Service Life Design for Sustainable Infrastructures
- Durability Design of Concrete Structures in Present Japan and Future -

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ABSTRACT: This paper introduces the durability design in Standard Specification of Concrete Structures issued by Japan Society of Civil Engineers (JSCE) which is considered the most advanced methodology in Japan. The main feature of the durability design is to provide appropriate verification methods for preventing any degradation of structural performance due to deterioration factors during service life. The Standard Specification provides the verification methods for chloride ion penetration, carbonation, freeze-thaw, alkali-silica reaction and chemical attack. This durability design is adopted in other design codes such as JSCE's Guidelines for Performance-Based Design of Steel-Concrete Hybrid Structures and Design Code for Railway Concrete Structures.

The latter half of this paper outlines the expected direction of the durability design in Japan and necessary research to improve the present durability design. More advanced durability design is to show how to predict chronological changes (or degradation) of structural performance. Most of the required performance is related to mechanical properties of structures and members, such as strength, stiffness, deformability, and cracking. Thus, the prediction of structural performance should be based on the material properties in damaged concrete structures. The mechanical properties of concrete member damaged by ingress of chloride ion and cyclic freeze-thaw are presented as an example.

Keywords: Durability design, Performance-based concept, Chronological change in structural performance

INTRODUCTION

Durability is a primary issue for any structure in the 21st century. Constructing a durable structure would conserve resources and energy providing an environmentally friendly solution. Japan is a leading country to introduce durability design in a practical structural design. This paper introduces durability design in the latest JSCE's Standard Specification [1], where verification formula to make structures durable are provided for the first time in Japan. Since the present methodology for the durability design is not in a final form, this paper introduces research direction to improve the durability design.

JSCE STANDARD SPECIFICATIONS FOR CONCRETE STRUCTURES

Japan Society of Civil Engineers has been publishing Standard Specifications for Concrete Structures for more than 70 years. These specifications serve as a model code for civil engineering structures in Japan. The latest version of the Standard Specifications published in 2001/2002 consists of the following 7 parts [1]:

- Structural Performance Verification
- Seismic Performance Verification
- Materials and Construction
- Maintenance
- Dam Concrete
- Paving
- Test Methods and Specifications

The Standard Specifications are prepared with the performance-based concept. This concept specifies performance requirements;

- Safety
- Serviceability
- Environmental adaptability (including aesthetics)
- Restorability (or reparability)
- Constructability
- Maintainability
- Economy

Recommended methods for verification, which are based on limit state design methodology, are provided for verification of safety, serviceability, restorability and constructability. Restorability is the ability to assure technologically and economically feasible restoration by limiting damages in a structure, which is at present only applied to Seismic Performance Verification.

Durability is not listed among the performance requirements. This, however, does not mean that the Standard Specifications ignore "durability". The Standard Specifications consider that "durability" is the ability to assure that all the performance requirements are satisfied during design service life.

Durability Design

All the provisions related to durability design appear in the Materials and Construction Part at present. Since degradation of structural performance due to environmental actions and mechanical loadings such as fatigue is a main problem for infrastructures, the durability issue has become important. It is, therefore, vital to predict chronological changes, which is usually degradation, in structural performance during service life. If the predicted structural performance satisfies all the performance requirements even after the chronological changes, the durability is assured (see Fig.1 (a)). In Fig.1 (a) ***R*** is structural performance showing a chronological change such as member strength while ***S*** is required performance such as maximum sectional force. ***R*** is always greater than ***S*** during the service life, meaning that the performance requirement such as safety is satisfied. In other word the verification of performance requirements should be conducted with consideration of chronological changes in structural performance.

In the current Standard Specifications to assure durable structures is to provide verification methods for prevention of the structures from being subjected to degradation of their structural performance except for degradation due to fatigue (see Fig.1 (b)). Figure (b) shows that ***R*** is greater than ***S*** at the initial stage and does not degrade during the service life, meaning that the performance requirement is satisfied. The reason for adopting this concept is that the current technological level is good enough to provide prevention measures for structural degradation but not to predict degradation of structural performance. Besides the performance verification can be simplified with this concept because the chronological changes in structural performance is not necessary to be considered.

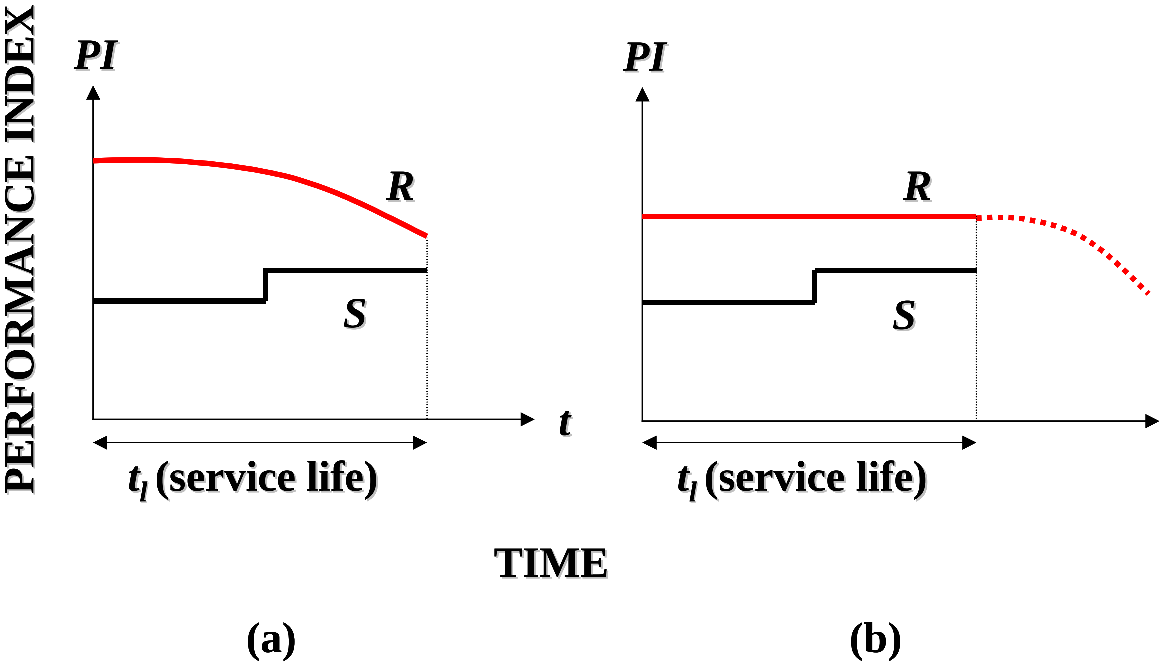


Figure 1 Concept of durability design in current JSCE Standard Specifications

The durability verification methods are provided for carbonation, ingress of chloride ions, cyclic freezing and thawing, chemical attack and alkali aggregate reaction. The verification methods for carbonation, ingress of chloride ions and cyclic freezing and thawing are given in quantitative ways with verification formula.

Verification for carbonation

Limit state for carbonation is initiation of corrosion of steel reinforcement. Carbonation depth, y is used as the index for verification. The verification formula is as follows:

$$\gamma_i \frac{y_d}{y_{\lim}} \leq 1.0 \tag{1}$$

where γ_i is a safety factor to represent the importance of the structure. The limit for carbonation depth, $y_{\lim}$ is

$$y_{\lim} = c - c_k \qquad\qquad y_d = \gamma_{cb} \cdot \alpha_d \sqrt{t} \tag{2}$$

where c is cover depth and c_k is remaining non-carbonated thickness, which may be taken to be 10 mm for a normal environment and 10 to 25 mm for chloride rich environments. On the other hand, the design value for carbonation depth is calculated by the following formula, which is based on the square-root law:

$$y_d = \gamma_{cb} \cdot \alpha_d \sqrt{t} \tag{3}$$

where γ_{cb} is a safety factor to account for the variation in the design value of carbonation depth, t is the design service life, and α_d is the design value of carbonation speed coefficient, which can be calculated as follows:

$$\alpha_d = \gamma_c \cdot \beta_e \cdot \alpha_k \tag{4}$$

where γ_c is a safety factor to account for a difference in concrete property between that at the actual site and at laboratory, β_e is a coefficient to represent the effects of environment and may be taken to be 1.6 for a part of a structure facing north. α_k is the characteristic value of carbonation-speed coefficient, which is set and assured by the following formula:

$$\gamma_p \frac{\alpha_p}{\alpha_k} \leq 1.0 \tag{5}$$

where γ_p is a safety factor to account for the accuracy in determining α_p, and α_p is an estimated value of coefficient representing rate of carbonation (mm/$\sqrt{year}$) and normally may be obtained from Eq. (6).

$$\alpha_p = a + b \cdot W/B \tag{6}$$

where a and b are constants based on the properties of the cement and other materials used, which should be determined using the real data obtained from experiments, and W/B is effective water- binder ratio. $a = -3.57$ and $b = 9.0$ are shown as test results for 17 different concrete mixes.

Verification for ingress of chloride ions

The limit state for ingress of chloride ions is also an initiation of corrosion in steel reinforcement. The index used for describing the limit state is the chloride ion concentration at steel reinforcement. The verification formula is as follows:

$$\gamma_i \frac{C_d}{C_{\lim}} \le 1.0 \tag{7}$$

where γ_i is a safety factor to represent the importance of the structure. The limit value for chloride concentration $C_{\lim}$ may be normally taken as 1.2 kg/mm^3. The design value of chloride ion concentration C_d at depth of steel reinforcement may be calculated by the following equation:

$$C_d = \gamma_{cl} \cdot C_0 \cdot \left(1 - erf\left(\frac{0.1 \cdot c}{2\sqrt{D_d \cdot t}} \right) \right) \tag{8}$$

where γ_{cl} is a safety factor to account for variation in the design value of chloride ion concentration, C_0 is chloride ion concentration at concrete surface (kg/m^3), which may be taken from Table 1, c is concrete cover (cm), t is the design service life (year) and $erf(s)$ is an error function given by the following equation:

$$erf(s) = \frac{2}{\pi^{1/2}} \int_0^s e^{-\eta^2} d\eta \tag{9}$$

Table 1 Chloride ion concentration at concrete surface (kg/m^3)

DISTANCE FROM COASTAL LINE (km)					
Tidal splash zone	Near coastal line	0.1	0.25	0.5	1.0
13.0	9.0	4.5	3.0	2.0	1.5

The design value of diffusion coefficient for chloride ion D_d may be calculated by the following equation:

$$D_d = \gamma_c \cdot D_k + \left(\frac{w}{l} \right) \cdot \left(\frac{w}{w_a} \right)^2 \cdot D_0 \tag{10}$$

where γ_c is a safety factor to take account of the difference in the quality of concrete in the actual structure and the cured 'specimen' in the laboratory, w is the calculated design crack width, w/l is the ratio of crack width to crack spacing, w_a is the allowable crack width specified in the Standard Specifications, D_0 is a constant to express influence of crack for chloride ion movement in concrete and may be taken to be 200 cm^2/year, and D_k is the characteristic value of diffusion coefficient for chloride ion, which is set and assured by the following formula:

$$\gamma_p \frac{D_p}{D_k} \leq 1.0 \tag{11}$$

where γ_p is a safety factor to take account of inaccuracy of determining D_p, which is an estimated diffusion coefficient of concrete, by the following equation:

$$\log D_p = a \cdot (W/C)^2 + b \cdot (W/C) + c \tag{12}$$

where W/C is water – cement (binder) ratio, and a, b and c are constants based on the properties of the cement and other materials used, which should be determined using the real data obtained from experiments. As an example, $a = -3.9$, $b = 7.2$ and $c = -2.5$ are given for normal Portland cement.

Verification for cyclic freezing and thawing

The limit state of verification for cyclic freezing and thawing is the initiation of mechanical damage such as strength and stiffness reduction in concrete. Since there is no commonly accepted knowledge on the mechanical damage in concrete due to cyclic freezing and thawing, the relative dynamic modulus of elasticity is chosen as an index for the verification. The verification formula is as follows:

$$\gamma_i \frac{E_{\min}}{E_d} \leq 1.0 \tag{13}$$

where γ_i is a safety factor to account for the importance of the structure, $E_{\min}$ is the minimum relative dynamic modulus of elasticity to prevent an impair of the structural performance due to cyclic freezing and thawing (shown in Table 2).

The design value of relative dynamic modulus of elasticity E_d is

$$E_d = E_k / \gamma_c \tag{14}$$

where γ_c is a safety factor to take into account the difference in the quality of concrete in the structure (*in-situ*) and that of laboratory cured 'specimen', and E_k is the characteristic value of relative dynamic modulus of elasticity, whose value is chosen appropriately. The following formula is provided to achieve the chosen value in the concrete.

$$\gamma_p \frac{E_p}{E_k} \le 1.0 \tag{15}$$

where γ_p is a safety factor to take into account an inaccuracy in determining the estimated value of relative dynamic modulus of elasticity E_p which may be obtained from the standard freeze-thaw test method (JIS A 1148 A method "the freeze-thaw test method of concrete") for usual cases.

Table 2 Minimum level (percentage of initial level) of relative dynamic modulus of elasticity

Climate		Frequently severe and cyclic freezing and thawing		Moderately severe with atmospheric temperature rarely dropping below 0°C	
Section		Thin	General	Thin	General
Exposure of structure	(1) Submerged in water or often saturated with water	85	70	85	60
	(2) Not covered in (1) above and normal exposure	70	60	70	60

EXPECTED DIRECTIONS FOR DURABILITY DESIGN IN JAPAN

As described at the beginning of the previous chapter, the most general approach for structural design with performance-based concept is to verify that all performance requirements are satisfied during the design service life taking into account chronological changes in structural performance. It is therefore necessary to develop methods to predict chronological changes in structural performance caused by various deterioration factors -- both environmental actions and mechanical loadings. Chronological changes due to corrosion of steel reinforcement, cyclic freezing and thawing and their combined effects are shown as examples.

Prediction of Chronological Changes in Structural Performance

Chronological change due to corrosion of steel reinforcement

The Standard Specifications of JSCE provides the verification method to assure that there would be no corrosion initiation in steel reinforcement during service life. In other words we can predict when the corrosion starts. After corrosion starts degradation of structural performance begins. The corrosion of reinforcing bar surface deteriorates its bond property. The corrosion also causes an expansion of the reinforcing bar volume resulting in cracking in and spalling-off of the cover concrete. Severe corrosion reduces the remaining strength of the reinforcing bar. Cracking may impair serviceability while the reduced reinforcing bar strength may impair safety.

Besides studies on prediction of carbonation rate and chloride ion concentration, the following studies are going on in Japan in order to predict the degradation of structural performance:

(1) To investigate bond stress – slip relationship of reinforcing bar after corrosion considering bond degradation due to the corrosion of reinforcing bar surface and splitting crack in cover concrete
(2) To investigate mechanical property of member with degrading bond
(3) To investigate crack initiation and propagation in cover concrete due to corrosion
(4) To investigate mechanical property of member with splitting crack in cover concrete
(5) To investigate stiffness/strength reduction in reinforcing bar due to corrosion
(6) To investigate mechanical property of member with reduced stiffness/strength in reinforcing bar

Examples of the studies can be found in references [2][3].

Chronological changes due to cyclic freezing and thawing

It is believed that frost damage in concrete causes not only cracking but also degradation in mechanical properties of concrete. However there are only few studies on the mechanical degradation. JSCE’s Standard Specifications, therefore, provides the verification method in which relative dynamic modulus of elasticity is used as an index. Serviceability may be affected by the cracking, while safety by the reduced strength.

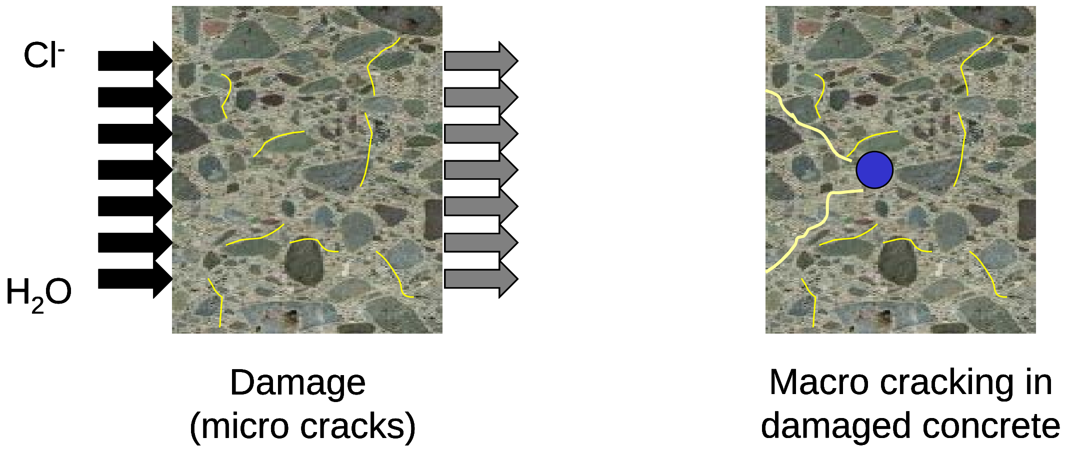
On-going studies in Japan to predict the mechanical properties of member with frost-damaged concrete are as follows:

(1) To investigate mechanism of frost damage
(2) To investigate stress – strain relationship of concrete with frost damage
(3) To investigate bond stress – slip relationship of concrete with frost damage
(4) To investigate mechanical property of member with frost-damaged concrete
(5) To investigate relationship between frost damage in actual structure and specimen in laboratory

Examples of the studies can be found in references [4][5].

Chronological changes due to combined effects of reinforcement corrosion and frost damage

It is known that there are combined effects of ingress of chloride ion and cyclic freezing and thawing. The considered frost damage mechanisms under the effects of chloride ion ingress are (i) increased penetration pressure of water containing chloride due to a difference in chloride ion concentration between large and small pores in the former of which ice is formed, (ii) presence of unfrozen layer which creates pressure due to volume increase during freezing, causing scaling effects in surface layer which is located outside of the unfrozen layer (the unfrozen layer is created by a combination of lowered freezing point due to chloride ion content and temperature gradient depending on the distance from concrete surface), and (iii) sudden decrease in temperature of surface concrete due to heat absorption while chloride sodium is dissolved into water [6]. Frost damage causing small cracks in concrete is believed to increase diffusion coefficient of chloride ion (see Fig. 2 (a)) and decrease split cracking strength due to reinforcing bar corrosion (see Fig.2 (b)).



Impermeability and micro cracks (damages)

(a)

Cracking in frost-damaged concrete due to corrosion

(b)

Figure 2 Coupled effects on concrete degradation by ingress of chloride ion and cyclic freezing and thawing

On-going studies in Japan are as follows:

(1) To investigate frost damage under effects of ingress of chloride ions provided by sea water and de-icer
(2) To investigate chloride ion diffusion through frost-damaged concrete
(3) To investigate cover concrete cracking due to reinforcing bar corrosion under effects of frost damage

CONCLUSIONS

Standard Specifications for Concrete Structures issued by Japan Society of Civil Engineers introduces the latest durability design concept where performance requirements are verified during design service life with consideration of chronological changes (degradation) in the structural performance. The Standard Specifications at present, however, provide only the verification method to assure that there would be no degradation during the service life because of difficulty to predict degradation accurately.

There are various studies going on in Japan to improve the present durability design by clarifying deterioration mechanism, constitutive models of degraded materials and mechanical behavior of members with material degradation.

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