General paper

New Deterioration Index of Durability and Strength Evaluation of Structural Concrete under Freezing and Thawing Action

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Abstract: The existing freezing and thawing test method of structural concrete leaves much room for improvement from the viewpoint of materials science research; that is, the concrete specimen is too large and heavy and the testing procedure is so time-consuming that the test itself cannot be practically used for evaluation of durability. Thus, the authors have reported that the standard cylindrical specimen ($\phi 10 \times 20$ cm) is the best type for the quality control of concrete and that the accelerative test method using the exposure temperature of $\pm 5^\circ\text{C}$ has been developed. The surface defect ratio has been defined on the basis of the fact that the gradual process of surface deterioration, namely, the popping-out, is fundamentally related to the internal destruction of concrete. This paper deals with the relationship between the relative dynamic modulus of elasticity, the number of freezing and thawing cycles, and the surface defect ratio. Thus it proposes a practical evaluation method of the compressive strength of structural concrete, which uses a new durability index of the surface defect ratio.

Key words: Concrete, Durability, Freezing and thawing action, Relative dynamic modulus of elasticity, Deterioration index, Surface defect ratio, Strength evaluation.

1. INTRODUCTION

The existing freezing and thawing test method applied to evaluate the durability of concrete under meteorological action is used globally. Numerous research works on the freezing and thawing meteorological action and durability improvement have been carried out to date. The relative dynamic modulus of elasticity and the mass change have been used as the detection index for determining the degree of deterioration of a concrete structure, in which the former can be determined on the basis of the ultrasonic propagation velocity but the latter cannot be determined practically. Therefore, a useful index in place of the mass change has been desired. Kamata and Koh [1] and Yamato [2] described that the residual expansive strain in the event of thawing corresponded well to the deterioration characteristics. Saeki *et al.* [3] indicated that the water content at the onset of surface scaling revealed the degree of deterioration. Yamura *et al.* [4] reported that the "Kaiser effect" by virtue of the AE signal is useful for determining the specimen deterioration under the freezing and thawing action. Hama *et al.* [5] presented an empirical formula based on the meteorological factors to estimate the service lifetime.

It can be understood as stated above that the ideal

specimen type and exposure temperature are still required for evaluating the degree of deterioration of structural concrete. However, the test conditions leave much room for improvement. In particular, the exposure temperature and the shape and dimensions of the test specimen are the most important factors, for which the temperature range of -5°C to $+5^\circ\text{C}$ instead of that of -18°C to $+5^\circ\text{C}$ and the ordinary cylindrical specimen of $\phi 10 \times 20$ cm for quality control instead of the regular prismatic specimen of $10 \times 10 \times 40$ cm were adopted on the basis of the experimental findings [6,7]. The JSCE Standard [8] in accordance with the ASTM Designation C-666 specifies the temperature range of $-18(\pm 2)$ to $+5(\pm 2)^\circ\text{C}$ and the cycle time of 3 to 4 hours, but it should be considered that there is no need to lower the exposure temperature until extreme temperatures are reached from the viewpoint of surface deterioration. Thus, the freeze-thaw cyclic action under the thermal condition to initiate to freezing ought to be ideal as an accelerative method. The above-mentioned temperature improvement has been applied in the present study.

The authors [6,7] have previously reported the surface deterioration mechanism caused by the popping-out and clarified that in particular, the variation of mass is the physical index that should be structure-insensitive. Thus, the "surface defect ratio" in place of the variation

Table 1. Specified mix proportion of AE concrete.

#	W/C (%)	Slump (cm)	s/a (%)	Unit Content (kg/m ³)				
				Water	Cement*	Fine aggregate	Coarse aggregate	Admixture**
1	50	18	42.1	182	364	725	997	0.91
2	55	18	43.8	176	320	777	997	0.80
3	60	18	44.6	175	292	803	997	0.73

* Ordinary portland cement
** AE water reducing agent

of mass has been found and defined for the first time

The present paper describes the relationship between the new characteristic index and the compressive strength and the validity of the effect of the index of durability deterioration from the viewpoint of materials science.

2. EXPERIMENTAL PROCEDURE

The test specimens used are cylindrical and have the dimensions of $\phi 10 \times 20$ cm for ordinary quality control, and were exposed to temperatures in the range of -5°C to $+5^\circ\text{C}$ for 45 min/cycle in accordance with the rationalized test method described in the previous report [7,8]. Table 1 displays the specified mix-proportion of AE concrete entrained with the apparent air content of 3%; after preparation, the specimens were cured underwater for 14 days. The following data are obtained for the specimens; the mass, the relative dynamic modulus of elasticity and the characteristic dimensions corresponding to the major diameter of A and the minor one of B of a small crater which popped out on the concrete surface.

Figure 1 illustrates the microcrater circled with the bold lines in (a) on the surface of the specimen as an example. Here, the "surface defect ratio" α is defined as follows:

$$\alpha(\%) = 100 \Sigma(A \cdot B) / S, \quad (1)$$

where S is the total surface area of the specimen.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Surface Defect Ratio as Deterioration Index

Figure 2 expresses the relationship between the relative dynamic modulus of elasticity and the repeating cycles of freezing and thawing action, together with the water-cement ratios. The relative dynamic modulus of elasticity β is defined by Eq. (2) as follows:

$$\beta = E_D / E_{D0} \times 100, \quad (2)$$

where E_{D0} and E_D are the initial dynamic modulus of elasticity

Fig. 1. Microcraters caused by popping-out.

and the current one, respectively.

It is also clear from Fig. 2 why it is recommended that the water-cement ratio and the unit content of cement be below 55% and above 270kg, respectively, in order to secure the extreme meteorological environments [9]. The present study does not deal with the mass variation, because it is a structure-insensitive property [7].

Figure 3 indicates the relationship between the surface defect ratio α and the number of repeating cycles N . There is no major difference between the surface defect ratios for the water-cement ratios W/C of 50% and 55%, similarly to the case of the dynamic modulus of elasticity. In general, the difference is small, but it increases rapidly above $W/C = 55\%$ and 200 cycles. This reveals that the decrease of the dynamic modulus of elasticity indicates the multiplication of the internal microcracks, and the increase of the surface defect ratio indicates that the surface deterioration proceeds inside the structural concrete member.

Fig. 2. Relationship between relative dynamic modulus of elasticity and cycles of freeze-thaw action.

Fig. 3. Relationship between surface defect ratio and cycles of freeze-thaw action.

Figure 4 signifies the relationship between the relative dynamic modulus of elasticity β and the surface defect ratio α , as given by Eq.(3).

$$\beta = 100 \exp(-0.0625\alpha) \quad [\gamma = -0.954] \quad (3)$$

where γ is the correlation factor.

Equation (3) has been quantitatively formulated with reference to the relationship between the internal physical property and the degree of external damage to the concrete structure. Thus, the relative dynamic modulus of elasticity β can be easily estimated when the surface defect ratio α on the concrete structure is observed. In general, the end conditions of the freeze-thaw test under the existing Standard [3] are at 300 cycles or below the relative dynamic modulus elasticity of 60% [8]; thus it is safe to say that the critical α is $\alpha_c = 8.2\%$, approximately, with 8.0% being suitable for an important "deterioration index," corresponding to the limiting durability degree $\beta_c = 60\%$. On the other hand, the measurement of dynamic modulus of elasticity for the existing concrete structure is not easier than that of the surface defect ratio.

Figure 5 represents the relationship between the compressive strength and the dynamic modulus of elasticity of concrete, obtained by rearrangement of the previously obtained data [10] similar to the result in [11], together with its static

Fig. 4. Relationship between relative dynamic modulus of elasticity and surface defect ratio.

modulus of elasticity E_c [12,13] for reference. The correlative equation and the estimated strength can be expressed by Eq. (4) and by Eq. (5), respectively;

$$E_D = 3.304 + 7.968 \ln f'_c (\gamma \approx 0.80), \quad (4)$$

$$f'_c = \exp(0.1255 E_D - 0.4147), \quad (5)$$

where E_D and f'_c are the dynamic modulus of elasticity in kN/mm^2 and the compressive strength in N/mm^2 of concrete, respectively.

3.2. Surface Deterioration Mechanism

Though the primary cause of the conventional deterioration mechanism of concrete is considered to be the internal collapse [14], the present paper takes into account the fact that the surface deterioration, that is, the scaling resulting from the gradual popping-out, proceeds toward the interior of the concrete on the basis of a visibly observed phenomenal fact. In general, one of the main causes of surface deterioration is the freezing pressure of water which has permeated into isolated bubbles. On the assumption that the elastic rupture of the thick shell occurs due to the freezing pressure as illustrated in Fig. 6, when the maximum tangential tensile stress $\sigma_{\theta, \max}$ [15] agrees with the tensile strength of matrix f_{td} , that is, $\sigma_{\theta, \max} \equiv f_{td}$, the radius ratio λ can be expressed by Eq. (6).

$$\lambda \equiv b/a = \left\{ \frac{1 + 0.098 (T/0.0099 - 1) / f_{td}}{1 - 0.5 \times 0.098 \times (T/0.0099 - 1) / f_{td}} \right\}^{1/3} \quad (6)$$

where T is the freezing temperature. When the internal stress $p = 2f_{td}$, then $\lambda \rightarrow \infty$; that is to say, this p indicates the beginning or the stagnation of elastic rupture. Furthermore, the freezing temperature in such a critical state may be called the "critical temperature," T_c .

Figure 7 displays the relationship between the radius ration and the freezing temperature as a parameter of the characteristic compressive strength of concrete, considering the critical temperature. The figure suggests the following conclusions.

Fig. 5. Relationship between dynamic modulus of elasticity and compressive strength of concrete.

- ① The freezing temperature decreases as the strength of concrete increases in the event of a constant radius ratio.
- ② The freezing temperature decreases as the radius ratio increases for the same strength of concrete.
- ③ The physical properties of concrete, for both the concrete strength and the freezing temperature, are "structure-sensitive" under the kink, that is, the singular radius ratio obtained from the log-log expression of the radius ratio versus the freezing temperature curves. On the other hand, it becomes "structure-insensitive" over the kink.
- ④ Finally, the improvement of durability involves changing the quality of concrete from the structure-sensitive layer to the structure insensitive layer.

Here, the structure-sensitive layer should be called the "critical layer" under the freezing and thawing action. This critical layer may correspond to the "critical absolutely dried depth," that is, the depth at which the surface cracking is initiated under the wet and dry action [11].

[EX.1] When $a = 250 \mu\text{m}$ and $b/a = 2.5$, then $b = 2.5 \times 0.25 \div 0.63 \text{mm}$; therefore, the critical layer b is approximately 0.7mm , which is smaller than 1mm regardless of the concrete strength.

Now, the present problem is analyzed by modeling an isolated bubble upon a plane stress state; however, when it is dealt with as a pressurized sphere in the semiinfinite body, the maximum tensile stress at the vertex is moderated to some extent as compared with the former case [16,17]; so, the present analysis is evaluated inside the safety zone.

3.3. Practical Application

Both the dynamic modulus of elasticity and the compressive strength can be evaluated by using the surface defect ratio for the inspected deteriorated concrete structure, according to the steps of the procedure shown in Fig. 8.

The initial minimum condition for evaluating the durability of the structures is the compressive strength of structural concrete (f'_c), from which the initial dynamic modulus of elasticity (E_{D0}) can be determined. Furthermore, the degree of deterioration of the structure due to the meteorological action can be estimated from the surface defect ratio (α), since the relationship between the relative dynamic modulus of elasticity (β) and the surface defect ratio (α) has been clarified quantitatively. Thus, any compressive strength of structural concrete (f'_c) can be estimated because any dynamic modulus of elasticity E_{D0} can be estimated and defined by βE_{D0} .

Fig. 6. Scaling model of matrix.

Fig. 7. Relationship between radius ratio and freezing temperatures as parameter of concrete strength.

[EX. 2] Suppose that the initial structural concrete strength is $f'_{\infty} = 30 \text{ N/mm}^2$ and the surface defect ratio α is 3.0%. The dynamic modulus of elasticities E_{DO} and E_D are unknown.

Solution:

① The initial modulus of elasticity from Eq. (4):

$$E_{DO} = 3.304 + 7.968 \ln 30.0 = 30.4 \text{ kN/mm}^2$$

② The relative dynamic modulus of elasticity β at $\alpha = 3.0\%$ from Eq. (3):

$$\beta = 100 \exp(-0.0625 \times 3.0) = 82.9\% \leq \beta_c = 60.0\%$$

The dynamic modulus of elasticity E_D at $\alpha = 3.0\%$:

$$E_D = \beta E_{DO} = 0.829 \times 30.4 = 25.2 \text{ kN/mm}^2$$

③ The deteriorated structural concrete strength from Eq. (5)

$$f'_c = \exp(0.1255 \times 25.2 - 0.4147) = 15.6 \text{ N/mm}^2$$

So, $f'_c / f'_{\infty} = 15.6 / 30.0 = 0.52$ (52%)

As is clearly evident from this example, the compressive strength decreases even under 52% of the initial strength, although E_D is over the critical relative dynamic modulus of elasticity. Therefore, this indicates that the concrete structure must be reconsidered also from the viewpoint of the load-carrying capacity of its member. The variation of the decreasing mass of the specimen was negligible until the complete 300 cycles of exposure. Now, the decreasing increment of dynamic modulus of elasticity ΔE_D can be given by Eq. (7), by applying the error-propagation rule to its fundamental equation [3].

$$\Delta E_D = K \Delta f_1 \quad (7)$$

where K is a constant, and f_1 and Δf_1 are the first-resonant cycle and its decreasing increment, respectively. Therefore, Δf_1 depends on the propagation velocity of a stress wave; so, in other words, it may safely be said that it results from the dependency on the internal microcrackings.

4. CONCLUSION

The present paper proposes a practical freezing and thawing test method from the viewpoint of materials science research and its validity has been verified on the basis of the new deterioration index in the case of the dominant environment of the freezing and thawing action.

(1) The surface deterioration resulting from the popping-out proceeds to the interior of structural concrete as if the thin skinlike layer were torn off.

(2) The present paper described a simplified hypothetical two-dimensional elastic failure model for explaining the popping-out mechanism; thus, it has been confirmed by analysis that there is a possibility that the matrix can easily be popped out under a low temperature near the freezing point, on the basis of this model.

(3) The "surface defect ratio" has been defined as the structure-sensitive physical quantity in place of the structure-insensitive mass variation.

(4) The relationship between the structure-sensitive relative dynamic modulus of elasticity β and the surface defect ratio α has been formularized for the first time as follows.

Fig. 8. Flow diagram of steps of procedure.

$$\beta = 100 \exp(-0.0625\alpha)$$

(5) The α vs. β correlative figure has also been constructed; thus, its strength characteristic, $E_D = \beta E_{D0}$, can be easily estimated, if the surface defect ratio on the existing concrete structure is observed.

(6) The compressive strength of existing structural concrete can be estimated as follows.

$$f'_c = \exp(0.1255 E_D - 0.4147)$$

(7) It is worth mentioning that the relative dynamic modulus of elasticity decreases to approximately 60% when the surface defect ratio α increases to nearly 8.0%

(8) The critical relative dynamic modulus of elasticity can be an important criterion for judging structural rehabilitation.

(9) The mechanism of surface deterioration due to the popping-out and the existence of a structure-sensitive critical layer contributing to the durability have been analyzed.

(10) The comparatively structure-sensitive dynamic modulus of elasticity basically depends on the detection precision of its variation; therefore, the decreasing increment ΔE_D is subject to the internal microcracks, in other words, the propagation velocity of the stress wave.

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