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Prediction of Concrete Deterioration by Cyclic Freezing and Thawing

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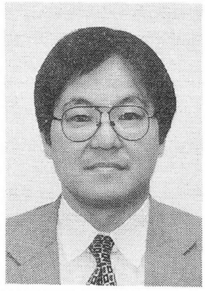


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This paper proposes a prediction method for the deterioration of dam concrete resulting from cyclic freezing and thawing. Based on the results of field exposure tests under natural conditions over twenty years, a formula is developed for the number of cyclic freezing and thawing cycles until concrete failure . The formula is made applicable to in relation with the following two parameters water-cement ratio and minimum temperature. The concept of a defined repetition number synthetically explains the effect of the two parameters on deterioration . This defined repetition number is thus applicable to the prediction of deterioration under various natural conditions where the minimum temperature varies.

Key Words: frost resistance, exposure test, rapid freezing and thawing, freezing and thawing cycle, standardized freezing and thawing cycle, prediction of deterioration

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1. INTRODUCTION

The Sub-committee for Field Experiments on Frost Resistance of Dám Concrete (Chairman: Kokubu Mashatane, Professor Emeritus, University of Tokyo) of the Japan Commission on Large Dams has been conducting long-term in-situ durability experiments using large one cubic meter concrete blocks at seven Japanese dams. The authors have been participating in this research since 1969 , carrying out tests involving the placing of these large concrete blocks as well as small ϕ 15 cm by 30 cm specimens in the regulating reservoir at the Midono Dam in western Nagano Prefecture. Annual measurements of the specimens have been carried out, primarily focusing on the dynamic modulus of elasticity and the authors , have also conducted a survey of deterioration over time. A detailed study of the state of deterioration in the 20th year of exposure was implemented and the results announced [1].

Over a period of many years, numerous valuable reports concerning the resistance of concrete to freezing and thawing have been published [2]. Many of these have been studies of the factors that influence frost damage and durability under conditions where the lowest temperature and freezing and thawing rate were stipulated, but there has been little research concerning the prediction of deterioration for a given lowest temperature. The prediction of deterioration caused by freezing and thawing is an extremely important to the search for more rational methods of concrete mix design and the durability design of concrete structures.

This project aims at forecasting deterioration for any given water -cement ratio and minimum temperature based on the results of laboratory rapid freeze-thaw experiments and a survey of the deterioration of the small specimens mentioned above . The acceleration characteristics of the laboratory tests were also studied by comparing the field results with the rapid freeze-thaw tests.

While it is known that the degree of moisture in a specimen greatly influences its frost resistance and strength, for the purposes of this study, it was hypothesized that the amount of moisture in the specimens was almost equivalent to that resulting from moist curing. We were able to make this assumption because the specimens were exposed within the range of operating water levels of the regulating reservoir, which is past of a pumped storage system. Thus they were submerged frequently and moist conditions were easily maintained.

2. WATER-CEMENT RATIO , MINIMUM TENMPERATURE, AND STANDARDIZED FREEZE - THAW CYCLE

(1) Effect of Water-Cement Ratio and Minimum Temperature on Freeze-Thaw Resistance

The water-cement ratio and the minimum temperature have an extremely significant effect on the freeze-thaw resistance of concrete. Figure 1 shows how the relative dynamic modulus of elasticity declined as the water-cement ratio and minimum temperature changed during freeze-thaw testing [3]. The following is an outline of test conditions at the time.

The materials used, ones as similar as possible to those used to make the exposure test samples, were moderate-heat Portland cement, fine and coarse aggregates kept in storage since the time the exposure test specimens were prepared (a mixture of crushed stone and river aggregate from the Azusawagawa River in Nagano Prefecture). The coarse aggregate used had a maximum size of 150 mm and a specific gravity of 2.66; it was classified into the ranges 150 to 80, 80 to 40, 40 to 20, and 20 to 5 mm. The fine aggregate had a fineness modulus of 2.78 and a specific gravity of 2.60.

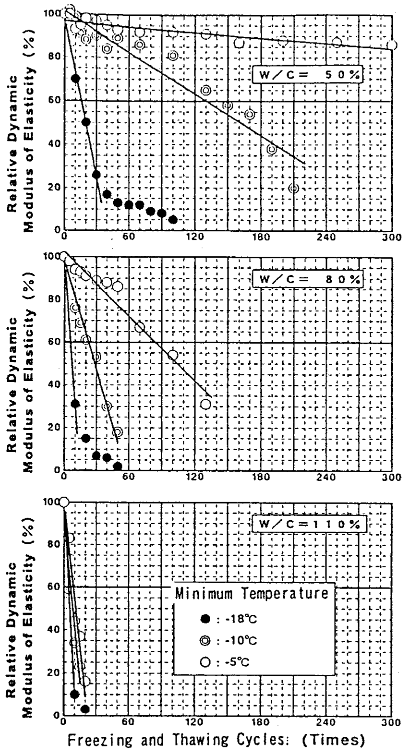
The mix proportions were designed to produce three kinds of concrete with water-cement ratios of 50%, 80%, and 110% without on AE agent. The unit water content was set based on trial mixing such that a slump of 3 ± 1 cm was obtained, the same value as exposure test specimens. The fine aggregate ratio was also set based on trial mixing so as to optimize it for each water-cement ratio. Refer to a separate report [3] for details of the mix proportions.

The freeze-thaw experiments were performed using the submerged- freezing, submerged-thawing method, with the minimum temperature during freezing at -18℃, -10℃, and - 5℃. In all cases, the highest temperature at thawing was set at 5℃, and the rate of change in temperature was maintained at an almost constant 9℃/hour in an effort to prevent any significant changes in temperature change under lowest temperature conditions. The freeze-thaw testing began at the age of 91 days. This was done to achieve conformity with conditions when the in- situ exposure test commenced.

No AE agent was used so that the effects of external force factors on freezing and thawing would be clarified. It has been reported that if deterioration caused by freezing and thawing is treated as caused by an exterior force and bearing force, the exterior force (freezing force) includes the minimum temperature, cooling rate, and duration of freezing, and of these, the effects of the minimum temperature are greatest [4]. The air distribution and strength of the structure can be considered aspects of the bearing force (relaxation force). Consequently, it is assumed that if, as part of a study of the effects of the minimum temperature, concrete containing an AE agent was tested by varying the minimum temperature, the effects of the bearing force side would be increased. So as to avoid this, concrete without an AE agent was tested.

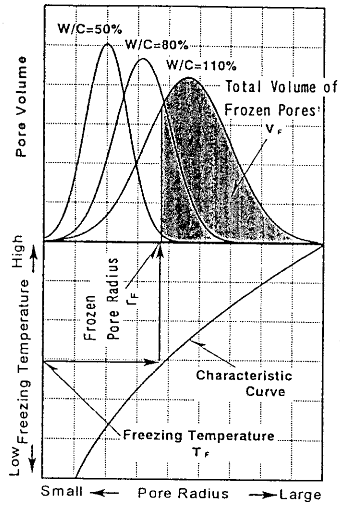
Figure 1 reveals that the higher the water-cement ratio and the minimum the lowest temperature, the greater the deterioration caused by freezing and thawing cycles. The authors' experiments demonstrate that there is a close relationship between the proportion of frozen water in the hardened concrete pore structure (pores found in mortar with the coarse aggregate removed based on the mercury pressure injection method) and the decline in dynamic modulus of elasticity, regardless of the water-cement ratio and the minimum temperature. This shows that the proportional relationship between water-cement ratio or minimum temperature of hardened concrete, and the percentage of frozen water in the pore structure of the hardened concrete has a considerable influence.

The proportion of frozen water in the pore structure of hardened concrete (referred to as the "frozen pore ratio") is found to be as



Note: Because linearity deteriorates at a relative dynamic modulus of elasticity of 20% or less, the relative dynamic modulus of elasticity was regressed above 20%

Fig.-1 Effects of Minimum Temperature and Water-Cement Ratio on Freezing and Thawing Resistance



Fif. -2 Frozen Pore Ratio Calculation Method

Table 1 Frozen Pore Quantity and Frozen Pore Ratio Calculated Results

Water-Cement Ratio W/C (%)	Total Pore Quantity V_0 (cc/g)	Frozen Pore Quantity V_f (cc/r) Minimum Temperature (℃)			Frozen Pore Ratio V_f/V_0 (%) Minimum Temperature (℃)		
		-5	-10	-18	-5	-10	-18
50	0.0738	0.0108	0.0319	0.0423	15	43	57
80	0.0962	0.0268	0.0476	0.0620	28	49	64
110	0.1308	0.0710	0.0888	0.1007	54	68	77

shown in the typical figure, Figure 2. Assuming that the concrete was in saturated condition, Higuchi's formula [5] representing the pore diameter - solidification point relationship was used to find the frozen pore size diameter for each minimum temperature based on the pore size distribution measurement results, and assuming that pores of larger size were frozen, the overall pore ratio was used to set the frozen pore ratio. Table 1 shows the frozen pore ratio. Here, the calculation of total pore quantity assumes a cylindrical model pore the voids and treats the mercury pressure insertion quantity of pores with a diameter between 3 nm and 15,200 nm.

(2) Frozen Pore Ratio and the Failure Cycle

If the freeze-thaw test results presented in Figure 1 are organized by frozen pore ratio and the number of cycles until failure (the "failure cycle number"), the relationship shown in Figure 3 is obtained.

So the failure cycle number is assumed to be the cycle at which a linear regression is performed on the relationship between number of freeze- thaw cycles and the relative dynamic modulus of elasticity and the relative dynamic modulus of elasticity is 60% [6]. According to reports of past tests in which regression was carried out on the relationship in Figure 1 with a minimum temperature of -18℃, there are cases where it is not necessarily very linear. In this experiment, however, because linearity is observed as long as the relative dynamic modulus of elasticity is over 20%, linear interpolation was applied in this range.

Figure 3 shows that there is a linear relationship between the common logarithm of failure cycle number and the frozen pore ratio regardless of the water-cement ratio and the minimum temperature.

The point in Figure 3 where W/C is 50% and the temperature is - 5℃ is an extrapolation point based on the linear interpolation in Figure 1. The extrapolation was adopted for the following two reasons.

First, even in a case where the minimum temperature falls with water- cement ratio constant, and even in a case where the water-cement ratio rises with the minimum temperature constant, a relatively good linear relationship is maintained over a range of relative dynamic modulus of elasticity above 20%.

Next, even if the point where W/C = 50% and the temperature is - 5℃ has been removed from Figure 3, the regression formulae are almost identical. Up to a failure cycle number of 100, for example, the maximum frozen pore ratio is 0.6% and up to a failure cycle of 1,000, the frozen pore ratio is almost identical at 1.6%.

The same figure shows that at a low frozen pore ratio, the failure cycle number is high, but at a high frozen pore ratio, the failure cycle number is lower. Strictly speaking, in the case of the freeze-thaw resistance of a porous material such as concrete, not only the quantity of pores but their distribution should be considered. However it has been reported that it is possible to evaluate freeze-thaw resistance using the quantitative approach described[7], so for this research project, the pore quantity was treated as an index.

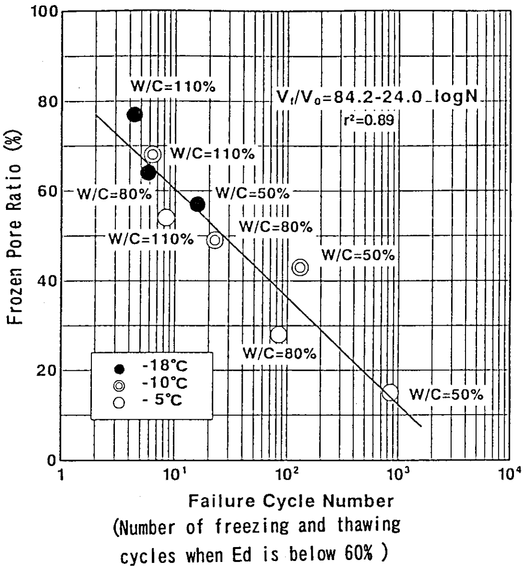
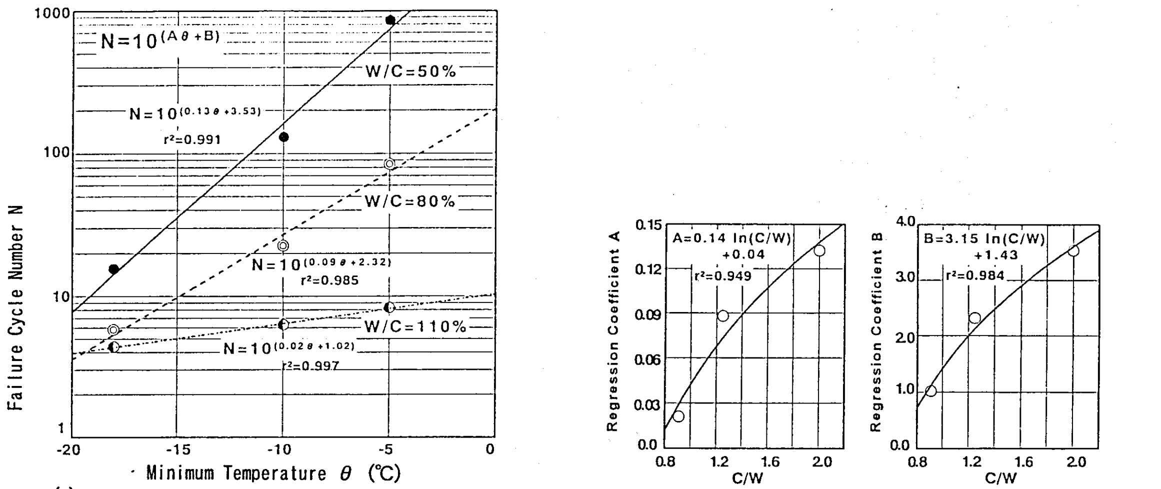


Fig.-3 Failure Cycle Number and Frozen Pore Ratio Relationship



(a) Minimum Temperature and failure Cycle Number Relationship for Each Water-Cement Ratio

(b) Regression Coefficient A

(c) Regression Coefficient B

Fig.-4 Effect of Minimum Temperature and Cement-Water Ratio on Failure Cycle Number

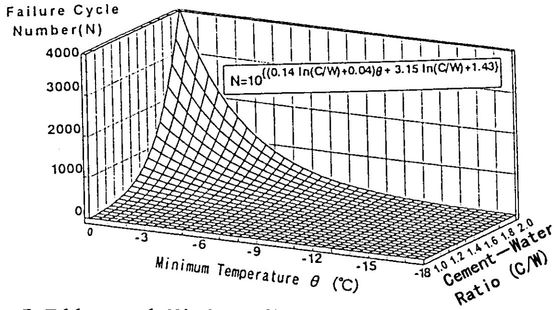


Fig.-5 Effect of Minimum Temperature and Cement-Water Ratio on the Failure Cycle Numeber

According to an earlier report [8], on the assumption that it is possible to treat the deterioration caused by freezing and thawing as a fatigue problem, it is conceptually a possible to treat the frozen pore ratio as something corresponding to the stress ratio in fatigue problems. Figure 3 reveals that the frozen pore ratio rises as the water-cement ratio increases at a constant minimum temperature, and also that it rises as the minimum temperature falls at a constant water-cement ratio. This indicates that in the case of deterioration caused by freezing and thawing, it is necessary to consider not only the number of cycles, but also the amount of damage caused by each cycle. At the same time, it tells us that if this is done, it is possible to simultaneously evaluate the effects of water-cement ratio and the minimum temperature.

(3) Water Cement Ratio, Minimum Temperature, and the Failure Cycle

Because special equipment is necessary to measure the pore quantity and it is believed that the frozen pore quantity itself is not necessarily a practical index. Instead of frozen pore ratio, the failure cycle number is organized by water-cement ratio and minimum temperature.

Figure 4(a) shows the relationship of lowest temperature versus failure cycle number N. Because the frozen pore ratio, as exemplified in Figure 2, is considered a function of the water-cement ratio and the minimum temperature, and because there is a linear relationship between the logarithm of failure cycle number and the frozen pore ratio as shown in Figure 3, the form of the regression formula for failure cycle number when the minimum temperature and water-cement ratio are treated as explanatory variables is given by Formula

$$N = 10^{(A\theta+B)} \qquad (1)$$

Where:

N: Failure cycle number;, θ: Lowest temperature;

A, B: Regression coefficients.

Regression coefficients A and B for each water-cement ratio are obtained as shown in Figure 4 (b) and (c) on the hypothesis that regression is possible using the following formula;

$$A = \alpha \ln(C/W) + \beta \qquad (2)$$

$$B = \gamma \ln(C/W) + \delta \qquad (3)$$

Where:

A, B: Coefficients in Formula (1); α,β,γ,δ: Coefficients.

If the regression formulas shown in Figure 4 (b) and (c) are substituted in to Formula (1), the failure cycle number for a given water-cement ratio and minimum temperature are obtained, as shown in Figure 5.

(4) Standardized Freezing and Thawing Cycle

As demonstrated in (3) above, it is possible to calculate the failure cycle number corresponding to an any given water-cement ratio and minimum temperature. Consequently, it is possible to simultaneously represent the effects of the water-cement ratio and minimum temperature by finding the ratio of the failure cycle number for a water cement ratio and minimum temperature to the reference water-cement ratio and minimum temperature as shown in formulae (4) and (5). Treating this as a weighting coefficient, the evaluation is performed by multiplying it by the freezing-thawing cycle number for each water-cement ratio and minimum temperature.

In this report, the freezing and thawing cycle calculated in this way is defined as "the standardized freezing and thawing cycle".

$$\varphi = \frac{Nd([C/W]st,[\theta]st)}{Nd([C/W]t,[\theta]t)} \qquad (4)$$

$$Ni' = \varphi \cdot Ni \qquad (5)$$

Where:

φ: Weight coefficient; $N_d([C/W]_t, [\theta]_t)$: Failure cycle number of the cement-water ratio and minimum temperature of the target concrete;

$N_d([C/W]_{st}, [\theta]_{st})$: Failure cycle number of the cement water ratio and minimum temperature of the standard concrete (both calculated as shown in Figure 5)

N_i': Standardized freezing-thawing cycle number;

N_i: Freezing and thawing cycle number.

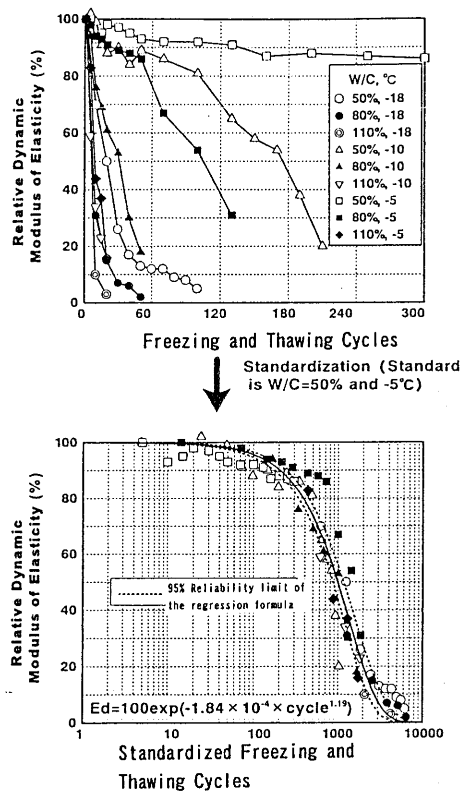


Fig. -6 Expression Based on Standardized Freezing and Thawing

Table 2 Concrete Mix Proportions

Code	G_{max} (mm)	W/(C+F) (%)	F/(C+F) (%)	s/a (%)	Unit Content (kg/m³) W	C	F	S	G	AEA	Slump (cm)	Air (%)
AF 49	150	49	25	22	98	150	50	467	1645	54cc	3.3	3.0
AF 71	150	71	25	24	92.5	97.5	32.5	519	1643	34cc	2.8	2.8
AF 91	150	91	25	24.5	90	75	25	532	1640	23cc	2.9	2.6
AF110	150	110	25	25	88	60	20	546	1636	16cc	2.6	3.1

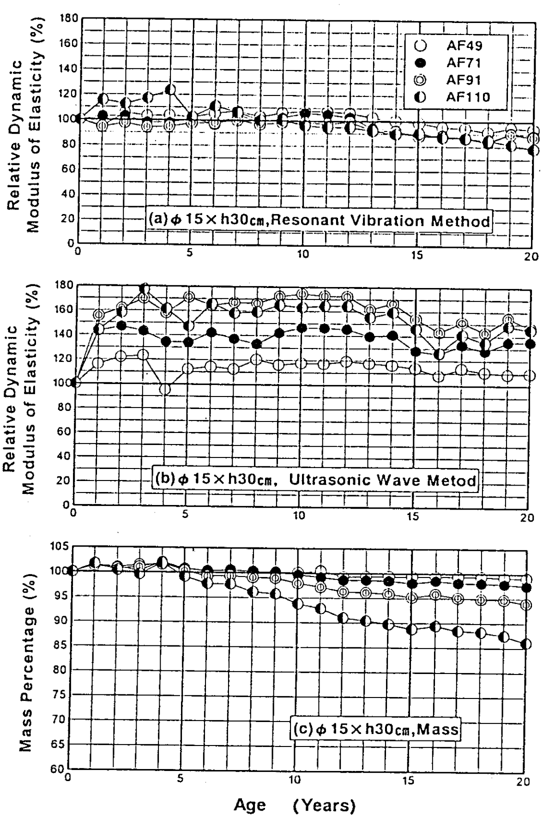


Fig. -7 Change Over Time in Relative Dynamic Modulus of Elasticity Mass Percentage

For example, Figure 6 shows the results of organizing the results in Figure 1 by weighting the freezing and thawing cycle number from Figure 5 using the failure cycle number for a water-cement ratio of 50% and a minimum temperature of - 5℃ as the reference. The figure also shows the 95% reliability limits of the regression formula. This reveals that it is possible to represent the relationship between standardized freezing-thawing cycle number and relative dynamic modulus of elasticity relationship as a single deterioration curve, regardless of the water-cement ratio and the minimum temperature. It shows that, for example, 100 cycles with a water cement ratio of 50% and a minimum temperature of - 18℃ (the symbol ○ in the figure), corresponds to about 6,400 cycles of the standardized freezing-thawing cycle. This can, inversely, be interpreted at meaning that the equivalent of more than 60 times as many cycles is applied by changing the minimum temperature from - 5℃ to - 18℃ when at a water-cement ratio of 50%.

From this understanding, it is possible to estimate a deterioration curve for any given conditions of water-cement ratio and minimum temperature using the standardized freezing-thawing cycle.

3. APPLICATION OF STANDARDIZED FREEZING-THAWING CYCLE TO EXPOSURE TEST

(1) Change over Time in Relative Dynamic Modulus of Elasticity

Figure 7 shows the change over time in relative dynamic modulus of elasticity and the mass change of the mix proportion using an AE agent and containing fly-ash from Table 2: this is one of the results of freeze- thaw testing obtained by the authors under natural conditions. Both (a) and (b) are the results of measuring cylindrical specimens with dimensions φ 15 x 30 cm (Gmax 40 mm; wet screening; referred to below as "small specimen"). The dynamic modulus of elasticity was computed using the resonant vibration method in case (a) (longitudinal vibration) [9] and the ultrasonic method [10] in case (b).

A cylindrical specimen was used to find the longitudinal vibration in the resonant vibration method, because when exposure of the coarse aggregate occurs as a result of scalling and other deterioration, it is difficult to make the measurement terminals well and to fix the specimen in place, which means there is a high likelihood of measurement errors occurring. Cylindrical specimens also allowed comparison of compressive strengths. Although the dynamic modulus of elasticity measurements were performed twice a year, only annual averages are presented here.

The same figure shows that at the 20-year point, the dynamic modulus of elasticity as measured by the ultrasonic method remained equal to or greater than the value when measurements commenced for both water-binder ratios. The trend seen in the results of accelerated laboratory tests, namely that the relative dynamic modulus of elasticity rises as the water-cement ratio falls, was not observed. Further the relative dynamic modulus of elasticity of the small specimen found using the resonant vibration method tended to be lower than that obtained using the ultrasonic method, but even in the case of the highest water-binder ratio of 110% (Code AF110), the relative value elasticity at the age of 20 years was 80%, indicating only very deterioration.

The large discrepancy between values of relative dynamic modulus of elasticity obtained by the resonant vibration and ultrasonic methods is assumed to result from the effects of different measurement principles and measurement locations [1]. It is assumed that when the ultrasonic method is used, damage to the surface has little effect because the sensors are applied to the end surface (one-side capping) of a cylindrical specimen, where deterioration is less than elsewhere. The dynamic modulus of elasticity is then calculated from the speed of the ultrasonic waves transmitted through the center of the specimen.

For example, as shown in Figure 7 (c), the loss of mass of AF91 and AF110 is great and (as pointed out in an earlier report [1]), photographs of their surfaces reveal exposure of the coarse aggregate and substantial surface damage. Nevertheless, the dynamic modulus of elasticity is unchanged from the value obtained prior to the beginning of exposure, indicating that it may not be possible to evaluate the influence of surface damage using the ultrasonic measurement method employed here.

Concerning the reason for thus slow deterioration, it has been reported that the frost resistance of concrete that has dried slightly before being subject to freezing and thawing is greater[11], and although this action can not be ignored, it was also influenced greatly by the increase in strength which occurred during the exposure period.

(2) Correction of Strength Increase during the Exposure Period

Table 3 shows the results of strength testing over the 20 years following the start of testing for both a standard-cured (water-cured) specimen and a specimen cured while exposed. A comparison of the strength 91 days and 18 years after dynamic elastic modulus measurements began the standard-curing case shows that the strength increased by 1.1 times for AF49, which had the lowest water-binder ratio, and by 3.3 times for AF110, whose water-binder ratio was the highest. The results were 1.3 times and 2.8 times respectively for the in-situ exposed specimens. It has been pointed out in the past that strength rises during freezing and thawing testing, and that this affects the relative dynamic modulus of elasticity [12]. The effect is greater under natural exposure conditions as compared with accelerated testing conditions.

The evaluation of the freeze-thaw resistance of a concrete structure must account for this increase in strength while exposed, but in order to predict deterioration it is necessary to clarify changes in dynamic modulus of elasticity with freeze-thaw deterioration while ignoring the effects of the strength increase. So with reference to the report by Choai et al., the relative dynamic modulus of elasticity was redefined by compensating for the effects of the increase in strength during natural exposure.

The flow chart in Figure 8 illustrates this strength compensation method. The maturity at the site is found, the change over time in dynamic modulus of elasticity without frost-induced deterioration (in this report, referred to as the "ideal dynamic modulus of elasticity") is estimated, and the modified relative dynamic modulus of elasticity is calculated from the ratio of this and the measured dynamic modulus of elasticity.

The dynamic modulus of elasticity is calculated from compressive strength rather than by a direct method because the measurements of dynamic modulus of elasticity for standard curing over the 20-year period are missing for some mix proportions and ages.

a) Calculation of Maturity - Compressive Strength Relationship

The maturity - compressive strength relationship was found from the age - strength relationship under standard curing (water curing).

The maturity - compressive strength relationship and the results of regression are shown in Figure 9.

Here, the form of the regression formula that given as Formula (6) [12].

$$f_c' = \frac{M - M_0}{(1/a) + \{(M - M_0)/b\}} \qquad (6)$$

Where:

fc': Compressive strength (N/mm^2); M: Maturity (DD),

Mo, a, b: Constants

Based on Figure 9, it can be concluded that the regression formula accurately reflects the results of compressive strength testing.

Table 3 Results of Compressive Strength Testing of Standard Curing(water cured) and Exposed Specimens

Specimen		Compressive Strength N/mm²					
Code	Curing	28days	91days	1year	5years	18years	20years
AF49	Standard Curing (water curied)	20.9	35.6	38.4	42.2	39.3	-
AF71		15.4	21.6	29.2	30.6	-	40.4
AF91		6.5	11.9	16.0	24.2	-	24.7
AF110		2.9	4.7	9.4	13.7	15.5	-
AF49	Exposure on Site	-	27.8	34.3	35.0	36.2	-
AF71		-	21.9	20.1	28.1	-	-
AF91		-	6.9	9.1	16.7	-	-
AF110		-	3.2	4.3	7.1	8.9	-

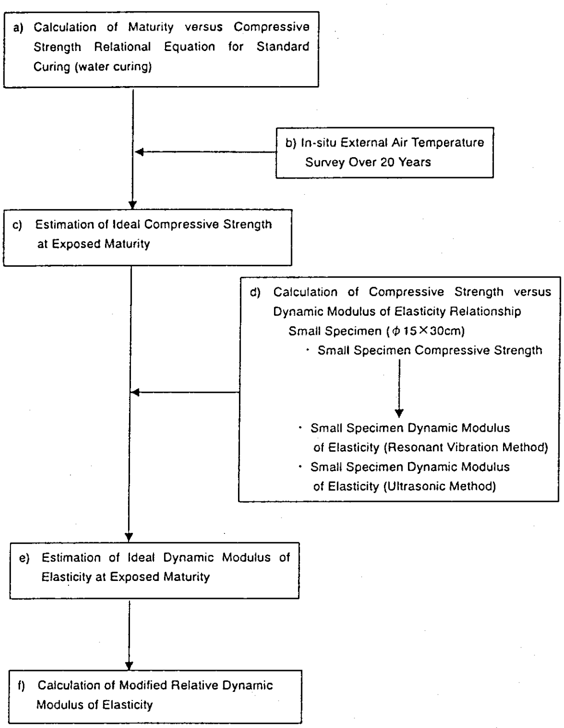


Fig. 8 Calculation Method for Modified Relative Dynamic Modulus of Elasticity after Strength Compensation

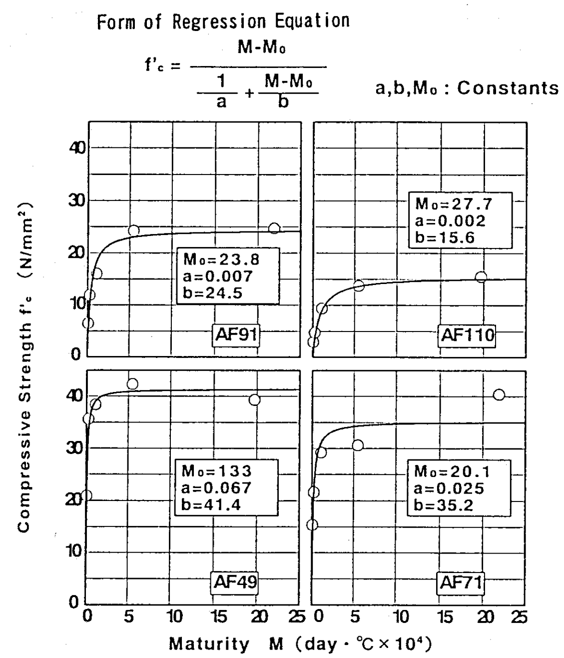
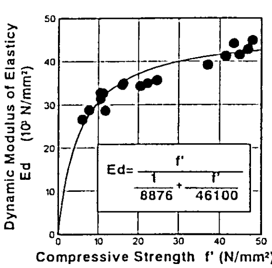
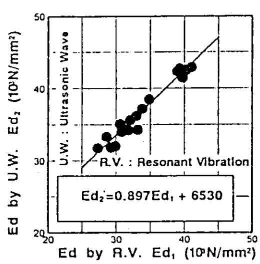


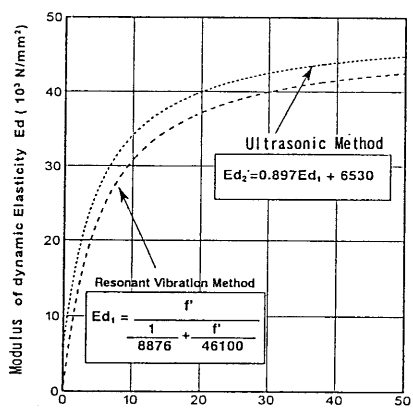
Fig.—9 Maturity and Compressive Strength Relationshi



(a) Compressive Strength and Modulus of Dynamic Elasticity Based on the Resonant Vibration Method



(b) Dynamic Modulus of Elasticity Based on the Resonant Vibration Metod and the Ultrasonic Method Relationshis



(c) Regression Curves of the Resonant Vibration Method and the Ultra Sonic Method

Fig.—10 Compressive Strength and Dynamic Modulus of Elasticity Relationship

b) Calculation of Exposed Maturity In-situ

The maturity was calculated based on daily average air temperatures during a 20-year period at the Midono Dam where the specimens were exposed. Maturity was calculated based on Formula (7) and (8) [12] with an exterior air temperature of 0℃ treated as the boundary.

When the exterior air temperature is above 0℃:

$$M = \sum t(\theta + 10) \qquad (7)$$

When the exterior air temperature is below 0℃:

$$M = 0.3 \cdot \sum t(\theta + 15) \qquad (8)$$

Where:

M: Maturity (DD); t: Age (days); θ: Exterior air temperature (℃)

c) Calculation of Ideal Compressive Strength for Exposed Maturity

The compressive strength was calculated under the hypothesis that no frost-induced deterioration under the exposed maturity (referred to as below as "ideal compressive strength").

The exposed maturity obtained as described in b) was substituted in the regression formula maturity and compressive strength found as described in a) to estimate the ideal compressive strength for a case where it is hypothesized that there is no frost-induced deterioration.

d) Calculation of the Compressive Strength - Dynamic Modulus of Elasticity Relationship

The relationship between the results of compressive strength testing performed at the same time as the freeze-thaw testing presented in Figure 1 and the dynamic modulus of elasticity obtained based by the resonant vibration method were regressed as shown in Figure 10(a). Measurements were performed prior to use of the specimen for freeze- thaw testing. Deflection vibration was used, and it was assumed that there is no discrepancy with the longitudinal vibration, particularly at the stage before it was subject to surface deterioration [14].

The dynamic modulus of elasticity versus compressive strength relationship obtained by the ultrasonic wave method was found using the resonant vibration method - ultrasonic wave method relationship (Figure 10(b)) because the ultrasonic wave method was not implemented at the same time as the testing shown in Figure 1. The results of regression of the resonant vibration method and the ultrasonic wave method are shown in Figure 10(c).

e) Calculation of Ideal Dynamic Modulus of Elasticity for Exposed Maturity

The ideal dynamic modulus of elasticity undamaged by frost at the exposure maturity was found. The relational equation of the ideal compressive strength at the exposed maturity found as described in c) with the dynamic modulus of elasticity found as described in d) was used to find the ideal dynamic modulus of elasticity at the exposed maturity.

f) Calculation of Modified Relative Dynamic Modulus of Elasticity

The modified relative dynamic modulus of elasticity was obtained based on equation (9) from the actual measured dynamic modulus of elasticity and the ideal dynamic modulus of elasticity under the exposed maturity found in section e).

$$REd_{md} = \frac{(Ed_m)_t}{(Ed_t)_t} \times 100\% \qquad (9)$$

Where:

REd_{md}: Modified relative dynamic modulus of elasticity (%);

$(Ed_m)_t$: Actual measured dynamic modulus of elasticity (N/mm^2) at age t;

$(Ed_i)_t$: Dynamic modulus of elasticity (N/mm^2) with no deterioration due to frost damage at age t.

(3) Change over Time of Modified Relative Dynamic Modulus of Elasticity

Figure 11 shows the changes over time of the modified relative dynamic modulus of elasticity obtained by compensating for the effects of increased strength during the exposure period. According to this figure, for any mix proportion, the relative dynamic modulus of elasticity is lower than the initial measured value, revealing the effects of the compensation. It also shows that the greater the water binder ratio, the smaller the relative dynamic modulus of elasticity and the more advanced the deterioration; a finding which coincides with the established theory that the greater the water cement ratio, the greater the deterioration [15].

(4) Calculation of Standardized Freeze-Thaw Cycle in a Natural Environment

In a natural environment, the minimum temperature of the exterior air acts on the concrete as an irregular value. Because during accelerated laboratory testing the minimum temperature is constant, the force that causes damage during each freeze-thaw cycle is constant, whereas the damaging force during each freeze-thaw cycle in a natural environment acts on the concrete as an irregular force because the minimum temperature is not constant.

So it is possible to evaluate the extent of irregular damage as the freezing and thawing cycle under a standardized temperature by using the standardized freezing and thawing cycle described above to weight the freezing and thawing cycle. In other words, the effect of repetition of an irregular minimum temperature can be evaluated by finding the frequency of the minimum temperature during the exposure period and, for each frequency, multiplying the minimum temperature for each water-cement ratio from Figure 5 by the corresponding weight as shown in equation (10). So Figure 5, obtained for concrete without an AE agent, evaluates the effects of the external force side. When it is applied to concrete containing an AE agent, differences on the bearing strength side, such as air quantity or the void spacing factor, are assumed to appear as discrepancies in the deterioration curve that is identified.

$$N' = \sum_{i=1}^{n}\{N'_i\} = [N_{ij}]\{\varphi_i\}$$

$$\{N'_i\} = \begin{Bmatrix} N'_{(1)} \\ N'_{(2)} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ N'_{(n)} \end{Bmatrix}, \qquad \{\varphi_i\} = \begin{Bmatrix} \varphi_{(0)} \\ \varphi_{(-0.5)} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \varphi_{(m)} \end{Bmatrix}$$

$$[N_{ij}] = \begin{bmatrix} N_{(1,0)} & N_{(1,-0.5)} & \cdot & \cdot & \cdot & N_{(1,m)} \\ N_{(2,0)} & N_{(1,-0.5)} & \cdot & \cdot & \cdot & N_{(2,m)} \\ \cdot & \cdot & & \cdot & & \cdot \\ \cdot & \cdot & & \cdot & & \cdot \\ \cdot & \cdot & & N_{(i,j)} & & \cdot \\ \cdot & \cdot & & \cdot & & \cdot \\ \cdot & \cdot & & \cdot & & \cdot \\ N_{(n,0)} & N_{(n,-0.5)} & \cdot & \cdot & \cdot & N_{(n,m)} \end{bmatrix} \qquad (10)$$

Where:

N': Standardized freeze-thaw cycle (cumulative value);

$\{N'_i\}$: Standardized freeze-thaw cycle at age I;

$[N_{ij}]$: Number of freezing and thawing cycles at age i and for minimum temperature j;

$\{\varphi_j\}$: Weight of minimum temperature j at the failure cycle when a certain water-cement ratio and minimum temperature j_0 are treated as the standard (both calculated based on Figure 5)

n: Evaluation age;

m: Lowest value of minimum temperature in-situ.

The number of freeze-thaw cycles $[N_{ij}]$ for age i and minimum temperature j can be calculated based on the exterior air temperature from the beginning of the exposure period. Figure 12 shows the number of freeze-thaw cycles during the exposure period at the Midono Dam in the case where freezing and thawing are both assumed to occur at 0℃ calculated for each 0.5℃ of minimum temperature.

(5) Standardized Freeze-Thaw Cycle and Modified Relative Dynamic Modulus of Elasticity

a) Standardized Freeze-Thaw Cycle

The standardized freeze-thaw cycle is a relative quantity calculated using a certain water-cement ratio and minimum temperature as a standard. For this reason, a standardized water-cement ratio and minimum temperature are needed.

At this time, the mix proportion AF49, with a water-binder ratio of 49%, is the standard for exterior concrete executed for dam construction, primarily to guarantee frost damage resistance and water tightness. This is identical to the mix proportion used at the Midono Dam. The standard minimum temperature (j_0) is - 5.7℃ ≒ - 6.0℃: the average value of the minimum temperature at the site

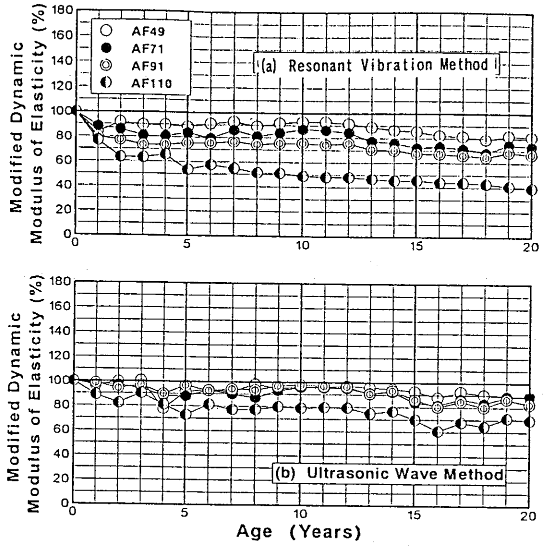


Fig. -11 Change Over Time in Modified Dynamic Modulus of Elasticity

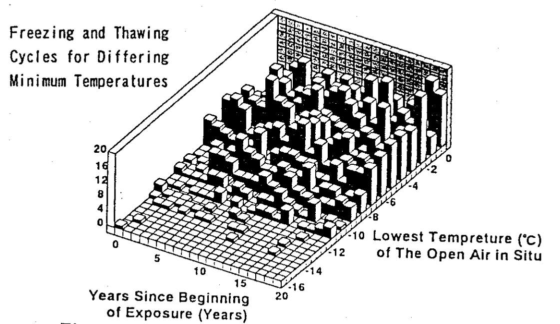


Fig.—12 Freezing and Thawing Cycles During Exposure Period

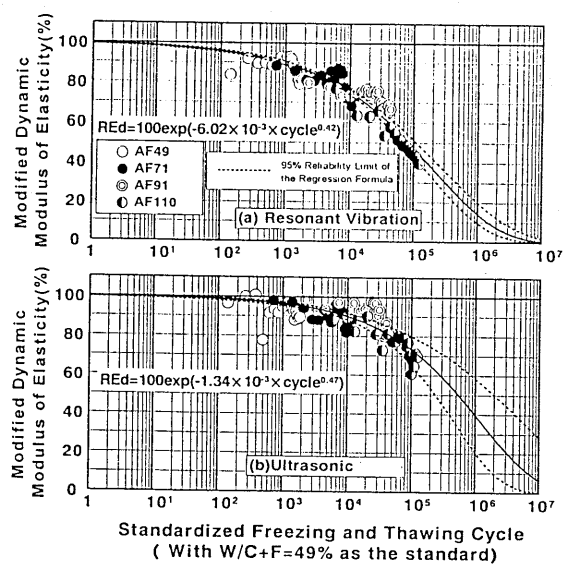


Fig.—13 Organization of Exposure Test Results Based on the Standardized Freezing and Thawing Cycle

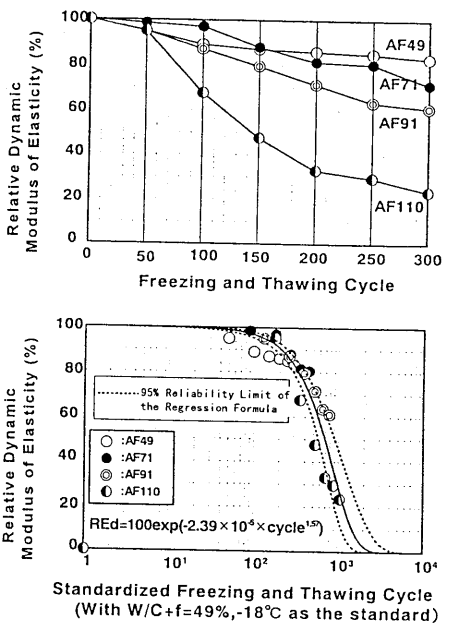


Fig.—14 Results of Laboratry Rapid Freezing and Thawing Testing of the \Concrete Used for the Exposure Testing

over a 20 year period. Based on this, the number of freezing and thawing cycles is calculated with a time when the weight $\{\varphi_j\}$ of the minimum temperature j on the failure cycle is a water binder ratio of 49% and a lowest temperature of - 6℃ is the standard. So, the number of freezing and thawing cycles is transposed with cases when the temperature is greater than - 6℃ , apparently it is lower than the frequency of its occurrence, and when the temperature lower than - 6℃, apparently, it is greater than the frequency of its occurrence. Its apparent weight is found based on the relationship shown in Figure 5.

b) Standardized Freeze-Thaw Cycle and Modified Relative Dynamic Modulus of Elasticity

Figure 13 shows the results of organizing the axis of abscissa of the change over time of the modified relative dynamic modulus of elasticity after the strength compensation presented in Figure 11 according to the standardized freezing and thawing cycle N', based on the standardized freezing and thawing cycle N' calculated above using $\{\varphi_j\}$ and $[N_{ij}]$. It shows that for all water binder ratios, the relationship between the standardized freeze-thaw cycle and the modified relative dynamic modulus of elasticity can be represented by a single curve as revealed by the results of the organization of laboratory experiments, even in a natural environment with an irregular lowest temperature.

It is possible to conclude that these deterioration curves equivalently represent the state of deterioration in a case where concrete with a water -binder ratio of 49% is placed in conditions where the lowest temperature is - 6℃.

4. CONMPARISON WITH RAPID FREEZE-THAW TEST

(1) Rapid Freeze-Thaw Test Results

Figure 14 shows the results of laboratory rapid freezing and thawing tests executed at the beginning of exposure using concrete specimens prepared from the same batch used to make the natural exposure test samples. Also show are the results of an organization by standardized freeze-thaw cycle. In this case also, the results can be represented by a single deterioration curve using the standardized freeze-thaw cycle and the effects of the water-binder ratio can be evaluated based on a lowest temperature of - 18℃. But the age at the beginning of testing was 1 year, later than in the present tests.

(2) Correction of Age at Beginning of Testing

In order to compare the results of in-situ exposure tests with the results of laboratory accelerated tests, the age at the beginning of laboratory testing must be replaced with a case where the testing was done at a standard age before the test results are evaluated. The current standard age at the beginning of freeze-thaw testing is 14 days, but in the case of dam concrete, the guaranteed age for the specified concrete strength is long at 91 days. And to account for the period until it is provided for use and for the curing conditions, the age at beginning of testing is widely set at 28 days. So based on the results of testing of material with an age of 1 year when the testing began, the rest results were corrected to results for testing with an initial age of 28 days.

Case AF49 is the standard for the discussion that follows. Because the pore size distribution was not measured when the exposure testing shown in Figure 14 began, the frozen pore ratio is estimated from compressive strength.

Because it is known that there is good correlation between pore quantity and compressive strength even win varying the age and water-cement ratio, in this estimation, it was assumed in this estimation that if the compressive strength is constant, the pore quantity will vary little. The strength of concrete varies considerably according to age and water-cement ratio even in cases where identical materials are used. This is, fundamentally, a result of changes in the solid phase quantity accompanying hydration of the cement according to age and water cement ratio. For example, Sone [16] performed an experimental study of the relationship between concrete compressive strength and total pore quantity by varying the type of cement and the curing temperature over wide ranges, reporting that the relationship be represented using an exponential function regardless of the age of the material. And Miura et al. [17] have reported that the same relationship in concrete with varying water-cement ratios and air quantities can be represented by a single hyperbolic function regardless of age.

The above findings indicate that the frozen pore ratio of AF49 at 28 days of aging is equivalent to that of concrete with a certain water-binder ratio and indcating the same strength at one year.

In the case of concrete containing fly ash, in order to hypothesize that the pore structure of the concrete is equivalent after age compensation on the basis of compressive strength, it is necessary in the strictest sense to perform a study to account for the degree of progress of the Pozzolanic reaction. However, since as in the case of ordinary cement the strength of fly ash cement depends on the quantity of voids with a radius equal to or greater than 25 nm [18], and that pore diameters with a diameter ranging from 10 nm to several 100 nm contribute to freezing in the lowest temperature range down to - 18℃[19], it is possible to indirectly represent the quantity of pores that contribute to freezing in terms of strength.

In the relationship between water-binder ratio and compressive strength presented in Figure 15, the compressive strength of AF49 at 28 days of aging is equivalent to compressive strength at a water-binder ratio of 76% at 1 year of age. From the above hypothesis, the advance in deterioration of AF49 in a case where the age at the beginning of testing is 28 days is assumed to be equivalent to the deterioration of AF76 with an age at the beginning of testing of 1 year. Freeze-thawing testing of AF76 was not performed, but because it is possible to oefficient φ from Figure 5.

(3) Comparison of Exposure Testing and Accelerated Testing

a) Comparison with Small Exposed Specimen

Figure 16 presents compares exposure testing with accelerated testing. In both cases, it is done by varying the dynamic modulus of elasticity found using the resonant vibration method. Of the accelerated test results, those performed with an age at the beginning of testing of 28 days were compensated based on the method described in (2). Table 4 presents the results of applying the regression formula presented in Figure 16 to determine the number of cycles for which the relative dynamic modulus of elasticity, which the authors treat as the failure criterion, falls below 60%. The resonant vibration method was used to calculate the dynamic modulus of elasticity in both accelerated testing and natural exposure testing, but deflection vibration was used for the former and longitudinal vibration for the latter case. Because no clear differences have been observed between these has methods in tests implemented by other organizations participating in this long-term exposure testing program[20], it is assumed that discrepancies caused by the different modes of vibration are small.

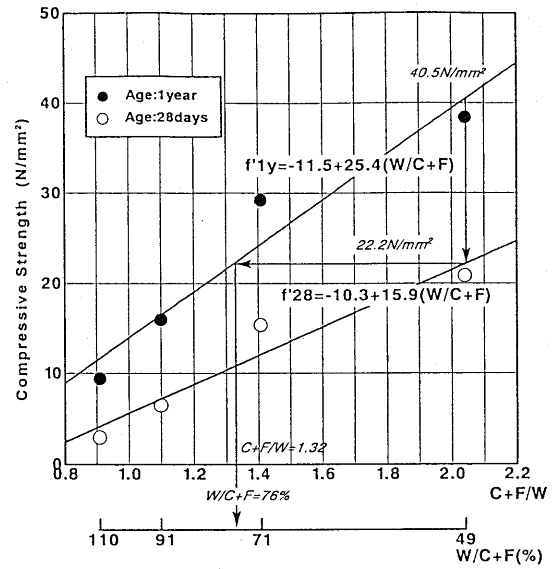


Fig.—15 Equivalent Water Binder Ratio (%) With 28 Days as the Age at Beginning of Testing

Table 4 Number of Cycles With the Relative Dynamic Modulus of Elasticity Below 60%

Conditions / Regression Formula	① On Site Exposure Standard of -6℃	② Laboratory Acceleration	③ On Site Exposure Standard of -18℃
(A)Core Value	41,000	290	840
(B)95% Upper Limit	54,400	380	1,090
(C)95% Lower Limit	32,100	240	650

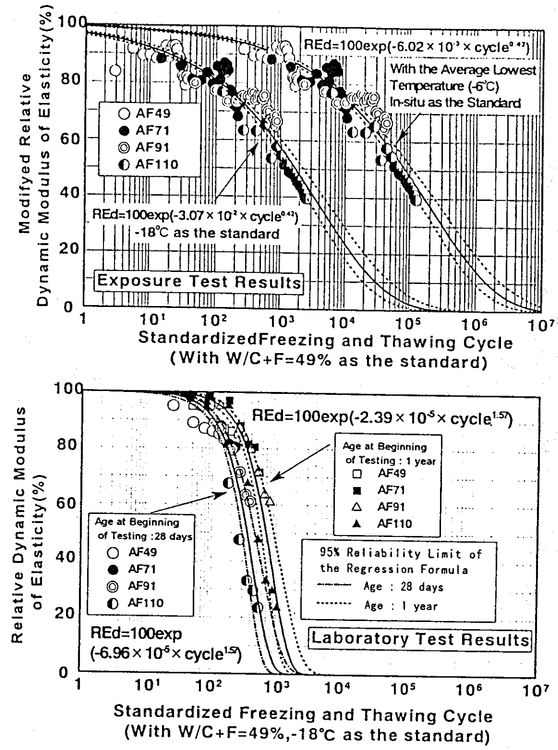


Fig.—16 Comparison of Exposure Testing and Laboratory Accelerated Test

First, the exposure test results standardized at an average in-situ minimum temperature of -6℃ are compared with the accelerated testing results (comparison of ① and ② in Table 4).

Assuming that it is possible to evaluate the acceleration property based on the ratio of the number of cycles in which the relative dynamic modulus of elasticity fell below 60%, in a case where it is compared at the center of the regression formula, the number of cycles is 41,000 for natural exposure testing but 290 cycles for the accelerated testing, revealing that accelerated testing is equivalent to 140 times the effect of natural exposure at the Midono Dam reservoir. Considering scatter, this acceleration ranges from 80 times to 230 times.

Next, the effects of freeze-thaw rate in the accelerated tests are compared (comparison of ② and ③ in Table 4). Assuming that the exposure test result was a lowest temperature of - 18℃, when it was compared at the center of the regression formula, the number of cycles where the relative dynamic modulus of elasticity was below 60% was 840 cycles and 290 cycles during the accelerated testing. Consequently, if the minimum temperature of accelerated testing is identical to that at the site, the acceleration effect is 2.9 times according to differences in the freezing and thawing rate. Considering scatter, it ranges from 1.7 times to 4.5 times.

In the minimum temperature versus failure cycle relationship presented in Figure 5, at a water-cement ratio of 49%, the failure cycles for temperatures of -18℃ and -6℃ are 14 and 673 cycles, respectively, indicating an acceleration effect of 48 times. Figure 5 was obtained from accelerated testing, and the freeze-thaw rate at that time was maintained at almost 9℃/hour, so the effects of freeze, thaw rate are assumed to be small. Assuming therefore, that this is affected only by the minimum temperature, multiplying this multiplier of 48 by 2.9, which is the multiplier of the acceleration effect of the above freeze-thaw rate, results in a value of 139 times, which is almost exactly the same as the multiplier of 140 obtained by comparing the results of exposure testing standardized by the average value of the minimum temperature at the site with the accelerated test results.

According to the above study, the minimum temperature has an extremely great effect on concrete frost damage. This result coincides with an earlier report based on laboratory test results [4].

5. CONCLUSIONS

The results obtained by this study are summarized below.

(1) A linear relationship was observed between the number of freeze- thaw cycles to failure in common logarithm form and the frozen pore ratio. Given that a relationship of this kind is observed, the progress of deterioration caused by freezing and thawing can be treated as a fatigue problem; that is ,it is a cumulative worsening of damage.

(2) Taking the number of freeze-thaw cycles until failure at a given water-cement ratio and minimum temperature as a reference, it is possible to simultaneously represent the effects of water-cement ratio and minimum temperature by finding its ratio to the number of freeze- thaw cycles until failure at another water-cement ratio and minimum temperature and, treating this as a weighting coefficient, standardize it by multiplying it by the number of freeze-thaw cycles for each water- cement ratio and minimum temperature.
This standardized freeze-thaw cycle can then be used to estimate the deterioration curve for a given water-cement ratio and minimum temperature.

(3) If the effect of increasing dynamic modulus of elasticity accompanying the rise in strength in a natural environment is corrected using the maturity, the extent of deterioration caused by the freezing and thawing versus water-binder ratio elevation relationship coincides, and the lower the water-binder ratio, the more durable the concrete.

(4) Even in a natural environment where the minimum temperature is irregular, it is possible to account for the effects of minimum temperature using the standardized freeze-thaw cycle, and it is also possible to estimate the deterioration curve at a given minimum temperature.

(5) It is possible to contrast laboratory accelerated testing with exposure testing using the deterioration curve for any minimum temperature, and it is also possible to quantitatively evaluate the acceleration effect of laboratory acceleration testing to a certain degree.

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