Experimental Study on the Deterioration Prediction of Concrete Structures*[1]

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Abstract

The purpose of this study is to analyze the deterioration mechanisms that affect the required performance (specifications critical to the operability) of concrete structures. A technique based on deterioration prediction is introduced which should prove useful in the maintenance and management of structures.

Neutralization and chemical attack were selected as two example mechanisms. Neutralization was examined in terms of its effect on reinforcement corrosion and bearing strength, while the effects of chemical attack on strength, esthetic appearance, and bearing strength were studied. A deterioration limit was established for the ultimate state of structures with a safety factor of 1.15. Deterioration was predicted about flexural strength.

In this way, a prediction method of neutralization and chemical attack was defined by arranged factor of deterioration. Flexural strength of neutralization was predicted by rate of neutralized thickness. Flexural strength of chemical attack was predicted by rate of strength deterioration.

1. Introduction

As a primary structural material in the construction industry, reinforced concrete finds wide application in a range of environments. Proper prediction of the deterioration of concrete structures is critical to the operation, maintenance, and design of durable structures.[1)] The aim of this study is to predict and evaluate the deterioration suffered by concrete structures through focusing on the deterioration mechanisms that affect their performance, with particular emphasis on concrete structural members. We also aim to develop maintenance and management technologies through the introduction of deterioration prediction.

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STUDY METHOD

Figure 2.1 shows the procedure used in this study of deterioration prediction. First, we look at existing research data relating to the durability of concrete and use this to clarify the performance required of concrete structural members as well as to examine the relationship between performance requirements and deterioration. Second, deterioration mechanisms are classified and factors causing deterioration extracted. This makes it possible to derive equations which predict performance and deterioration. Finally, service life is predicted based on a defined deterioration limit.

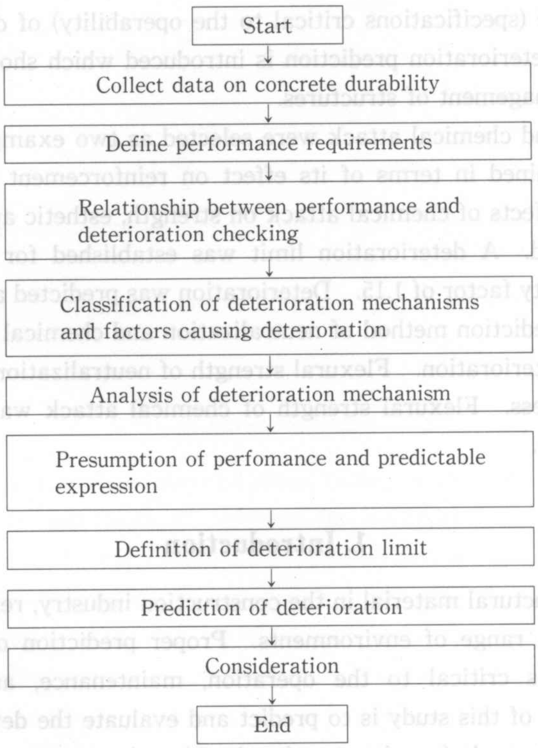

Figure 2.1 Procedure for the study of deterioration prediction

3. Details of study

3.1 Relationship between performance requirements and deterioration

The performance requirements of a structure vary according to its purpose, the structural elements it contains, and the type of structural members used. It is important to investigate, classify, and define these requirements before an understanding of the effects of deterioration is possible. In this study, we consider the following six types of performance requirements: load-bearing strength, durability, aesthetic appearance, strength, deformation, and corrosion resistance of the reinforcement. Table 3.1 shows the relationship between these performance requirements and the types of deterioration that influence them.

Table 3. 1 Relationship between performance requirements and types of deterioration forms

Performance requirement	Type of deterioration
Load-carrying capacity	Neutralization, frost damage, chemical attack and fatigue
Durability	Frost damage, alkali-aggregate reaction and fatigue
Aesthetic appearance	Chloride-induced corrosion, frost damage, chemical attack and alkali-aggregate reaction
Strength	Chloride-induced corrosion, frost damage, chemical attack and alkali-aggregate reaction
Deformability	Frost damage, alkali-aggregate reaction and chloride-induced corrosion
Corrosion resistance of reinforcement	Chloride-induced corrosion, neutralization and chemical attack

3. 2 Type of deterioration and factors

Taking into account the mechanism by which deterioration influences a concrete structure, deteriorations can be categorized into the following types : chloride-induced corrosion, neutralization, frost damage, alkali-aggregate reaction, chemical attack, fatigue and others. In this paper, we consider only neutralization[2),3),4)] and chemical attack.[3),5)] Tables 3. 2. 1 and 3. 2. 2 list the deterioration indicators, processes, and determining factors for neutralization and chemical attack, respectively.

Table 3.2.1 Deterioration indicators, processes, and determining factors in the case of neutralization

Type of deterioration quantifying item	Relating performance requirements	Indicators	Phenomena causing deterioration	Factors affecting deterioration	
				External factor	Internal factor
Neutralization	• Corrosion resistance of reinforcement • Strength retention • Load-carrying capacity	• Neutralized concrete depth (mm) • Ratio of neutralized concrete depth (%)* • pH at steel depth	• Neutralization (decline in alkalinity) • Corrosion of reinforcement	L : service year(year) CO_2 content (%) Temperature (℃) Humidity -No effect of rain -Effect of rain	W/C : water-cement ratio (%) R : neutralization factor Type of cement Type of aggregate Type of AE agent Curing conditions Working conditions D : concrete cover (mm)

* Ratio of neutralized concrete depth to concrete cover

Table 3.2.2 Deterioration indicators, processes, and determining factors in the case of chemical attack

Type of deterioration quantifying item	Relating performance requirements	Indicators	Phenomena causing deterioration	Factors affecting deterioration	
				External factor	Internal factor
Chemical attack	• Aesthetic appearance • Corrosion resistance of reinforcement • Load-carrying capacity	• Average depth of scaling (mm) • Depth of scaling (%) • Percentage reduction in strength (%) • Ratio of change in dynamic modulus of elasticity (%)	• Surface deterioration • Sectional loss	L : service year(year) Concentration of solution (%) : sulfate, magnesium sulfate, 〔sea water, sulfuric acid, nitrate, acetate, lactic acid, tannic acid, etc.	W/C : water-cement ratio (%) Kc : Coefficient of water permeability H : Sectional size of member D : concrete cover (mm)

3.3 Deterioration mechanism

In this section, we discuss the mechanism of deterioration, which influences the performance of concrete structural members, as exemplified by the two types of deterioration adopted for study : neutralization and chemical attack.

3.3.1 Neutralization

Ordinary Portland cement contains about one-third calcium hydroxide, a material that indicates strong alkalinity with a pH of 12～13. Air contains approximately 0.03% carbon dioxide. Calcium hydroxide reacts with atmospheric carbon dioxide to form calcium carbonate with a pH of 8.5～10. This phenomenon is known as the neutralization (carbonation) of concrete. The major effect of neutralization on concrete is a decline in alkalinity. Figure 3.3.1 is a block flow diagram showing how concrete structural members deteriorate due to neutralization. The increase in neutralized depth with time can be calculated using the following equation, which is widely used where the water-cement ratio is less than 60%.[2)]

$$x(t)=\sqrt{\frac{R^2(0.046W/C-1.76)^2}{7.2}t} \quad \text{Eq. (3.3.1.1)}$$

$$X=\frac{x(t)}{D} \quad \text{Eq. (3.3.1.2)}$$

where, x(t) : neutralized concrete depth (mm) ; X : ratio of neutralized concrete depth to concrete cover (%) ; R : neutralization factor (dimensionless) ; W/C : water-cement ratio (%) ; t : service life (year) ; and D : concrete cover (mm).

This study assumes R = 1.0, W/C < 60%, and D = 3 cm.

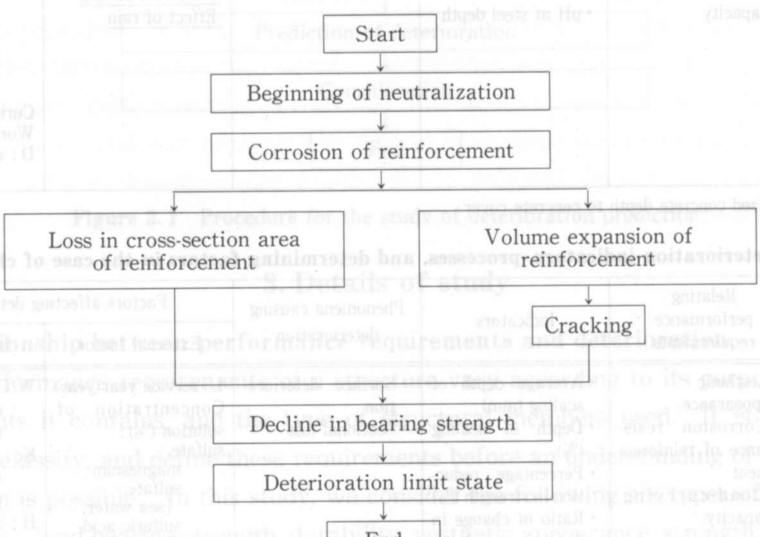

Figure 3.3.1 Deterioration of concrete due to neutralization

3.3.2 Chemical attack

Chemical attack causes expansion cracks on the surface of the concrete, and where many cracks form the surface peels off. The cracked concrete may then corrode from within if corrosive solutions infiltrate through the cracks. Although in severe cases the reinforcement may corrode after deterioration of the concrete cover, the discussion in this study is limited to deterioration of the concrete itself. Figure 3.3.2 is a block flow diagram showing the deterioration process. This study assumes specimens measuring 25 cm by 15 cm by 120 cm, a concrete cover of 3 cm, a concrete strength of 240 kgf/cm^2, a reinforcement diameter of 1.3 cm, and a reinforcement yield strength of 3,500 kgf/cm^2.

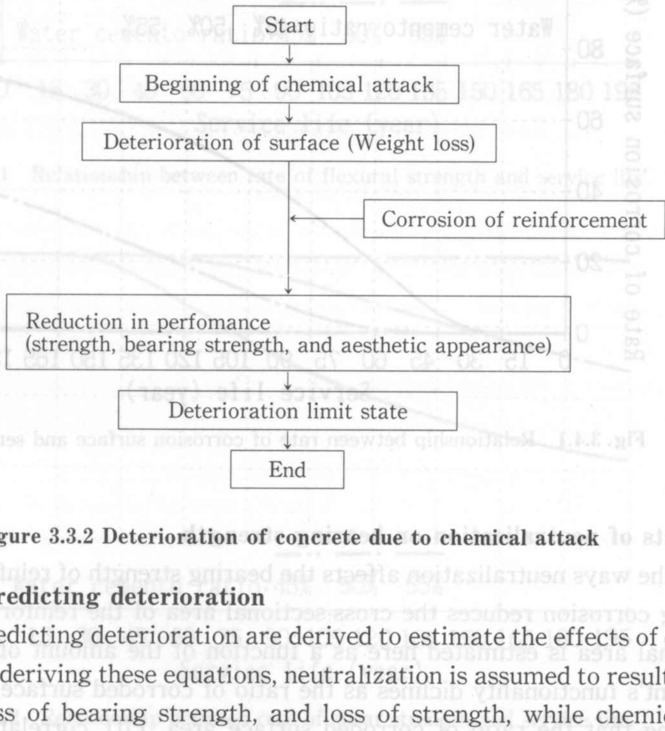

Figure 3.3.2 Deterioration of concrete due to chemical attack

3.4 Equations for Predicting deterioration

Equations for predicting deterioration are derived to estimate the effects of deterioration on performance. In deriving these equations, neutralization is assumed to result in corrosion of reinforcement, loss of bearing strength, and loss of strength, while chemical attack is assumed to affect strength, appearance and bearing strength.

3.4.1 Effects of neutralization on corrosion of reinforcement

Neutralization does not directly cause deterioration of the concrete. However, the decline in alkalinity causes corrosion of the reinforcement, which in turn leads to reduced bearing strength. Reinforcement corrodes when the pH falls below 11 as neutralization develops in the concrete. The ratio of corroded reinforcement surface area as a function of time, P(t), which represents the development of neutralization over time, can be calculated by obtaining a normal distribution function, F, from the reinforcement corrosion probability using Hastings' approximation, as given below[3]

$$P(t)=(1-\Phi(D-x(t))/0.41x(t))\cdot 100 \quad \text{Eq. (3.4.1)}$$

where,
$x(t)$: average neutralized concrete depth at t (mm) ; and D : concrete cover (mm). Figure 3.4.1 shows how the ratio of corroded surface area changes with the passage of time.

In addition, according to accelerated neutralization tests carried out to measure the corrosion of reinforcement with a concrete cover of 2 cm, reinforcement corrosion begins at an average ratio of neutralized concrete depth to concrete cover of 70~100%, and the ratio of corroded surface area reaches 20~50% when the average ratio reaches 120~140%.[4]

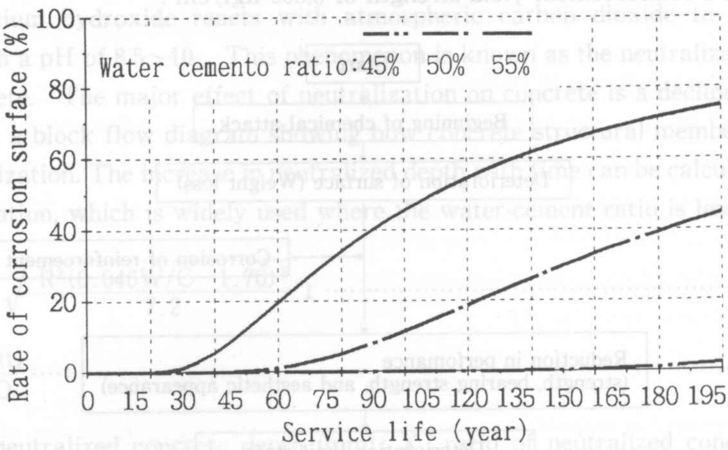

Fig. 3.4.1 Relationship between rate of corrosion surface and service life.

3.4.2 Effects of neutralization on bearing strength

One of the ways neutralization affects the bearing strength of reinforced concrete is that the resulting corrosion reduces the cross-sectional area of the reinforcement. This loss in cross-sectional area is estimated here as a function of the amount of reinforcement. The reinforcement's functionality diclines as the ratio of corroded surface area increases.

Assuming that the ratio of corroded surface area, $P(t)$, correlates perfectly with the reduction in cross-sectional area of the reinforcement, then the time-dependence of cross-sectional area of the reinforcement, $A_s(t)$, reduction in flexural strength, $M_{ud}(t)$, and shear strength, $V_{yd}(t)$, are given, respectively, by the following :

$$M_{ud}(t)=A_s(t)\cdot f_{yd}(d-y_c) \quad \cdots\cdots \text{Eq. (3.4.2.1)}$$

$$V_{yd}(t)=V_{cd}+V_{sd} \quad \cdots\cdots \text{Eq. (3.4.2.2)}$$

where, $A_s(t)$: total cross-sectional area of reinforcement (cm^2) ; f_{yd} : yield strength of reinforcement (kgf/cm^2) ; d : effective depth (cm) ; y_c : $0.416x_n$; x_n : depth of neutral axis ; V_{cd} : shear strength without shear reinforcement[6] ; V_{sd} : shear strength increment due to shear reinforcement.[6]

Figures 3.4.2.1 and 3.4.2.2 show the percentage loss in flexural strength and shear strength with the passage of time, respectively.

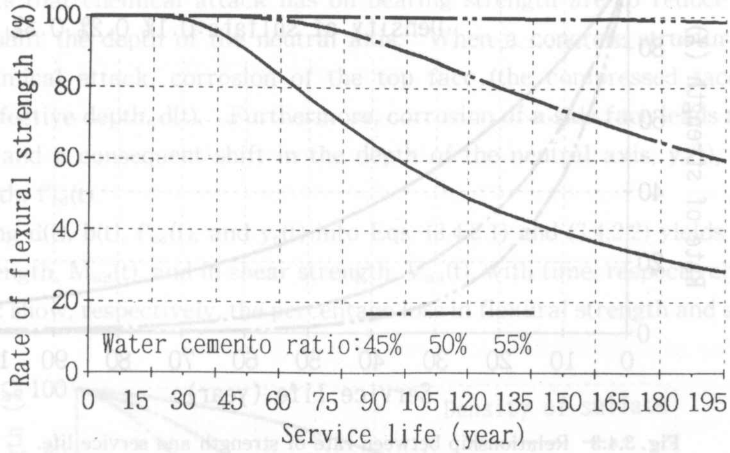

Fig. 3.4.2.1 Relationship between rate of flexural strength and service life.

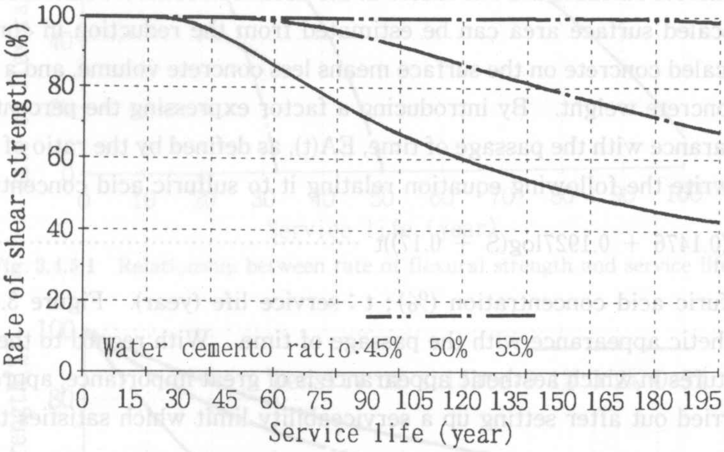

Fig. 3.4.2.2 Relationship between rate of shear strength and service life.

3.4.3 Effect of chemical attack on strength

Chemical attack causes expansion cracks on the concrete surface. The interior then corrodes as corrosive chemicals infiltrate through the cracks, causing a loss in strength. It can therefore be assumed that the percentage loss in concrete strength with the passage of time, SN(t), will vary significantly according to the sulfuric acid concentration. A regression analysis of the available experimental data[5] leads to the following equation for the relationship with sulfuric acid concentration :

$$SN(t)=100\exp((-0.2482S-0.0732S^2)t) \quad \text{Eq. (3.4.3)}$$

where, S : sulfuric acid concentration (%) ; t : service life (year). Figure 3.4.3 shows the percentage loss in strength with the passage of time.

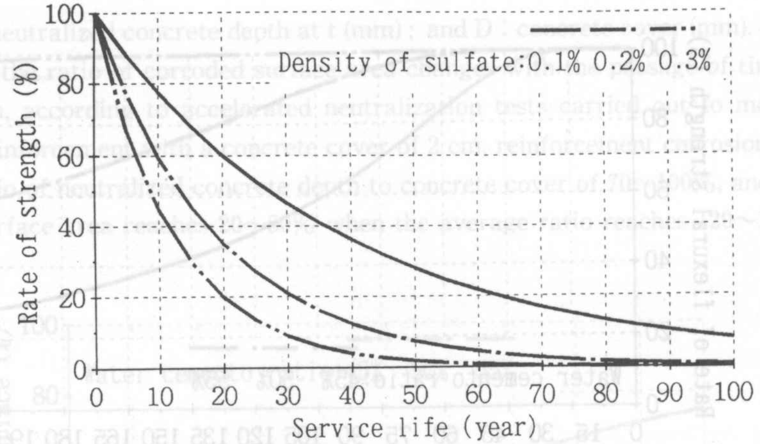

Fig. 3.4.3 Relationship between rate of strength and service life.

3.4.4 Effect of chemical attack on appearance

Scaling concrete surfaces are one factor in the decline in concrete's aesthetic appearance. The ratio of scaled surface area can be estimated from the reduction in concrete weight; that is, more scaled concrete on the surface means less concrete volume, and a corresponding reduction in concrete weight. By introducing a factor expressing the percentage decline in aesthetic appearance with the passage of time, EA(t), as defined by the ratio of scaled surface area, we can write the following equation relating it to sulfuric acid concentration:

$$EA(t) = (0.1476 + 0.1927\log(S + 0.17))t \quad \cdots\cdots \text{Eq. (3.4.4)}$$

where, S: sulfuric acid concentration (%); t: service life (year). Figure 3.4.4 shows this decline in aesthetic appearance with the passage of time. With regard to the serviceability limit[7] of structures in which aesthetic appearance is of great importance, appropriate studies need to be carried out after setting up a serviceability limit which satisfies the usage.

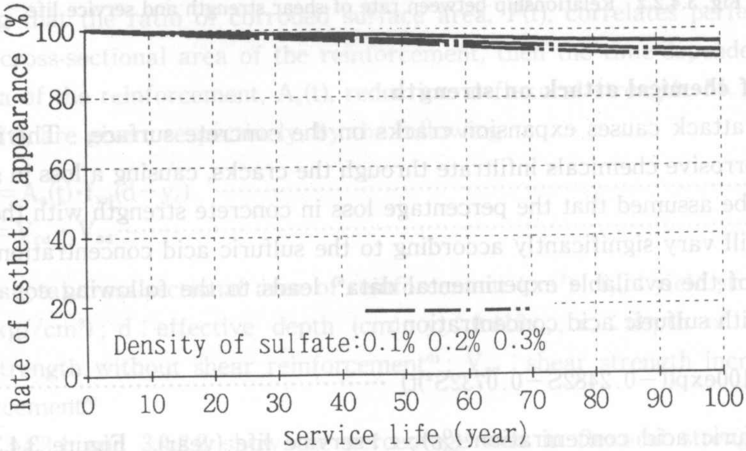

Fig. 3.4.4 Relationship between rate of esthetic appearance and service life.

3.4.5 Effects of chemical attack on bearing strength

The effects that chemical attack has on bearing strength are to reduce the effective depth and to shift the depth of the neutral axis. When a concrete structural member is subject to chemical attack, corrosion of the top face (the compressed face) leads to a reduction in effective depth, d(t). Furthermore, corrosion of a side face leads to a reduction in width, b(t), and a consequent shift in the depth of the neutral axis, $y_c(t)$, and a loss in bearing strength, $f'_{cd}(t)$.

Substituting d(t), b(t), $f'_{cd}(t)$, and $y_c(t)$ into Eqs. (3.4.2.1) and (3.4.2.2) yields the reduction in flexural strength, $M_{ud}(t)$, and in shear strength, $V_{ud}(t)$, with time, respectively. Figures 3.4.5.1 and 3.4.5.2 show, respectively, the percentage loss in flexural strength and shear strength as time passes.

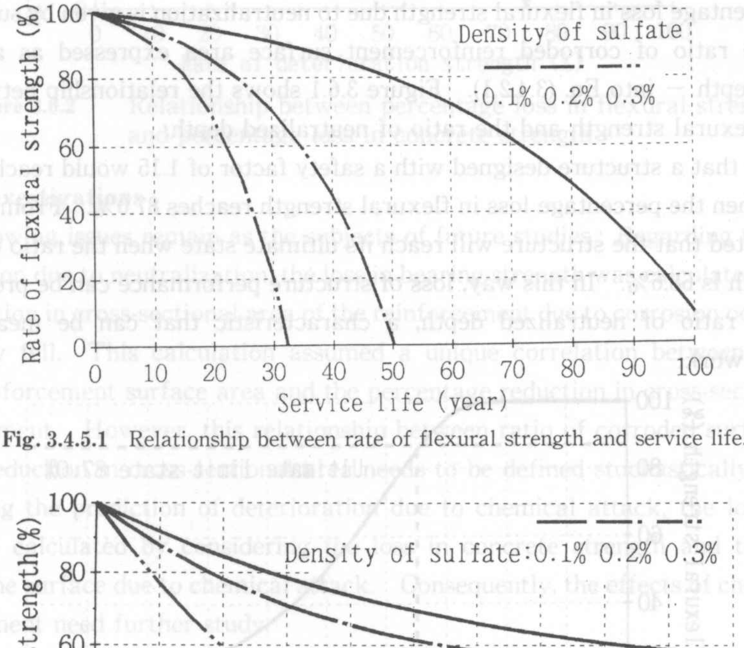

Fig. 3.4.5.1 Relationship between rate of flexural strength and service life.

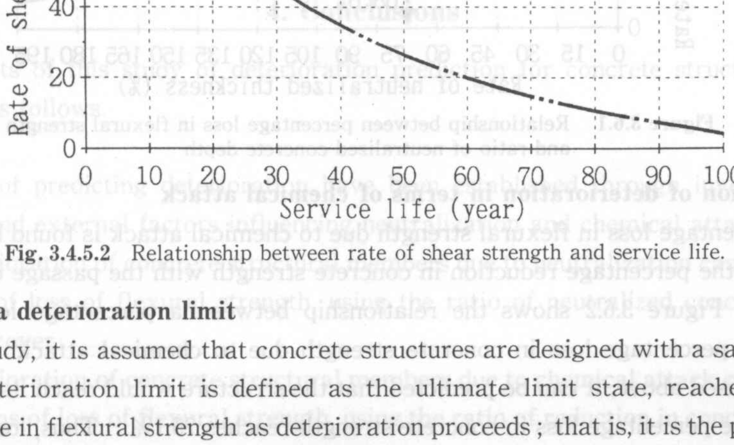

Fig. 3.4.5.2 Relationship between rate of shear strength and service life.

3.5 Defining a deterioration limit

In this study, it is assumed that concrete structures are designed with a safety factor of 1.15. The deterioration limit is defined as the ultimate limit state, reached during the gradual decline in flexural strength as deterioration proceeds ; that is, it is the point at which the safety factor drops below 1.0 due to the loss in flexural strength. In this study, the safety factor is taken to include all non-deterministic factors, such as those for the materials, although these are usually specified separately[8].

3.6 Prediction of deterioration

To operate and manage concrete structures in an optimum manner, it is necessary to predict how their performance will have fallen off due to deterioration at any given time in their service year. In this study, flexural strength is taken as a measure to predict the reduction in performance as deterioration takes place.

3.6.1 Prediction of deterioration in terms of neutralization

The percentage loss in flexural strength due to neutralization is given by substituting Eq. (3.4.1) – the ratio of corroded reinforcement surface area expressed as a function of neutralized depth – into Eq. (3.4.2.1). Figure 3.6.1 shows the relationship between percentage loss in flexural strength and the ratio of neutralized depth.

We infer that a structure designed with a safety factor of 1.15 would reach the ultimate limit state when the percentage loss in flexural strength reaches 87.0%. From this figure, it can be predicted that the structure will reach its ultimate state when the ratio of neutralized concrete depth is 68.6%. In this way, loss of structure performance can be predicted on the basis of the ratio of neutralized depth, a characteristic that can be measured during maintenance work.

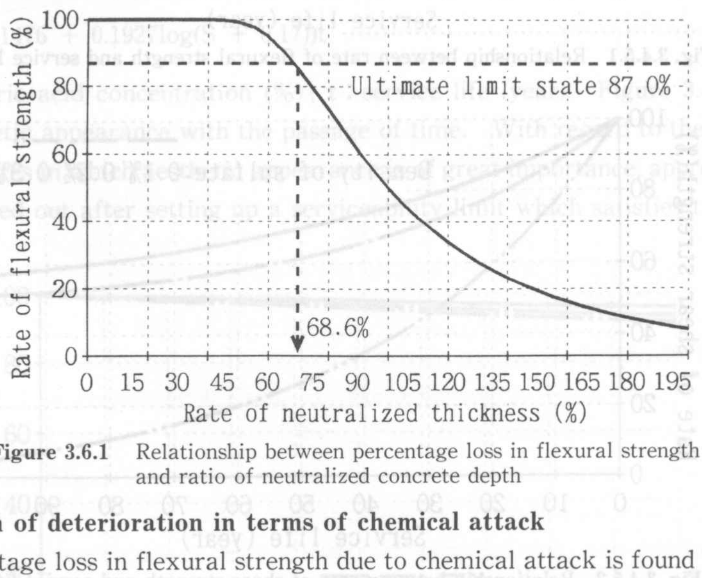

Figure 3.6.1 Relationship between percentage loss in flexural strength and ratio of neutralized concrete depth

3.6.2 Prediction of deterioration in terms of chemical attack

The percentage loss in flexural strength due to chemical attack is found by substituting Eq. (3.4.3) – the percentage reduction in concrete strength with the passage of time – into Eq. (3.4.2.1). Figure 3.6.2 shows the relationship between a percentage loss in flexural strength and percentage loss in concrete strength due to chemical attack. By the same inference as used above, it can be predicted that the structure would reach its ultimate limit state when the percentage loss in concrete strength reaches 75.1%. Thus, loss in structural performance can be predicted on the basis of the percentage loss in concrete strength, a characteristic that can be measured during maintenance work.

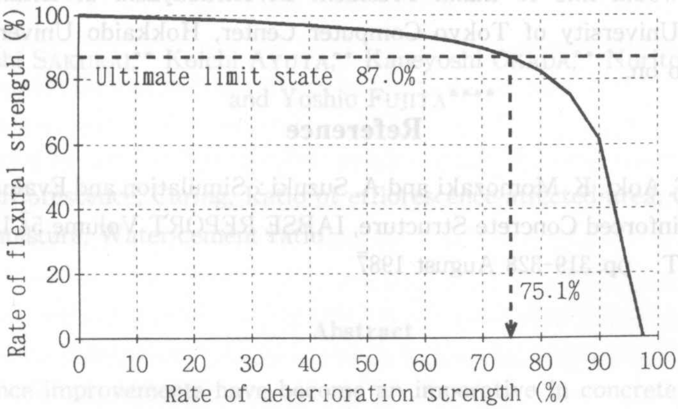

Figure 3.6.2 Relationship between percentage loss in flexural strength and percentage loss in concrete strength

3.7 Future investigations

The following issues remain as the subjects of future studies: Regarding the prediction of deterioration due to neutralization, the loss in bearing strength was calculated by considering the reduction in cross-sectional area of the reinforcement due to corrosion occurring when the alkalinity fell. This calculation assumed a unique correlation between the ratio of corroded reinforcement surface area and the percentage reduction in cross-sectional area of the reinforcement. However, this relationship between ratio of corroded surface area and percentage reduction in cross-sectional area needs to be defined stochastically.

Regarding the prediction of deterioration due to chemical attack, the loss in bearing strength was calculated by considering the loss in concrete strength and the scaling of concrete at the surface due to chemical attack. Consequently, the effects of chemical attack on reinforcement need further study.

4. Conclusions

The results of this study of deterioration prediction for concrete structures may be summarized as follows.

(1) Methods of predicting deterioration have been established through investigating the internal and external factors influencing neutralization and chemical attack.
(2) The deterioration of concrete structural members due to neutralization can be predicted, in terms of loss of flexural strength, using the ratio of neutralized concrete depth to concrete cover.
(3) The deterioration of concrete structural members due to chemical attack can be predicted, in terms of loss of flexural strength, using the ratio of reduction in concrete strength.

Acknowledgements

The author would like to thank President Dr. Hirabayashi at Kitami Institute of Technology, University of Tokyo Computer Center, Hokkaido University Computer Center and So on.

Reference

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