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Study Concerning Examination and Analysis of Equation for Estimating Deterioration in Evaluating the Service Life of a Concrete Structure*

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Abstract

This paper deals especially with the examination and consideration of an equation for predicting deterioration in evaluating the service life of concrete structures. In this study, the equation for estimating deterioration of the surface of concrete in a cold sea environment was begun with the analysis of laboratory tests and experiment test in which the concrete was exposed to such an environment.

1. Introduction

1.1 Background

Recently, calculation of the cost of a structure in terms of its life cycle (life cycle cost) and the quantifying of the service life of concrete structures have been of particular concern, along with the establishment of rational and objective techniques for quantifying the durability of new structures at the planning stage. There is a need for an improvement in terms of durability and the progress of deterioration needs to estimated in a more reliable manner. The reliability of such methods is established by the pursuit of investigation of existing structures through simulation tests using data obtained from model specimens of RC members, etc. Furthermore, it is necessary to test the appropriateness and accuracy of the terms in which the estimation of the progress of deterioration is expressed in the case where model specimens are exposed to the actual environment in the acceleration test.

1.2 Purpose of this Study

The purpose of this study is to investigate how accurate the equation for estimating the progress of deterioration is. This is done by an analysis of the data obtained from the laboratory test and previously obtained data when compared with the results of the test in which the samples are exposed. We see if

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there is an improvement in reliability. The quantifying item investigated for quantification is the surface deterioration which took place in a cold sea environment.

2. Investigation Method and Data

2.1 Investigation Method

2.1.1 The Process of Investigation

The flow diagram of the investigation of the equation for estimating deterioration in order to evaluate how many years the RC structure would be in service (service years of RC structure) is shown in Fig. 1.

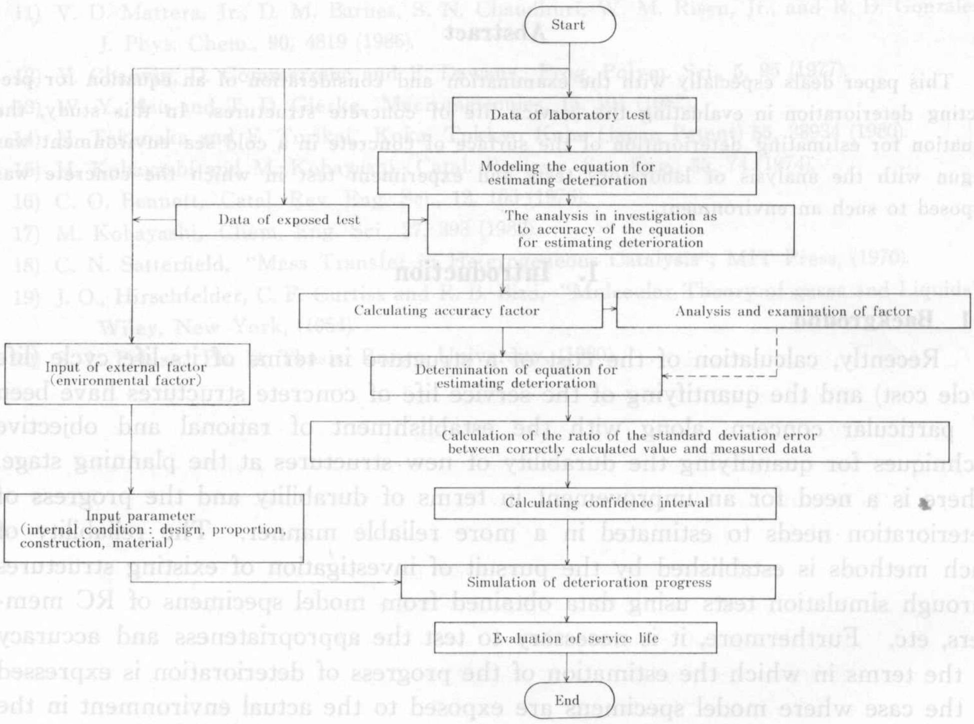

Fig. 1. The flow of investigation of an equation for estimating deterioration for evaluating service years of RC structure.

2.1.2 The Analysis Method in Investigating of the Accuracy of the Equation for Estimating Deterioration

The change in conditional variance can be expressed by the following equation.

$$\mathrm{Val}(Y|x) = \sigma^2 g^2(x) \qquad (1)$$

Where the value of $g(x)$ is assumed to be same as in the following equation.

$$g(x) = Cx \qquad (2)$$

C is then calculated by liner regression analysis. Where σ is unknown constant.

Furthermore, it is defined by the following liner regression equations;

$$E(Y|x)=\theta+\omega x \tag{3}$$

It is assumed that the area, which has the smaller variance and the smaller calculation value, has a larger weight than that which has the larger calculation value. The weight is assumed to be defined by the inverse proportion. i. e. it is expressed as the following,

$$W_i'=\frac{1}{\mathrm{Val}(Y|x_i)}=\frac{1}{\sigma^2 g^2(x_i)} \tag{4}$$

Accordingly, the square error is expressed as follows,

$$\Delta^2=\Sigma W_i'(y_i-\theta-\omega x_i)^2 \tag{5}$$

Therefore, the estimation of least squares is as follows,

$$\hat{\omega}=\frac{\Sigma w_i(\Sigma w_i y_i x_i)-(\Sigma w_i y_i)(\Sigma w_i x_i)}{\Sigma w_i(\Sigma w_i x_i^2)-(\Sigma w_i x_i)^2} \tag{6}$$

$$\hat{\theta}=\frac{\Sigma w_i y_i-\hat{\omega} w_i x_i}{\Sigma w_i} \tag{7}$$

Where,

$$w_i=\sigma^2 W_i'=\frac{1}{g^2(x_i)} \tag{8}$$

The non partial estimation is expressed as follows,

$$S^2=\frac{\Sigma w_i(y_i-\hat{\theta}-\hat{\omega}x_i)^2}{n-2} \tag{9}$$

Accordingly, the estimation of conditional variance is given by following expression,

$$S^2_{Y|x}=S^2 g^2(x) \tag{10}$$

The variance is as follows,

$$S_{Y|x}=Sg(x) \tag{11}$$

2.2 The Data for Investigation

The data under investigation are the measured data, which are of the average damage depth measured in the exposed specimens, data in a cold sea environment, and the calculation value. The environmental data for from the external factors and the material, proportion and construction data obtained from the inner factors are shown in Table 1. It is assumed that the relationship between the surface deterioration (deterioration indicator) and other deterioration indicators is the relationship as shown in Table 2. The exponent of (W/C)/55 in the equation for estimating the progress of deterioration as shown in Table 3 is 3. The calculation value is obtained by the factor of scaling in Fig. 2. The measurement data is shown in Table 4.

Table 1. Environmental data from external factors and material, proportion and construction data from inner factors

External factor		Internal factor					
Cycles of freeze-thaw a year (cycles)	Distance from sea (sea side) (m)	No.	C · W/C · CC · CD	No.	C · W/C · CC · CD	No.	C · W/C · CC · CD
59.4 (the average 8 years)	From 30 to 50 (Seasonal change)	1	N 55 F* 0	8	F B 55 F 0	15	B B 55 F 0
		2	N 55 F 5**	9	F B 55 F 5	16	B B 55 F 5
		3	N 55 F 14	10	F B 55 F 14	17	B B 55 F 14
		4	N 55 S* 5	11	F B 55 S 5	18	B B 55 S 5
		5	N 45 F 5	12	F B 45 F 5	19	B B 45 F 5
		6	N 45 F 14	13	F B 45 F 14	20	B B 45 F 14
		7	F A 55 F 5	14	F C 55 F 5		

*F: Fresh water curing, S: Sea water curring

**: Specimen measuring temperature is the same mix proportion as N55F5 Specimen.

Note C: cement, W/C: water cemen ratio, CC: curing condition, CD: number of curing days

Table 2. The relationship between surface deterioration (deterioration indicator) and other deterioration indicators

Item	Deterioration Phenomenon											
	Neutralization	Reinforcing Steel Corrosion	Crack	Deterioration of Strength	Deformation	Frost Damage	Surface Deterioration	Dry Shrinkage and Thermal Shrinkage	Alkali-Aggregate Damage	Strain of Creep	Diffusion of Chloride	Crack of Steel Stress	Diffusion of Sulfate
Surface deterioration (Average depth of damage : mm)						■	○						

Note ○ : Deterioration phenomenon subordinates other deterioration phenomenon and it is not converted to deterioration indicator.
■ : Deterioration phenomenon subordinates other quantifying item and it is converted to deterioration indicator.

Table 3. The deterioration indicator, factor and equation for estimating surface deterioration

Quantifying Item	Selected Indicator		Factor [ ] variable		Calculation of Deterioration Indicator (durability) at Lapse of Year	Grading
	Indicator	Phenomenon	External Factor	Inner Factor		
g. Surface deterioration	Average depth of damage H (mm)	① Surface deterioration of frost damage	[t: Service life (year)] N: Cycles of freeze-thaw year W: Coefficient of supplying seawater	W/C: Water cement ratio (%) α: Coefficient of type of cement and curing condition fc: Compressive strength of concrete K: Rate of decreasing surface strength	$H=W\cdot\alpha(N^{\left(\frac{W/C}{55}\right)^3}-(0.001195k^2\cdot fc^2)^{\left(\frac{W/C}{55}\right)^3})\ 20)$	0: $H<1$ 1: $1\leqq H<2$ 2: $2\leqq H<3$ 3: $3\leqq H<4$ 4: $4\leqq H$

Note 1) β: The ratio of distance from axial of neuturality to center of reinforcing steel to distance from axial of neuturality to tensile side in the case of beam 1.2.

A: The area of tensile side concrete of symmetry with steel number of reinforcing steel.

Note 2) Superpose the development strength at the age

$$\begin{bmatrix} SN=-55.32+16.60\ln(365t) \\ DN=-41.49+12.54\ln(365t) \end{bmatrix}$$

Note 3) ε_{te}: Total contraction after peak temperature due to heat of hydration.

Table 4. The measured data (mm) of exposure test

Specimen \ Lapse year (year)	2	3	4	5	6	7	8
N 55 F 5 (1)	0.002	0.005	0.006	0.008	0.009	0.028	0.040
N 55 F 5 (2)	0.003	0.008	0.009	0.012	0.014	0.016	0.034
N 55 F 14	0.001	0.002	0.002	0.011	0.003	0.004	0.007
N 45 F 5	0.001	0.005	0.005	0.003	0.005	0.010	0.014
N 45 F 14	0.0002	0.0004	0.001	0.001	0.002	0.001	0.004
FA 55 F 5	0.005	0.009	0.010	0.011	0.010	0.026	0.049
FB 55 F 5	0.008	0.012	0.019	0.024	0.017	0.052	0.121
FB 55 F 14	0.004	0.009	0.009	0.011	0.013	0.031	0.078
FB 45 F 5	0.003	0.008	0.006	0.009	0.010	0.013	0.027
FB 45 F 14	0.002	0.005	0.006	0.008	0.008	0.012	0.032
FC 55 F 5	0.024	0.042	0.059	0.063	0.064	0.131	0.317
BB 55 F 5	0.044	0.097	0.093	0.114	0.105	0.243	0.364
BB 55 F 14	0.016	0.112	0.074	0.072	0.073	0.153	0.343
BB 45 F 5	0.006	0.013	0.018	0.020	0.021	0.036	0.050
BB 45 F 14	0.002	0.004	0.004	0.006	0.005	0.009	0.027

3. The Result of Investigation and Examination

3.1 The Result of Investigation

3.1.1 The Relation Between Calculation Value and Measuring Value

The relationship between the number of curing days and the scaling factor which is the least square error analysis of the exposure test data, while the coefficient of sea water (W) supply is defined as 0.01 is shown in Fig. 2. In this relation, the factor of scaling tends to decrease with an increase in the number of curing days. Therefore, in 5 days curing the scaling factor of Portland blast-furnace cement type B and Portland fly-ash cement type B were 10.1 times and 2.6 times greater respectively compared to Normal Portland cement.

The relationship between the calculated value and the measured value is shown in Fig. 3. In this relationship, the measured value tends to be greater when the calculation value is small. Because there is the tendency of occurrence of popout. There is the tendency that the larger calculation value shows the smaller variation.

3.1.2 The Accuracy of the Calculation Value

In order to confirm the accuracy of the calculation value, the limit of measured data to calculated data was calculated by the method shown in 2. 1. 2.

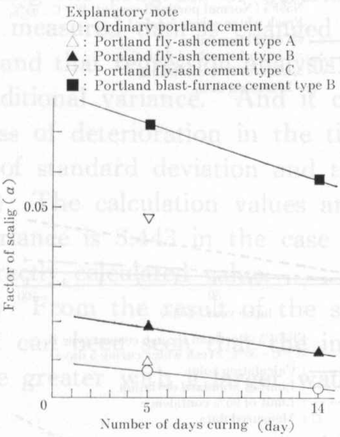

Fig. 2. The relationship between the number of days of curing and the factor of scaling (α).

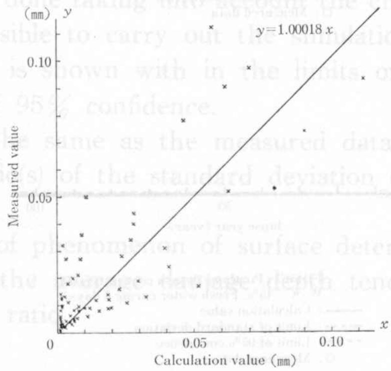

Fig. 3. The relationship between the calculated value and the measured value.

Table 5. The accuracy factor (C) of measured data to calculated value and the ratio (S) of the standard deviation error between correctly calculated value and measured data to correctly calculated value

The accuracy factor C $\left(\frac{\text{Measured data}}{\text{Calculation value}}\right)$	The ratio S $\left(\frac{\text{Correctly calculation value}}{\text{Standard deviation}}\right)$
1.00018	3.44347

First, the ratio of the measured data to the calculated value was calculated and defined as the accuracy factor C. The ratio (S) of standard deviation error between correctly calculated value, which is multiply by the correctness factor (the correctness calculation value being $g(x)$), and the measured data to the correctly calculated value is shown in Table 5. In this calculation, the variance is 3.44347 at the ratio (S) which is the standard deviation error between the correctly calculated value and the measured data divided by the former.

3.2 Examination

3.2.1 Simulation of Progress of Deterioration

The simulations of the progress of deterioration and the limit of each of the factors of the exposed specimens of FB55F5 and FB45F5 are shown in Fig. 4 and Fig. 5. In these figures, the limit of standard deviation and the limit of 95% confidence can be compared to the correctly calculated value. The measured data of the exposure experiment specimens are shown, too. According to these, the calculation values have almost the same value as the measured data. Furthermore, according to the results of the simulation with the larger water cement

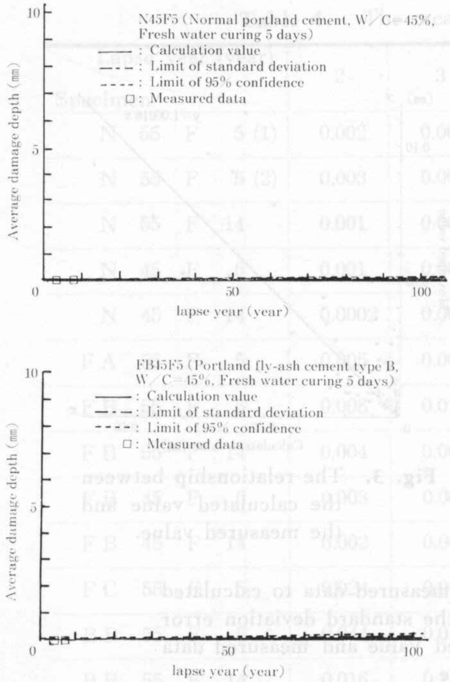

Fig. 4. The estimation of deterioration progress (surface scalling) and the range (W/C=45%)

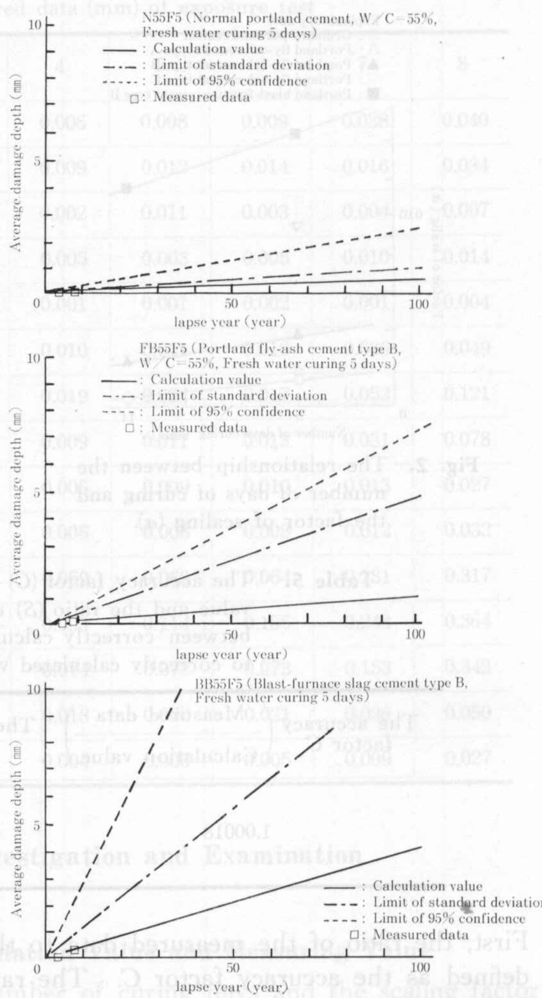

Fig. 5. The estimation of deterioration progress (surface scalling) and the range (W/C=55%)

ratio as shown in Fig. 4, the average damage depth tends to be great. There is a larger increase in the average damage depth than with that of the smaller water cement ratio.

3.2.2 The Improvement in the Accuracy of the Equation for Estimating Deterioration

In order to improve the accuracy of the equation for estimating the progress of deterioration from now on, the function type of the expression must be considered with factors such as the mix proportion of the water cement ratio, and so on, by multiple regression analysis etc.. And it may be possible to confirm results more accurately by using simulation with data from existing structures.

4. Conclusion

According to the examination and analysis of the equation for estimating deterioration to evaluate the service life of a concrete structure, the following have been made clear.

(1) As the method of analysis to confirm the accuracy of the equation for

estimating the progress of deterioration, it is effective to assume that the limit of the measured data is changed with the calculation value, which is a control value, and that regression analysis should be done taking into account the change of conditional variance. And it can be possible to carry out the simulation of progress of deterioration in the time which is shown with in the limits of the range of standard deviation and the limit of 95% confidence.

(2) The calculation values are nearly the same as the measured data and the variance is 3.443 in the case of the ratio(s) of the standard deviation error to correctly calculated value.

(3) From the result of the simulation of phenomenon of surface deterioration, it can been seen that the increase of the average damage depth tends to become greater with a larger water cement ratio.

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