Prediction and Evaluation of Service Life of Concrete Structure in cold Regions*

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Abstract

With the growing amount of concrete in the capital infrastructure, the maintenance and management burden is increasing and the calculation of life-cycle-cost and service lifetime are gaining in importance. The design, construction, maintenance, and management of structures raises the following questions: (1) Will the concrete structure provide service over its lifetime without reinforcement and repair? (2) How will performance and safety deteriorate if the structure is left alone? (3) How can current durability designs be checked? Accordingly, there is a need to predict the deterioration and service life of concrete structures. A method of achieving this needs to be established as soon as possible. The purpose of this study is to develop a technique for predicting and evaluating the service life of concrete structure (reinforced concrete [RC] structures) design in cold regions through predicting deterioration. This paper describes the development of a technique and a case-study in which the technique is applied to a tentative model. The case-study results show that the water-cement ratio and depth of cover over reinforcing steel influenced deterioration over time due to neutralization and steel corrosion. Between some cases of choosing of the rate, several-fold variations in neutralization depth and a factor of two in the time until the onset of steel corrosion were recognized. As shown in Fig. 4, it was determined that the difference in synthetic degree of deterioration was 20% at 50 years after construction.

1. INTRODUCTION

With the growing amount of concrete in the capital infrastructure, the maintenance and management burden is increasing and the calculation of life-cycle-cost and service lifetime are gaining in importance.

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The design, construction, maintenance, and management of structures raises the following questions: (1) Will the concrete structure provide service over its lifetime without reinforcement and repair? (2) How will performance and safety deteriorate if the structure is left alone? (3) How can current durability designs be checked? Accordingly, there is a need to predict the deterioration and service life of concrete structures. A method of achieving this needs to be established as soon as possible.

The following problems are presented in the prediction and evaluation of these characteristics: (1) There are many kinds of deterioration which affect the life of a concrete structure, and many factors influence deterioration. It is a complex matter. (2) The relationship between design and service life is not well understood because almost no design and construction data for existing structure have been preserved. (3) The inspection data of structures are not being put to practical use. (4) Techniques of maintenance and management are not well established and those in the field do not take it seriously enough. (5) The durability assessment of concrete structures is only now being developed in Japan and abroad and is not yet mature enough to meet the demands of the fields.

The purpose of this study is to develop a technique for predicting and evaluating the service life of concrete structures (reinforced concrete [RC] structures) designed in cold region through predicting deterioration. This paper describes the development of a technique and a case-study in which the technique is applied to a tentative design model.

2. METHOD

2.1 Development of Prediction and Evaluation Methods

The method is able to predict the deterioration and evaluate the service life of RC structures designed for cold climates. Initially, the essential criteria for deterioration-prediction were studied. Because deterioration-prediction must take into consideration the importance of the structure and its component members, it was divided into two levels: the general level (level 1) and a level in which greater accuracy is demanded such as for structural members of particular importance, safety, function, or demanding maintenance-free installation (level 2). In this study, level 1 of deterioration prediction was considered.

Next, the following issues were studied to develop a system able to predict deterioration: [1] (1) The choice of indicators of prediction and evaluation. (2) The procedure for prediction and evaluation (Fig. 1). (3) The collation and analysis of existing studies and experimental data. (4) A deterioration-prediction equation. (5) The grading of deterioration. (6) The weighting of predictions and evaluations. As shown in Table 1, this led to suggestions for the method of prediction and evaluation of deterioration of RC structure.

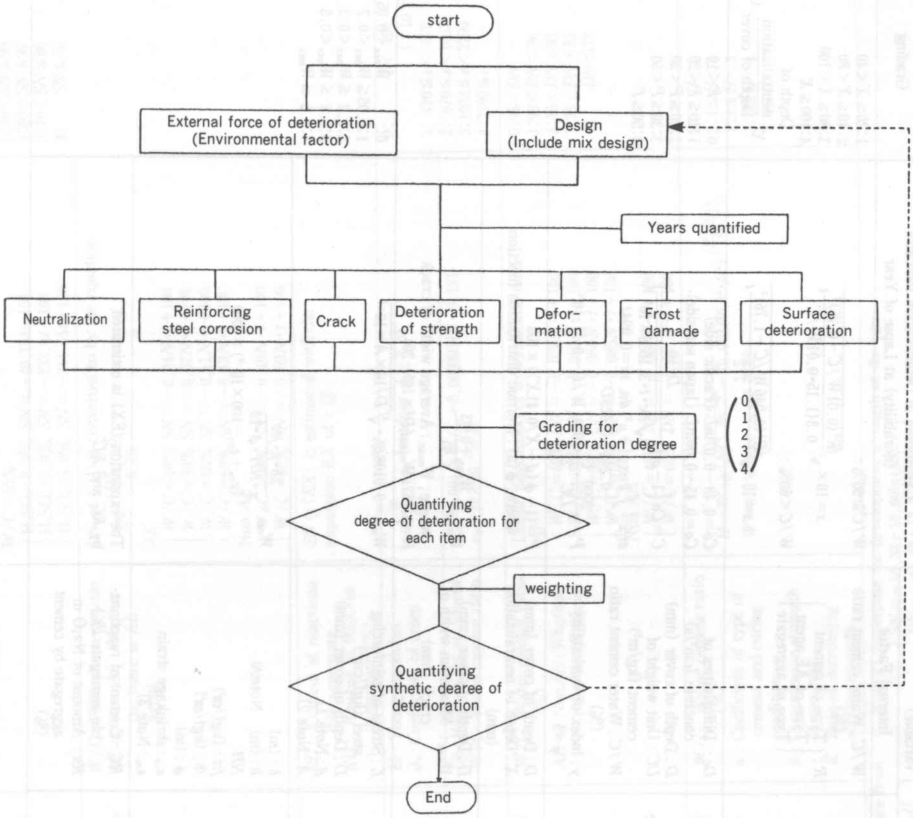

Fig. 1 The prediction and evaluation procedure for RC structures

Table 1 (a) Deteirioration indicator, factor, calculation, and grading for items quantified

Quantifying Item	Selected Indicator		Factor ([ ] variable)		Calculation of Deterioration Indicator (durability) at Lapse of Year	Grading
	Indicator	Phenomenon	External Factor	Internal Factor		
a. Neutralization	Depth of neutralization x (mm)	① Neutralization	[t: Service life (year)]	W/C: Water cement ratio (%) R: {Type of cement, Type of AE agent, Type of aggregate}	$W/C \geqq 60\%$: $x=10\times\sqrt{\frac{R^2(0.01W/C-0.25)^2}{0.3(1.15\cdot0.01W/C}t}$ $W/C<60\%$: $x=10\times\sqrt{\frac{R^2(0.046W/C-1.76)^2}{7.2}t}$	1: $20\leqq X<40$ 2: $40\leqq X<80$ 3: $80\leqq X<100$ 4: $100\leqq X$ X: $\frac{\text{Depth of neutralization}}{\text{Depth of cover}}$ (%)
b. Reinforcing steel ctmmosion	Ratio of corrosion surface P (%)	① Corrosion of penetrating chloride	[t: Service life (year)] L: Distance from sea (m) Co: Amount of chloride from sea (wt%)	Dc: Diffusivities of concrete (cm²/s) D: Depth of cover (mm) UC: Unit weight of cement (kg/m³) W/C: Water cement ratio (%) γ: Index of workability: $\gamma=1$	$Co=0.48-0.07\ln L$ (Pacific side) $Co=0.45-0.06\ln L$ (Japan sea side) $C=Co\left(1-erf\frac{D/10}{2\sqrt{Dc\cdot t\cdot 3.1536\times10^7}}\right)$ $erfx=\int_0^x \exp(+\mu^2)\,d\mu,\ m=0.094t+0.245-0.029D$ $P=\gamma\frac{2000}{UC}\cdot\frac{C}{2}\cdot(0.01W/C-0.3)\cdot10^m$	0: $P<10$ 1: $10\leqq P<20$ 2: $20\leqq P<30$ 3: $30\leqq P<50$ 4: $50\leqq P$
		② Corrosion of neutralization		D: Depth of cover (mm) X: Depth of neutralization (mm)	$P=(1-\phi(d-X/0.41X))\times100$ where; ϕ(a): Normal distribution function	
		③ Corrosion of crack		D: Depth of cover (mm) W_{max}: Maximum width of crack (mm)	$W_{mean}=\frac{W_{max}+0.03}{1.91}$ where; W_{mean}: Average width of crack $P=0.167(W_{mean}/D^2\times10^6-20)$	
c. Crack	Maximum width of crack (mm)	① Crack of steel stress		f_s: Stress of reinforcing steel (kgf/cm²) D: Depth of cover (mm) β: Note 1) A: Note 2)	$W_{max}=0.0108\beta f_s\cdot\sqrt[3]{D/10\times A}\times10^{-3}$	0: $W_{max}<0.05$ 1: $0.05\leqq W_{max}<0.2$ 2: $0.2\leqq W_{max}<0.3$ 3: $0.3\leqq W_{max}<0.5$ 4: $0.5\leqq W_{max}$
		② Cracp of dry and temperature shrinkage	TC: Change of temperature (°C)	b: (m) h: (m) Note(A) NH: fct: (kgf/cm²) fb: (kgf/cm²) ϕ: (m) ε_{cs}: shrinkage strain ε_{te}: Note 3)	$W_{max}=\frac{2b\cdot h\cdot fct}{\pi\cdot NH\cdot\phi\cdot 1b}(\varepsilon_{cs}+\varepsilon_{te}-100\times10^{-6})\times1000$	
		③ Crack of alkali silica reaction		RG: Content of reactionable aggregate (%) Ru: Amount of Na_2O in aggregate by cement (%)	The expansion (EX) is estimated by RG and RU	

Note(A) b: Width of the section(m), h: Depth of the member(m)
NH: Number of steel members

Table 1(b) Continued

Quantifying Item	Selected Indicator: Indicator	Selected Indicator: Phenomenon	Factor ([ ] variable): External Factor	Factor ([ ] variable): Internal Factor	Calculation of Deterioration Indicator (durability) at Lapse of Year	Grading
d. Deterioration of strength	Notes 2) Ratio of compressive strength SN (%)	① Deterioration of penetrating sulfate	[t: Service life (year)]	W/C: Water/cement ratio	Linear Regression of experimental data $W/C=55\%$ H_2SO_4: 0.3%, $SN=-40.15t+100$ H_2SO_4: 2.0%, $SN=-233.6t+100$ H_2SO_4: 5.0%, $SN=-244.55t+100$	0: $95<SN$ 1: $90<SN\leqq 95$ 2: $80<SN\leqq 90$ 3: $70<SN\leqq 80$ 4: $SN\leqq 70$
		② Deterioration of frost damage	[t: Service life (year)] N: Cycles of freezethaw a year	W/C: Water/cement ratio AE or Non AE: Whether the there is AE agent	DN of f. ① is converted to by the equation $SN=\frac{DN-25}{0.75}$ AE $W/C=40\%$ $SN=-0.04N\cdot t+100$ $W/C=50\%$ $SN=-0.07N\cdot t+100$ $W/C=55\%$ $SN=-0.11N\cdot t+100$ $W/C=60\%$ $SN=-0.12N\cdot t+100$ Non AE $W/C=30\%$ $SN=-0.49N\cdot t+100$ $W/C=60\%$ $SN=-0.69N\cdot t+100$	
		③ Deterioration of alkali silica reaction aggregate		RG: Content of reactionable aggregate RU: Amount of Na_2O in aggregate (%)	SN ($f(EX)$) is estimated with the expansion EX of c ③	
e. Deformation	Strain ε (%)	① Deformation of creep strain	σ: Stress of concrete loading (kgf/cm²)	Ec: Youngs modulus ϕ_c: Coefficient of creep	$\varepsilon=\frac{\sigma}{Ec}\cdot\phi_c$ (outdoor $\phi_c=2.0$)	0: $\varepsilon<420$ ($\times 10^{-6}$) 1: $420\leqq\varepsilon<670$ 2: $670\leqq\varepsilon<1033$ 3: $1033\leqq\varepsilon<2290$ 4: $2290\leqq\varepsilon$
		② Deformation of dry and temperature	Tc: Change of temperature (℃)	Uc: Unit weight of cement W/C: Water cement ratio	$\varepsilon_{cs}=0.00148W/C+0.000301U_c-0.131$ $\varepsilon_{te}=10\times 10^{-4}\times T_c$	
f. Frost damage	Change rate in relative dynamic modulus of elasticity DN (%)	① Frost damage	[t: Service life (year)] N: Cycles of freezethaw a year	W/C: Water cement ratio (%) AE or NonAE: Whether there is AE agent	Linear Regression of experimental data AE $W/C=40\%$ $DN=-0.028N\cdot t+100$ $W/C=50\%$ $DN=-0.053N\cdot t+100$ $W/C=55\%$ $DN=-0.080N\cdot t+100$ $W/C=60\%$ $DN=-0.085N\cdot t+100$ Non AE $W/C=40\%$ $DN=-0.36\ N\cdot t+100$ $W/C=60\%$ $DN=-0.51\ N\cdot t+100$	0: $96<DN$ 1: $93<DN\leqq 96$ 2: $85<DN\leqq 93$ 3: $78<DN\leqq 85$ 4: $DN\leqq 78$
g. Surface deterioration	Average depth of degree H (mm)	① Surface deterioration of frost damage	[t: Service life (year)] N: Cycles of freeze-thaw a 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 R: Rate of decreasing surface strength	$H=W\cdot\alpha(Nt^{(\frac{W/C}{55})^3}-(0.001195k^2\cdot fc^2)^{(\frac{W/C}{55})^3})$ $W=0.5$ where; $\alpha=0.0129$	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
$$\left(\begin{array}{l} SN=-55.32+16.60\ln(365t) \\ DN=-41.49+12.54\ln(365t) \end{array}\right)$$

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

2.2 Case Study of Prediction and Evaluation Method

As shown in Fig. 2, a case-study in which the technique was applied to a tentative design model was called out. The subject of the case-study was a storage pit to be built half underground which was required to have a long service life. It was designed at a tentatively designed model.

These internal and external factors are shown in Table 2.

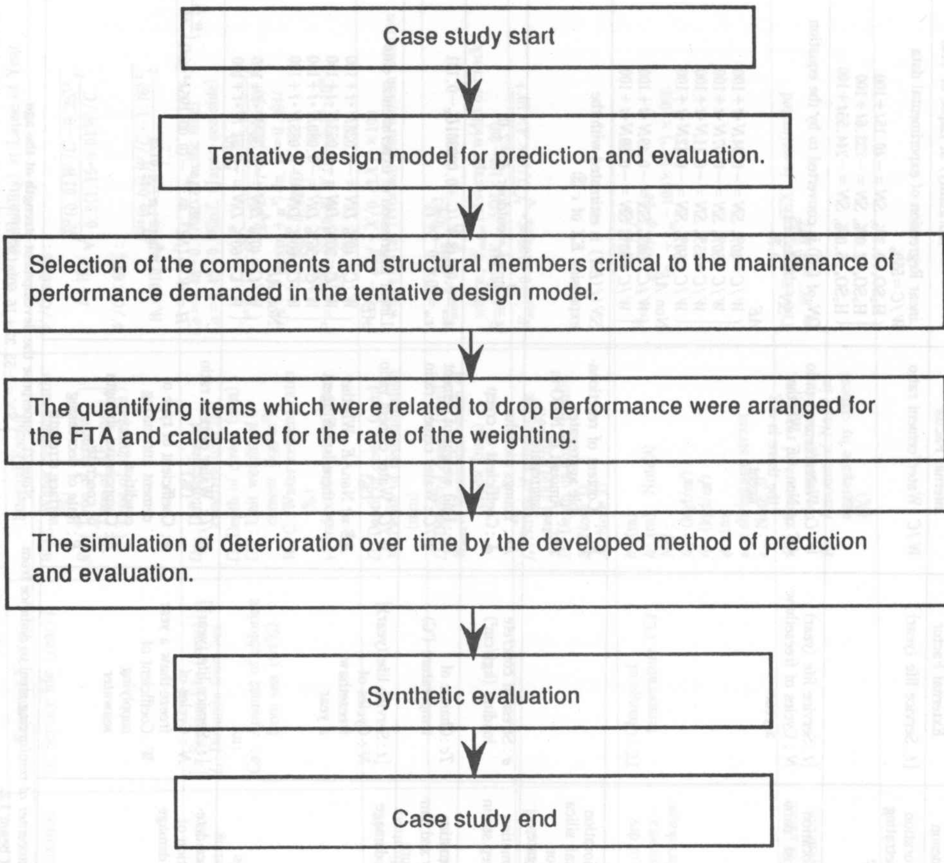

Fig. 2 The case-study procedure

In accordance with our method of examination, the component and structural members important to the maintenance of the performance called for in the tentative design model were selected and the changes over time in deterioration were evaluated and predicted using the developed method. Two conditions were studied: (1) unrepaired initial hydration cracks and (2) damage due to freezing and thawing for a year. For condition (1), the water-cement ratio and the concrete cover selected from internal factor of deterioration were and varied. For condition (2), weighting the rates of the synthetic degree of deterioration were varied. The characteristics demanded of the tentative design model were assumed to be bearing load and watertightness. The criteria used to quantify the performance loss were arranged by FTA (Fault Tree Analysis) and given for the appropriate weighting.

Table 1 The main external and internal factors of the tentative design model

Factor		Mark : Parameter (unit)	Datum
External factors	External factors of dete-rioration	t : Service life (years)	100
		L : Distance from sea (m)	3000
		N : Cycles of freeze-thaw per year (cycles)	110
Internal factors	Material	f_{ct} : Tensil strength of concrete (kgf/cm^2)	25
		f_b : Average bond strength of concrete and steel (kgf/cm^2)	48
		D_c : Diffusivities of of concrete	1.8×10^{-8}
		ϕ_c : Coefficient of creep	2
		R : Type of cement	Normal
		Type of agent	AE agent
		Type of aggrigate	river sand and river gravel
		AB : Absorption rate of aggrigate (%)	2

3. CASE-STUDY RESULTS

The simulation results, shown in Fig. 3, show that the water-cement ratio and the depth of cover over reinforcing steel influenced deterioration over time due to neutralization and steel corrosion. As a result of varying the water cement ratio and the Concrete cover, several fold variations in the neutralization dapth and 2 fold variation in the time until the onset of steel corrosion were observed. As shown in Fig. 4, it was determined that the difference in synthetic degree of deterioration was 20% at 50 years after construction.

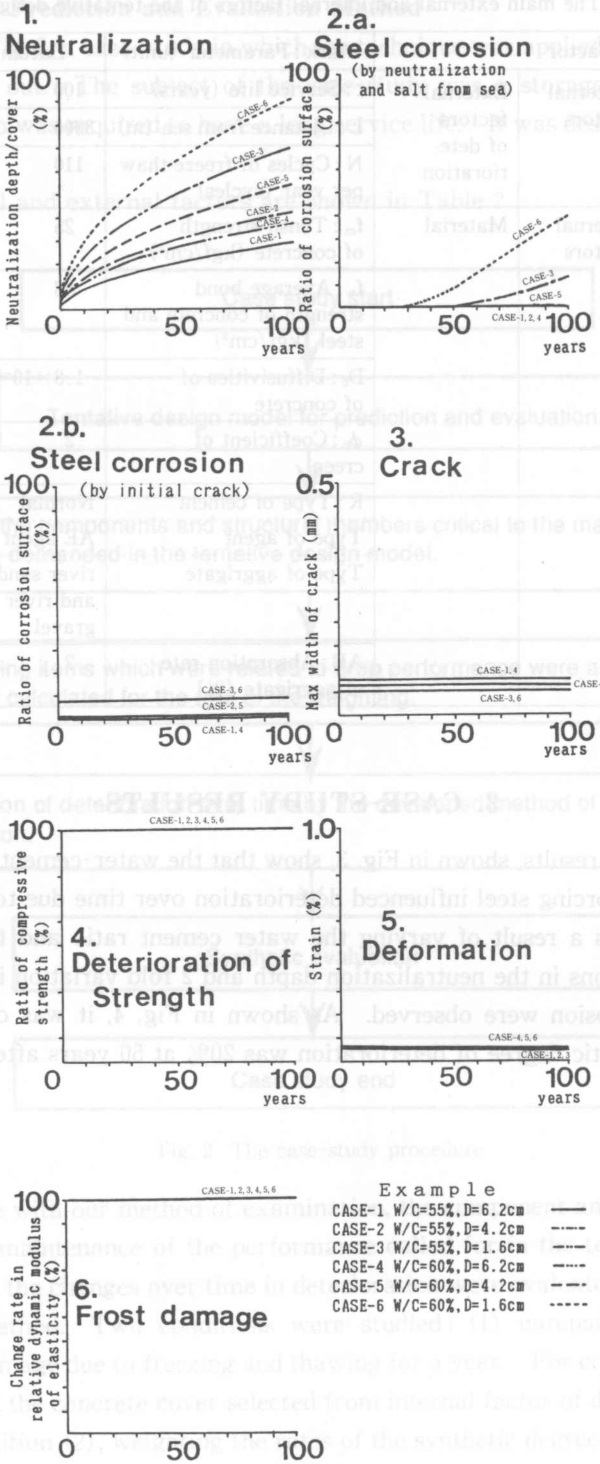

Fig. 3 Change in deteioration indicator with variation in deterioration factor (unrepaired initial cracks and frost damage for a year)

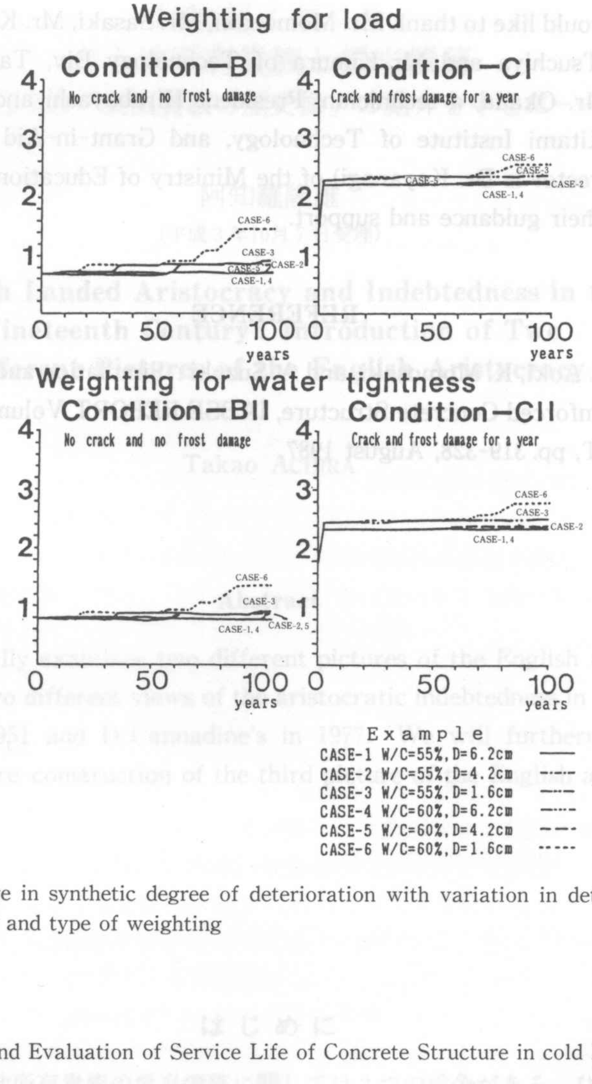

Fig. 4 Change in synthetic degree of deterioration with variation in deterioration factor and type of weighting

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4. CONCLUSION

A method has been proposed for the prediction and evaluation of the service life of RC structures in cold regions. Basic study led to the proposal that deterioration over time be predicted on the basis of internal design and construction factors and external environmental factors. The most suitable parameters and rates of internal factors were selected according to external factors, at the location of the RC structure. The simulation was able to predict the deterioration during the expected life of the RC structure and to evaluate the service life of the structure. We were able to check the durability design considered the most suitable and acquire the technical information needed to judge the most suitable time for repair. The possibility of prediction and evaluation of service life of RC structures in cold climates was proved.

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