Experimental study on the deterioration prediction of concrete structure by reliability theory

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Abstract

The prediction and evaluation of concrete service life are essential to the the maintenance and durablity design concrete structures. The purpose of this study is to examine deterioration prediction of concrete structure by reliability theory to analyze data of RC model specimens during rapid freeze-thaw tests and exposure tests, large specimens during exposure tests at Okhotsk shoreline, and mortal specimens during tensile strength test. These concrete durability data is assessed by reliability analysis. This analysis can predict the deterioration of concrete structures using reliability theory.

From these examinations, we conclude that the Weibull distribution gives the best fit to frequency distribution of scaling that exceeds the hazard level in depth. The hazards were judged with the set-up ratio to each deterioration index. The water/cement ratio is important for covariant variable of reliability theory. When the water/cement ratio is low, the reliability is high. The service life and repair plan of RC structures can be estimated as time(year) on a index of reliability 75%, 95%, etc.

1. Introduction

The prediction of service life of concrete structure is necessary and essential to durability design and, maintenance and management of concrete structure. Deterioration prediction is important and mainly subject in this task. Deterioration prediction for the service life of concrete structures is classified as deterministic or probablistic. Probablistic deterioration prediction by reliability analysis is discussed in this paper with data from accelerated test and exposed test of RC model specimens, large specimens at seaside and long-term strength mortal specimens.

The purpose of this study is to examine deterioration prediction of concrete structure by reliability theory to analyze data of RC model specimens during rapid freeze-thaw tests and exposure tests, large specimens during exposure tests at Okhotsk shoreline, and mortal specimens during tensile strength test. In this study, the set-up ratios to the some level

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of deterioration were assumed. The suitableness of reliability theory was checked. Method of deterioration prediction by reliability analysis and the index of judgement were considered.

2. Study Method

2.1 Study process

The flow of study process is shown in Fig. 1. In this proses, deterioration is first defined. The deterioration limit and set-up ratio, which regards a hazard level within the deterioration limit, are assumed. The theoretical equation of reliability analysis is introduced. Data obtained from the experiment, which are described in 2.3., are imputed. The main factors of deterioration are selected by multiple regression analysis and the factors are used as covariate in reliability analysis. The deterioration which reached the set-up ratio is assumed as a hazard and suitable probability density function (PDF) is obtained by reliability analysis (the analysis program is SAS. LIFEREG). The reliability function is obtained by integral of the PDF. The shape of the function's curve is checked by changing the covariate of the reliability function. The change in time of reliability in each case and the index of judgement are checked.

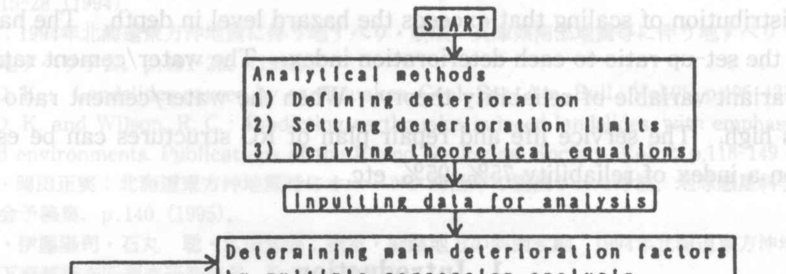


Fig. 1 Flow of study procedure

2.2 Theoretical equation of reliability analysis

The suitable function selected for the following functions, where, the time when a hazard occured was response variate, t.

(1) Distribution of exponent

If events can be assumed to occur at random by Poisson process, the time t (a response variate) at which an event first occurred obeyed the distribution of exponent, can be obtained from the following equation.

The PDF : $f(t)=\alpha\exp(-\alpha t)$ ……………………………………Equation (1)

Where, $\alpha=\exp(-\mu)$, μ is the product of covariate vector and unknown parameter vector.

(2) Distribution of logarithmic-normal

If log(t) of response variate t obeys normal distribution, the probability distribution of t called the of logarithmic-normal distribution. It is obtained from the following equation.

The PDF : $f(t)=\frac{1}{\sqrt{2\pi}\,\sigma t}\exp\left(\frac{(\log t-\mu)^2}{2\sigma^2}\right)$ ……………………………………Equation (2)

Where, σ was scale parameter.

(3) Weibull distribution

The Weibull distribution, which is suitable and often used for probability distribution in engineering, was assumed as PDF. The reliability function and PDF are shown as follows:

The reliability function : $R(t)=\exp\left(-\left(\frac{t}{\beta}\right)^{\alpha}\right)$ ……………………………………Equation (3)

Where $\alpha=1/\sigma$, σ is scale parameter, and the unreliable function is

$F(t)=1-R(t)$

The PDF : $f(t)=F'(t)=\frac{\alpha t^{\alpha-1}}{\beta^{\alpha}}\exp\left(-\left(\frac{t}{\beta}\right)^{\alpha}\right)$ ……………………………………Equation (4)

Additionally, for these distributions from (1) to (3), the factors of deterioration are taken as covariates. The reliability function is obtained. The equation of parameters and covariate are shown as follows.

$\beta=\exp(\mu)=\exp(x'b)=\exp(b_0+x_1b_1+x_2b_2+\cdots\cdots+x_nb_n)$ ……………………………………Equation (5)

Where, x' is a covriate vector. b was unknown parameter vector.

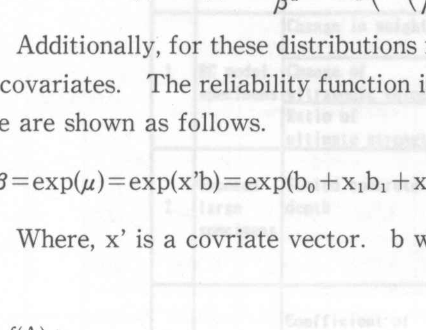


Fig. 2 Relationship between probability density function f(t) and reliability function R(t)

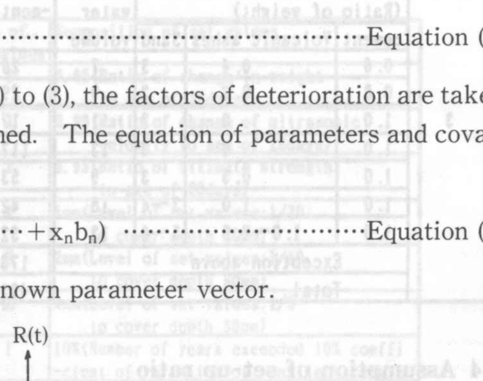


Fig. 3 Relationship between shape of reliability function R(t) and parameter σ or β

The relationship between the PDF and the reliability function is shown in Fig. 2. The relationships between reliability function and parameters σ and b are shown in Fig. 3. In this figure, if $t/\beta >= 1$, and $b > 0$, R(t) becames grate, σ and b increase.

2. 3 Experiment method

The concrete mix proportion of each experimental case is shown in Table 1. Case 1 is the mix proportion of RC model specimen. Case 2 is the large specimen exposed at seaside of Okhotsk Sea. Case 3 is typical mix proportion and the number of combination of long term strength tests of mortar specimens. The Table 2 shows the experiment method and the shape and size of RC model specimen, large specimens exposed at the seaside, and mortar specimens.

Table 1 Mix proportion of concrete (RC model specimen), Exposed large specimens at seaside and Mortar specimens

Case	Type of mix proportion	Type of cement	W/C (%)	s/a (%)	Specified mix (Kg/m³) W	C	S	G	Admix-ture *1 (cc)	Property of fresh concrete Slump (cm)	Air content (%)
1	451	Normal portland cement	45	31	152	338	564	1277	48.5	6.3	3.5
	452	Normal portland cement	45	31	152	338	564	1277	39.7	8.0	4.8
	55	Normal portland cement	55	34	152	276	634	1258	46.9	8.0	4.5
	65	Normal portland cement	65	34	152	234	647	1279	52.9	9.2	5.1
2	N45	Normal portland cement	45	–	135	300	718	1177	–	3.9	4.5
	N55	Normal portland cement	55	–	136	248	770	1166	–	4.5	5.6
	BB45	Blast-furnance slag cement	45	–	128	233	780	1182	–	2.9	4.0
	BB55	Blast-furnance slag cement	55	–	130	289	722	1186	–	6.0	3.0

Case	Ratio of mix proportion (Ratio of weight) cement	Volcanic ashes	Sand	Kind of water volume	Assort-ment
3	0.6	0.4	3	7	28
	0.8	0.2	3	9	29
	1.0	0	2	1	17
	1.0	0	3	13	117
	1.0	0.5	3	9	53
	1.0	1.0	3~4	18	42
	1.0	1.0~2.0	5~6	12	32
	Exception above				173
	Total				491

*1:AE agent

2. 4 Assumption of set-up ratio

A hazard, each was presupposed for reliability analysis. A level was set-up which recognized hazard to each deterioration indicator of damage. It was called a set-up ratio. The set-up ratios which recognized hazards were shown in Table 3.

In case 1, the set-up ratios of change in weight, change of ultrasonic velocity, and ratio of ultimate strength were set by the standards of 28 days age data rate. The rate for 28 days was set at 1. In case 2, the depth of cover was assumed to 80 mm. The allowable limit for depth of cover(The deterioration limit of scaling) was assumed to be 20 mm. Set-up ratio at the level of 1/5, 1/10 and 1/20 to the deterioration limit were shown in Table 3. In case 3, the set-up ratios of the coefficient variation of tensile strength were assumed to be at levels of over 10%, 15% and 20%. Additionally, other set-up ratios of tensile strength were assumed to be at levels below maturity age 28 days, 3 months, and 1 year.

Table 2 Experimental method (RC model specimen, Exposed large specimens at seaside and Mortar specimens)

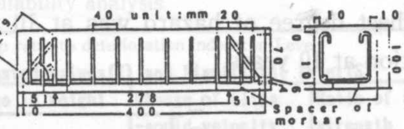
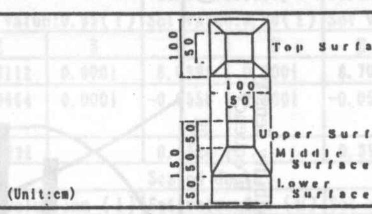
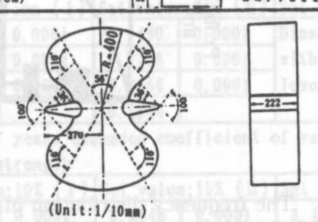
Case	Specimens	①Exposure conditions ②Measurement Item (deterioration index) ③Term of mesurement (cycle)	Size and form of the specimens
1	RC model specimens	①Exposure test and rapid freeze-thaw test ②Weight, ultrasonic velocity, ultimate strength (change in weight, change of ultrasonic velocity, ratio of ultimate strength) ③Rapid freeze-thaw test (300 cycles of 6 cycles in a day). Exposure test (56 cycles in a year)	
2	Exposed large specimens	①Site 40m from the shoreline ②Scaled depth which were classified as either scaling or pop-out. ③15 year (56 cycles in a year)	
3	Mortar specimens	①In air, in sea water, in water ②Tensile strength which masured by fixing both ends of test specimens of model of gourd (tensile strength) ③The tests data were ten thousands. The tests continued for 95 years. Test age of a week, four weeks three months, six months, a year, two years four years, five years, seven years, ten years and on and after every five tears	

Table 3 Assumption of the set-up ratio

Case	Specimens	Deterioration index	Level of set values	Supposition of set values
1	RC model specimens	Change in weight	I	0.95 (Ratio of change in weight to age of 28days)
		Change of ultrasonic velocity	I	0.90 (Ratio of change of ultrasonic velocity to age of 28days)
		Ratio of ultimate strength	I	0.95 (Ratio of ultimate strength to age of 28days)
2	Exposed large specimens	Scaled concrete depth	I	1mm (Level of set values: 1/20 to cover depth 80mm)
			II	2mm (Level of set values: 1/10 to cover depth 80mm)
			III	4mm (Level of set values: 1/5 to cover depth 30mm)
3	Mortar specimens	Coefficient of variation of tensile strength	I	10% (Number of years exceeded 10% coefficient of variation of tensile strength
			II	15% (Number of years exceeded 15% coefficient of variation of tensile strength
			III	20% (Number of years exceeded 20% coefficient of variation of tensile strength
		Declinning of tensile strength	I	A year (Number of years declined tensile strength at age of a year)
			II	Three months (Number of years declined tensile strength at age of three months)
			III	28 days (Number of years declined tensile strength at age of 28 days)

Note: In the case 2, the deterioration limit was assumed to be 20mm.

3. Analysis results and consideration

3.1 Analysis results

3.1.1 Choosing suitable PDF

In order to choose a suitable PDF, data of the mix proportion of normal portland cement and W/C=45%(N45) in case 2 of the large specimen exposed at seaside were analyzed to determine whether the exponent, logarithmic-normal, and Weibull distributions were obeyed. The results are shown in Table 4. The histogram of set-up ratio 2mm, distribution of exponent, distribution of logalithmic normal, and Weibull distribution were shown in Fig. 4. The highest degree of hazard was at 10 yeas. The peak was the same as the Weibull distribution at 10 years.

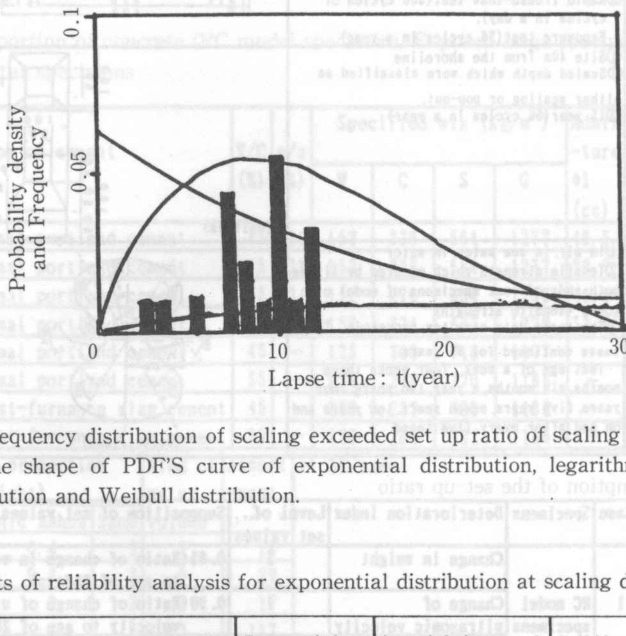


Fig. 4 The frequency distribution of scaling exceeded set up ratio of scaling depth 2mm, and the shape of PDF'S curve of exponential distribution, legarithmic normal distribution and Weibull distribution.

Table 4 Results of reliability analysis for exponential distribution at scaling depth 2mm.

Distribution		Exponential		Logarithmic normal		Weibile	
Estimated values:E Significant level:S		E	S	E	S	E	S
Intercept		3.8912	0.0001	3.5043	0.0001	3.4490	0.0001
Coefficient of	Ferric oxide	0.3492	0.0028	0.3386	0.0001	0.2768	0.0001
Covariant variable	Water-cement ratio	0.0493	0.0010	-0.0465	0.0001	-0.0366	0.0001
Scaling population parameter (σ)		1.0000		0.7107		0.5654	

3.1.2 The results of reliability analysis.

The reliability analysis at each level in each case us shown in Table 5. In case 1 of RC model specimens, the water/cement ratio was chosen as a covariate. The coefficients of parameter were negative. The significance levels of the coefficient of parameter were 1%. In case 2 of large specimen exposed at seaside, the ferric dioxide content in cement and water/cement ratio were chosen as a covariate. The coefficient of ferric de oxide content in cement was negative. That of the water/cement ratio was positive. These significance level of these were within 1 %. In case 3 of the mortar specimen for long-term strength test, the ratio of cement proportion, the ratio of volcano ash proportion and the water／cement ratio were chosen as covariates. The significance level of water/cement ratio was high.

Table 5 Results of reliability analysis.

Case	Specimens	Kind of coefficient of reliability function		Set-up ratio to deterioration indecator (Level) Estimated values(E) and Significant level(S)					
				Change in weight Set value:0.95(I)		Change of ultra-sonic velocity Set value:0.90(I)		Ratio of ultimate strength Set value:0.95(I)	
				E	S	E	S	E	S
1	RC model specimens	Intercept		8.9112	0.0001	8.0995	0.0001	8.7036	0.0001
		Coefficient of covariant variable	Water-cement ratio	-0.0664	0.0001	-0.0556	0.0001	-0.0526	0.0050
		Population parameter (σ)		0.2232		0.1614		0.3914	
2	Exposed large specimens			Scaled depth					
				Set value:1mm (I)		Set value:2mm (II)		Set value:4mm (III)	
		Intercept		2.6127	0.0001	3.4490	0.0001	Dissatisfaction with significant level	
		Coefficient of covariant variable	Ferric oxide	0.2300	0.0004	0.2766	0.0001		
			Water-cement ratio	-0.0356	0.0001	-0.0366	0.0001		
		Scaling population parameter (σ)		0.5953		0.5654			
3	Model specimens			Number of years exceeded coefficient of variation of tensile strength					
				Set value:10% (I)		Set value:15% (II)		Set value:20% (III)	
		Intercept		4.7036	0.0001	6.2940	0.0001	8.4673	0.0001
		Coefficient of covariant variable	Ratio of mix proportion of cement	-1.2636	0.0009	-1.8372	0.0003	-3.0598	0.0001
			Ratio of mix proportion of volcanic ashes	0.3409	0.0001	0.3478	0.0006	0.2147	0.1014
			Water-cement ratio	-0.6343	0.1139	-1.6754	0.0025	-2.8483	0.0002
		Population parameter (σ)		1.0425		0.9393		0.8358	
				Number of years declined tensile strength					
				Set value: a year (I)		Set value: three months (II)		Set value: 28 days (III)	
		Intercept		6.2559	0.0001	6.0699	0.0001	4.4132	0.0161
		Coefficient of covariant variable	Ratio of mix proportion of cement	-3.6654	0.0001	-3.8213	0.0116	-2.6761	0.1591
			Ratio of mix proportion of volcanic ashes	0.0626	0.6946	0.5159	0.3084	1.5559	0.0656
		Population parameter (σ)		0.5322		0.9201		1.1142	

3.2 Consideration

3.2.1 Deterioration prediction by reliability function

The reliability at the most past time when many data points were obtained in each case was aimed. The change in weight, the ultrasonic velocity change, and the ratio of ultimate strength in case 1 are shown in Fig.5, 6, and 7. Set-up ratios were 0.95, 0.90, and 0.95, respectively. Reliabilities for each set-up ratio in water/cement ratio of 45% were 70%, 15 %, and 80%.

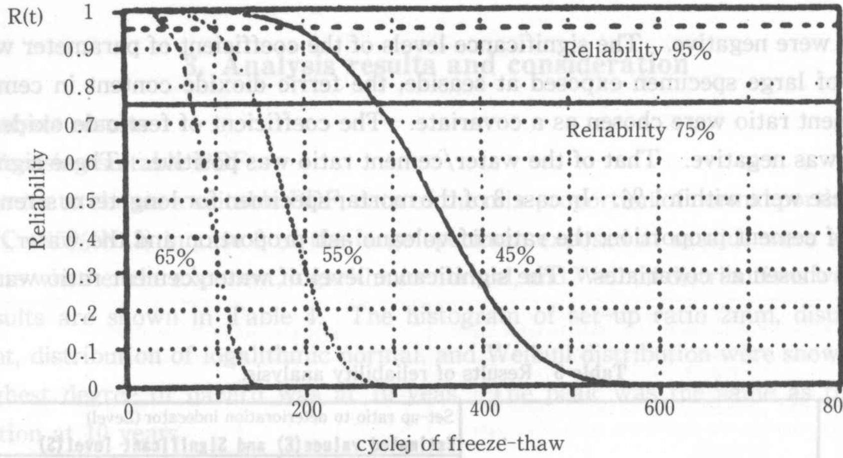


Fig. 5 Between lapse cycles of freeze-thaw and veliability (R(t)) to the hazard of the change in weight to the initial at set up ratio 0.95.

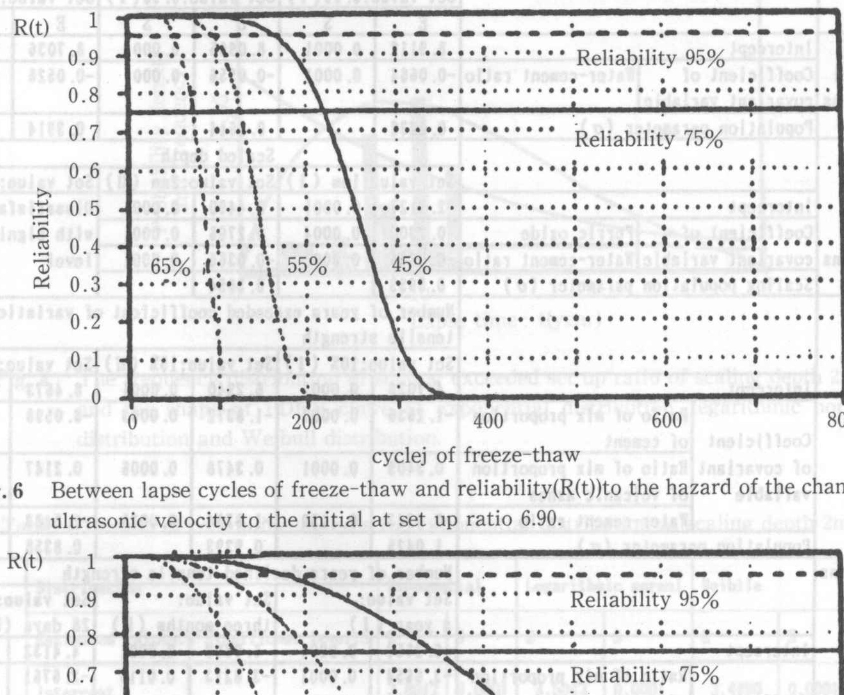


Fig. 6 Between lapse cycles of freeze-thaw and reliability(R(t))to the hazard of the change of ultrasonic velocity to the initial at set up ratio 6.90.

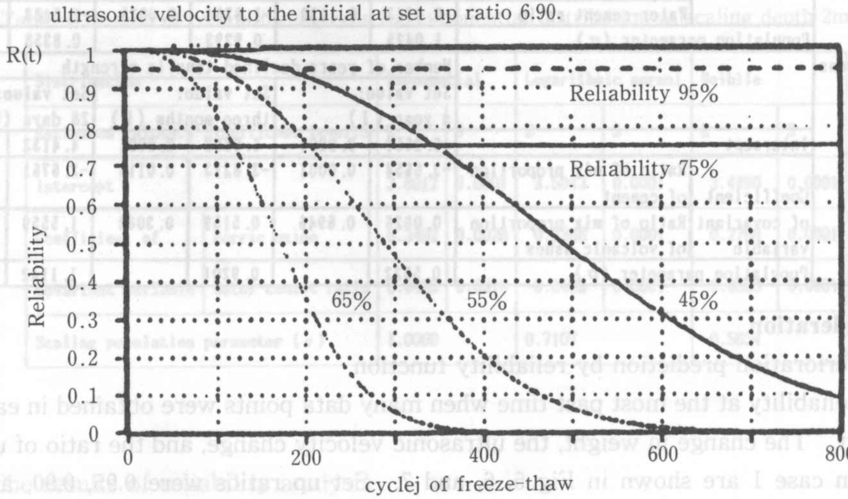


Fig. 7 Between lapse cycles of freeze-thaw and reliability(R(t)) to the hazard of the ultimate strength to the initial at set up ratio 0.95.

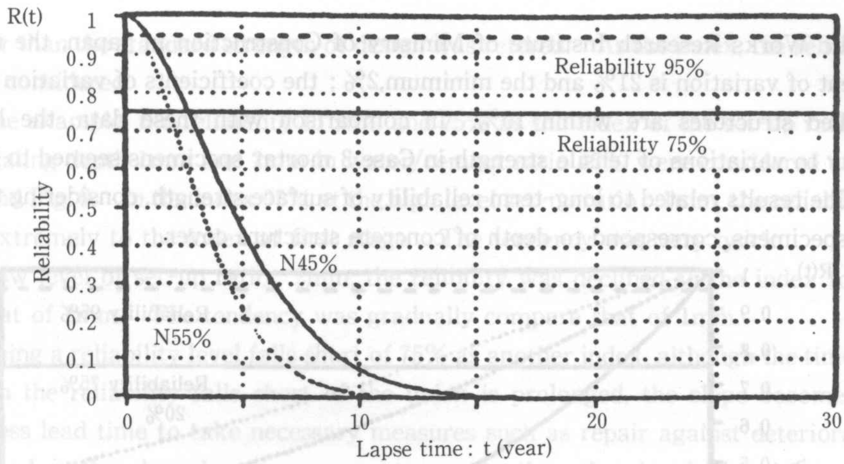


Fig. 8 Between lapse time : t(year) and relialility (R(t)) at set-up ratio of scaling depth 1mm(N45, N55).

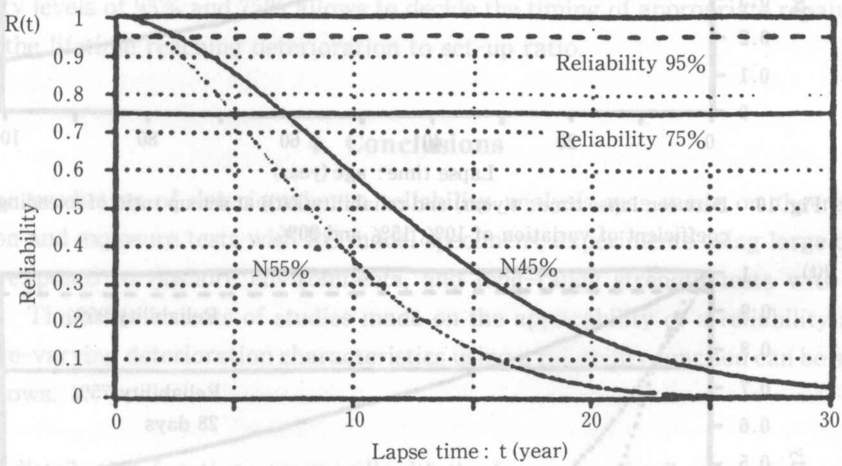


Fig. 9 Between lapse time : t(year) and reliability(R(t)) at set-up ratio of scaling depth 2mm(N45, N55)

The reliability at the set-up ratio 1mm of level I is shown in Fig. 8. The reliability of N45 was 8% at 10 years. The reliability of N55 was 1% at 10 years. The reliability at the set- up ratio 2mm of Level II is shown in Fig. 9. The reliability of N45 was 58% and the reliability of N55 was 36% at 10 years.

The reliability at the set-up ratio exceeding coefficient of variation of 10%, 15%, and 20 % of each level I, II, and III in case 3 of mortar specimen for long term strength test are shown in Fig. 10. At the age 80 years, the reliability within coefficient of variation of 10% was 20%, that of 15% ; 41%, and that of 20% ; 50%.

The reliability at the set-up ratio declining the tensile strength at ages 28 days, 3 months, and 1 year of each level I, II, and III are shown in Fig. 11. At the age 80 years, the reliability of not declining the tensile strength age 28 days was 52%, that of 3 months ; 5%, and that of 1 year ; nearly 0%.

Furthermore, in reference to coefficient of variation of strength in case 3, according to the Public Works Research Institute of Ministry of Construction in Japan, the maximum coefficient of variation is 21% and the minimum,2% ; the coefficients of variation in 80% of the studied structures are within 10%. In comparison with these data, the long term reliability to variations of tensile strength in Case 3 mortar specimens seemed to be mostly kept. The results related to long-term reliability of surface strength, considering the size of mortar specimens, correspond to depth of concrete structure cover.

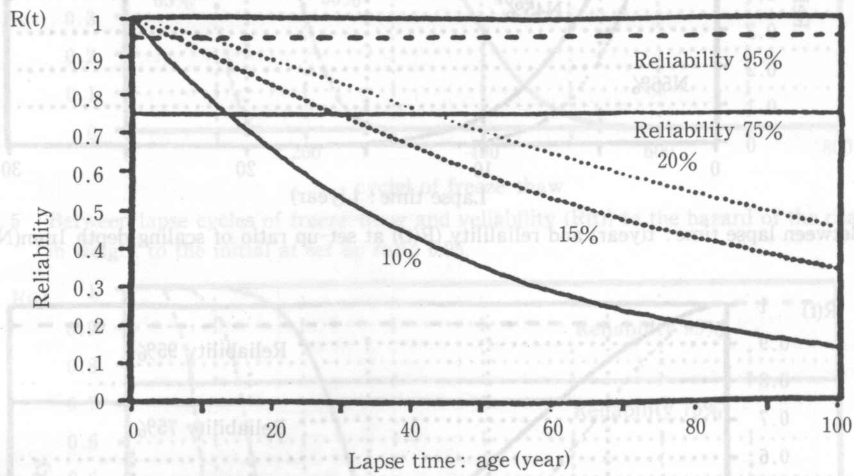


Fig. 10 Between lapse time : t(year) and reliability(R(t)) at set-up ratio of exeeding coefficient of variation of 10%, 15% and 20%.

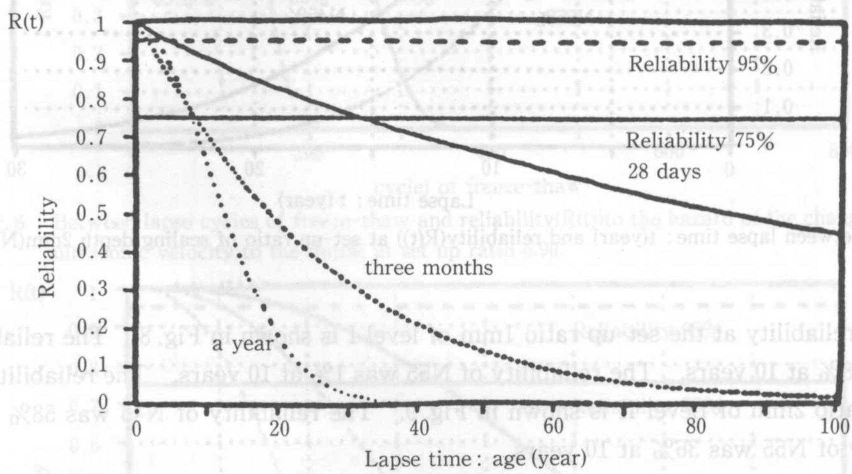


Fig. 11 Between lapse time : t(year) and reliability(R(t)) at set up ratio declining the tensile strength at age 28days, 3months, and 1years.

3. 2. 2 Study on index for predicting deterioration with reliability.

Setting of the extremely hight set-up ratio was not always required, because ordinary civil structures could usually repaired. Therefore, in order to judge by reliability with refering JSCE standard specification of concrete, the probability is within 5% that the strength must not be lower than the standard strength of design. As this index, the reliability to 95% was considered. As the same, the probability was within 25% that the strength were lower than the standard strength of design was refered. As the index, the reliability to 75 % was considered.

For the example, the reliability to 95% and 75% as the index of the set-up ratio at the level of scaling depth 1mm and 2mm in water/cement ratio 45% were considered as shown in Fig. 8 and Fig. 9. In the index 95% at the high level set-up ratio : 1mm, the reliability was declined extremely to the index at first stage. The tendency was very quick.

The low level of set-up ratio : 2mm, the relibility was declined to the index for twice time to that of 1mm. The tendency was gradually compare that of 1mm.

Assuming a reliability level falls short of 75% as another index, although the time period over which the reliability falls short of the index is prolonged, the slope becomes steep. There is less lead time to take necessary measures such as repair against deterioration of structures when the slope becomes more steep. On the other hand, the time to repair structures is allowed when the slope is gentle. As discussed above, assuming indexes such as reliability levels of 95% and 75% allows to decide the timing of appropriate repair as well as predict the lifetime reaching deterioration to set-up ratio.

4. Conclusions

For the prediction of deterioration, a reliability analysis was made on the results of acceleration and exposure tests with RC model specimens, experiments using large concrete specimens exposed to onshore environments, and long-range strength tests with mortar specimens. The achievements of studies made on the applicability of a reliability analysis and the time-varying deterioration characteristics using a reliability function can be summarized as follows.

(1) Weibull distribution function agrees well with the frequency distribution of deterioration indicator exceeding set-up ratio such as scaling depth.

(2) Deterioration indicator can be represented as a reliability function by taking into account set-up ratio determining hazard and their indicators.

(3) A water/cement ratio is an important deterioration factors as a covariate of the reliability function. The reliability becomes higher as water/cement ratio decreases.

(4) Predicting deterioration using a reliability level as an index allows to decide the timing of taking necessary measures such as repair as well as predict useful service life.

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