10°C. Freezing of this part of pore solution greatly increases ice content in concrete. At temperatures below −10°C, solution in smaller pores freezes. The amount of smaller pore solution is much less, and its freezing does little harm to the concrete. Therefore, study of freeze-thaw durability of ordinary concrete should concentrate on the temperature range between 0°C and −10°C.

High-strength concrete is denser, and its most probable pore size is smaller, than that of ordinary concrete. The freezing point of the pore solution decreases with the decrease of pore radius. Compared with ordinary concrete, the amount of pore solution freezing above −10°C a is less and below −10°C is is more (Fig. 3). So the turn of freezing rate is slower in the freezing process of high-strength concrete. With the greater rate of ice formation below −10°C, whether the frost damage in this temperature range can be neglected still needs further investigation.

Conclusions

1. Due to the hysteresis of ice formation in freezing process, ice content in thawing process is not suited for evaluating frost damage.
2. The freezing rate of concrete pore solution is higher above −10°C than below −10°C, so frost damage mainly occurs above −10°C. To ordinary concrete, although pore solution goes on freezing below −10°C, the consequent damages are so small that they can be neglected. To high-strength concrete, which is denser, the seriousness of damage caused by freezing below −10°C still needs further study.
3. Test results in this paper will possibly help to calculate the internal hydraulic pressure caused by ice formation and enable structural design and maintenance that consider the freeze-thaw durability of concrete.
4. Studying ice formation process through the change of electrical conductivity is a method suitable to concrete and worth developing. It is simple, quick, and most importantly can be applied to representative concrete specimen.
5. Air entraining affects mainly the mechanical properties of concrete. Its effect on pore solution behavior is not obvious.

Acknowledgment

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