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Deterioration Model of Concrete Bridge Girder in Urban Environment

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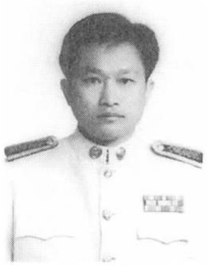

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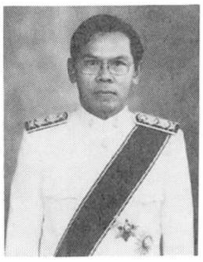

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Summary

Concrete is classified as durable materials compared to other building materials. Permeability characteristics and tensile strength are fundamentaly affect to the concrete durable properties. Aggressive anions and gas can penetrate to the concrete pores by diffusion process. This leads to the deterioration process beneath the concrete surface by physical, chemical or both actions. Concrete can also be damaged by physical process such as frost attack, abrasion, and etc. Strength, serviceability, or structural performance of concrete structures can be reduced with time by these deterioration mechanisms and processes. Such deterioration process can be predicted by mathematical function described the loss of material properties and performance with time by considering the environmental factors and concrete properties. The deterioration models can be utilized in durability design or service life prediction of concrete structures that are the useful information to impose the maintenance policies. This paper presents the basic concept of degradation modeling and mathematical models of deterioration of concrete bridge girders in Bangkok area considering the environmental factors and concrete properties.

1. Introduction

Concrete structures are distinguished as very long service life compared to other building materials. With proper service conditions concrete structures can last a definite time without reduction load - carrying capacity. This arise from the fact that the strength of concrete increases with time. Since concrete is porous material, the most important factors which influence the poor durable properties of concrete are pore size and its distribution. The durable properties of concrete are also affected by the environmental factors such as relative humidity, temperature, penetration of gasses or ions and etc. Good quality of concrete, small volume of pore and low permeability can be achieved by good curing, adequate cement content, and low water cement ratio. In aggressive environment concrete structures can be attacked by degradation factors such as mechanical, biological, chemical, and physical process. These processes can be simulated by appropriated mathematical models, which describe the degradation with time of concrete structures by considering the environmental factors and concrete properties. The purpose of this paper is to present the basic concept of degradation or performance modeling. The mathematical model of deterioration of concrete bridge girders in Bangkok area considering the environmental factors and concrete properties are used as examples.

2. Degradation Factors and Process

Degradation of concrete structures can be represented by mean degradation curve as shown in Fig 1. The curve is increased by degradation factors divided into mechanical, biological, chemical, and physical. Mathematical presentations which shown an increase of degradation with time and with appropriate parameters are called degradation models. Degradation can alternatively be presented as decrease in performance as shown by Fig 2. Mathematical presentations of structural performance with time and appropriate parameters are called performance models. Both empirical and analytical views are considered to develop the model. In general, degradation model can be proceed as the following equation.

$$\mu(D) = D(x_1, x_2, \ldots, x_n, t) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where D = degradation

$\mu(D)$ = mean degradation

$x_1, x_2, \ldots, x_n$ = material ,structural ,and environmental parameters

t = the age of structure years

Performance models derived from degradation models, can also be written in the same manner.

3. Deterioration model of concrete bridge girder.

The durability models which express deterioration of concrete with time has been proposed to obtain modeling of frost attack, surface deterioration, abrasion of concrete , corrosion of reinforcement etc. This model can be used to predict the status of performance or degradation of concrete structures. The selection of relevant durability model are based on concrete properties and conditions surrounding the structures. Since concrete is porous material, so permeability is the most important durable property of concrete. Adequate cement content, low water cement ratio, and good curing can reduce capillary pore volume and permeability. The environmental conditions such as relative humidity, temperature and concentration of aggressive anions or gasses are effected to the transportation of moisture and ions within the pores in concrete. In this paper corrosion model which is the important degradation process for concrete in urban environment is considered.

Model of corrosion of steel in concrete

Steel in concrete are protected by thin oxide layer called passive film which can be formed under the condition of high alkalinity of concrete surrounding steels. The formation of passive film is called "passivation". Depassivation of steels embedded in concrete occur when aggressive anions such as chloride which penetrate to the concrete pores reach the critical concentration. Passive film can also be destroyed by the reduction of alkalinity caused by reaction of calcium hydroxide in cement paste and carbon dioxide dissolved in pore water. This is called carbonation. Corrosion of steels in concrete start after the depassivation of steel caused by these phenomenon. The rate of corrosion depend on moisture and diffusion coefficient of oxygen in concrete pores. The volume of corrosion products is many times that of the original metal. The greater need for volume causes tensile stress in concrete around the steel bar, leading to cracking or spalling of concrete cover. Corrosion model was proposed by Tutti as shown in Fig 3. This model is used for predicting the service life of steel embed in concrete. Initiation period is the time at which concentration of chloride reach the critical value or carbonation front reach steel-concrete interface. The high rate of corrosion commence after the initiation period. For conservative, initiation period is considered as the service life of structural members. In this paper carbonation induced corrosion model is considered.

Carbonation-induced corrosion

Nipon[1] has been developed model of carbonation induced corrosion for bridge structures located in urban environment .Base on Fick's first law the following expression can be derived for the depth of carbonation

$$x = \left(\frac{2D_c(C_1 - C_2)t}{a}\right)^{\frac{1}{2}} \qquad \text{................(2)}$$

where x = carbonation depth (m),
a = amount of alkaline substance in concrete,
D_c = effective diffusivity for CO_2 at a given moisture distribution in the pores (s)
$C_1 - C_2$ = concentration difference of CO_2 between air and the carbonation front (m^3)
t = time

Concrete is porous materials so the evaluation of effective diffusivity of carbon dioxide is very complex since many factors such as water cement ratio , temperature, and relative humidity are involved. Capillary pore volume is directly affected by water cement ratio while the degree of pore saturation within concrete pore is affected by relative humidity. Effective diffusivity can be obtained by the equation proposed by Papadakis et al.[2,3,4]

$$\sqrt{D_c} = B_o \varepsilon_p \left(1 - \frac{RH}{100}\right) \qquad \text{..............(3)}$$

where D_c = effective diffusivity of carbon dioxide sec^2
ε_p = cement paste porosity
B_0 = 1.2×10^{-3}
RH = relative humidity (%)

ε_p can be estimated by the following equation base on experimental data performed by Papadakis et al.

$$\varepsilon_p = 0.63w - 0.05 \qquad \text{................(4)}$$

where w = water cement ratio

The data of relative humidity and carbon dioxide concentration in Bangkok were collected. By using the appropriate confidence level the mean value of involving parameter are used in the calculation of deterioration model. Concrete strength and carbonation depth were collected from 8 bridges. Field concrete strength at the present time can be converted to 28 days strength by method proposed by CEB Model Code 1990. Water cement ratio used in equation (4) can be estimated using the relation between 28 days compressive strength and water cement ratio proposed by ACI committee 211.

material with carbon dioxide in gaseous phase. By substituting the above data to equation (2), (3) and (4) the appropriate carbonation prediction model for bridge structures can be obtained as shown by equation (5).

$$x = 13.58(0.63w - 0.05)\sqrt{wt} \qquad \text{...............(5)}$$

where x = carbonation depth (mm)
w = water cement ratio
t = time (year)

The model is verified by the actual inspection of carbonation depth as shown in Fig 4. The comparison between this model and the other models proposed by previous researchers were shown in Fig 5.

Corrosion of steel embedded in concrete

The degree of corrosion in steel bar at any time was estimated using the Faraday's law of electrolysis. This law states that the mass of any substance lost by a current is proportional to the quantity of electricity which has passed. In the mathematical form this law can be expressed by the following equation [5].

$$m = EIt \qquad \text{...............(6)}$$

where m = mass lost
I = current density
t = time
E = constant

The constant E can be obtained by the consumption of oxygen in cathodic area. Current density can be obtained using the relation of concrete pore saturation and current density proposed by Gonzalez et al [6]. Using the information of local relative humidity, which can be converted to degree of concrete pores saturation, corrosion rate are obtained for initiation and corrosion period as follow.

$$R_{ci} = 11623\ i_{ci} \qquad \text{................ (7)}$$
$$R_{cc} = 11623\ i_{cc} \qquad \text{................ (8)}$$

where R_{ci} = corrosion rate for initiation period (mm/year)
R_{cc} = corrosion rate for corrosion period (mm/year)
i_{ci} = current density for initiation period (amp/cm^2) = 1.0×10^{-4} amp/cm^2
i_{cc} = current density for corrosion period (amp/cm^2) = 6.11×10^{-7} amp/cm^2

The reduction in steel area can be calculated at the certain time using equation (7) or (8). These are useful information for calculation of the reduction of strength and stiffness of reinforced concrete members with time. The corrosion rate of 10 mm. diameter steel embed in concrete for various relative humidity was shown in Fig 6.

Mayta [7] has been studied the reduction of strength and serviceability of reinforced concrete bridge girder using the degradation model proposed by Nipon. Kasatsuek bridge which is reinforced concrete bridge located in Bangkok was used as the case study. High rate of corrosion accelerated by crack are also considered in the calculation of these performance properties. Section properties of reinforced concrete girders such as concrete area, moment of inertia and steel reinforcement area are reduced with time by carbonation and reinforcement corrosion. Using ACI method, nominal moment and shear capacity of the girder at the expected time can be calculated. Maximum deflection at mid span can be obtained by the method proposed by ACI using the concept of effective moment of inertia and mechanics of materials. Only reduction of nominal moment capacity of bridge girder was shown in Fig 7. It can be found that performance, strength and stiffness, of 65 year-old bridge girders are deteriorated with time. The higher rate of deterioration is found ,if the bridge is carrying the heavy truck HS-20.

5. Conclusion

Permeability characteristic and tensile strength of concrete play the important role of its deterioration. Degradation of concrete can be caused by mechanical, physical, chemical and the combination of these degradation processes. Degradation model of each process can be obtained by analytical or empirical method. Both of these methods are considered to develop the degradation models and then the performance models can be derived forword. The study of deterioration rate by considering the environmental factors and concrete properties of 65 year-old bridge located in Bangkok is used as illustrative example. Carbonation induced corrosion model proposed by Nipon is used as degradation model while the performance model proposed by Mayta which express the reduction of strength and stiffness of girders is used as performance model.

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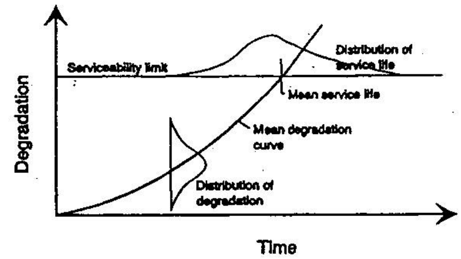

Figure 1 Degradation of concrete structures [8]

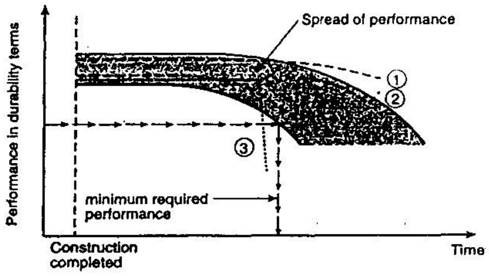

Figure 2 Performance of concrete structures [9]

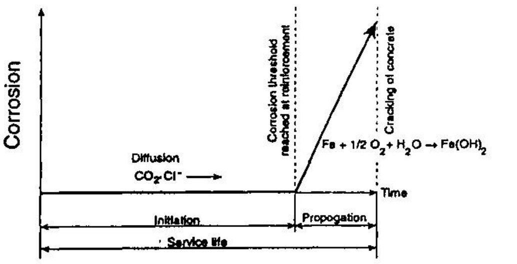

Figure 3 Corrosion model proposed by Tutti [9]

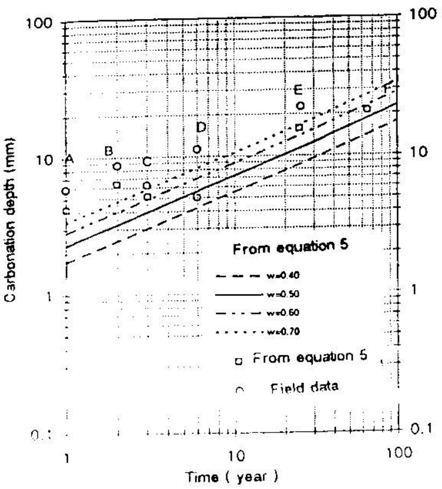

Figure 4 Comparison of carbonation depth with field data

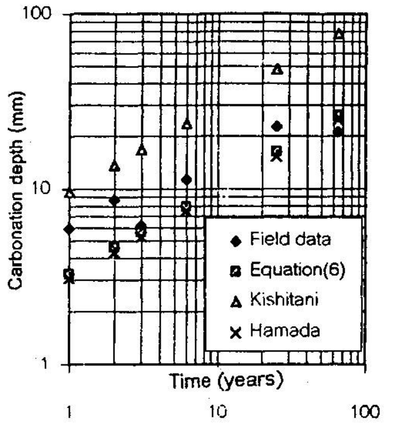

Figure 5 Comparison of carbonation depth predicted by equation (5) and other researchers, (based on average water cement ratio from field data)

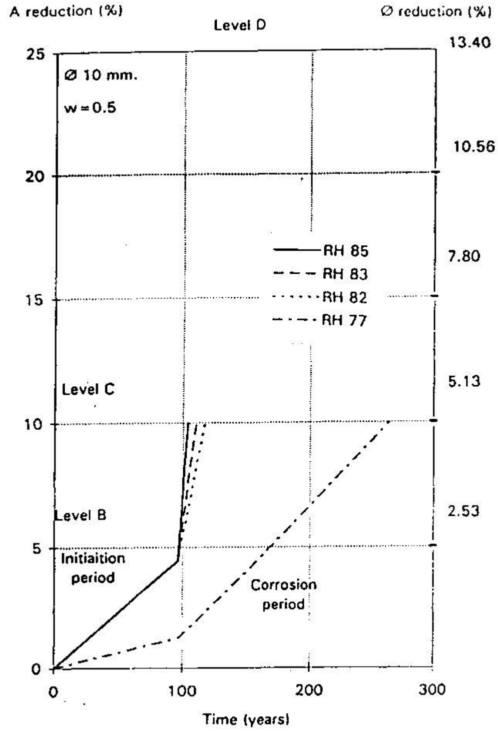

Figure 6 Corrosion rate of 10 mm. diameter steel embedded in concrete for various relative humidity.

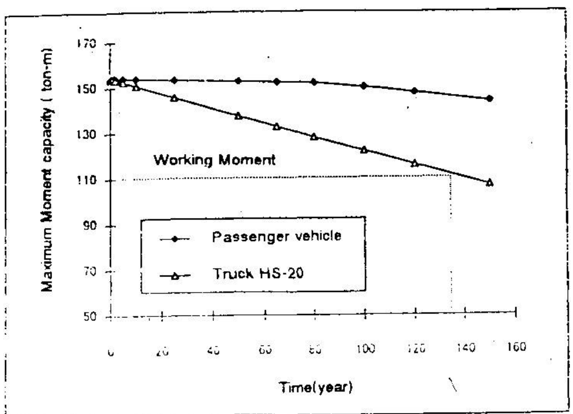

Figure 7 Reduction of moment carrying capacity of Kasatsuek bridge girder.