International Journal of Engineering & Technology, 7 (3.7) (2018) 478-481

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Influence of Supplementary Cementitious Materials on the Service Lifeof Concrete Structure Under Chloride Exposed Environment

Kyung-Joon Shin[1], Yun Yong Kim[1] and Bong-Seok Jang[2*]

[1]*Department of Civil Engineering, Chungnam National University, Daejeon, Korea*
[2]*K-Water, Daejeon, Korea*
**Corresponding author E-mail: concrete@kwater.or.kr*

Abstract

Recently, a variety of studies has been carried out to predict or design a service life of concrete. To insure a targeting service life and long-term performance of concrete structures under chloride ingress environments, mixture proportion of concrete needs to be selected properly based on knowledge about the role and performance of each constituent of mixtures. Recently, supplementary cementitious materials have been widely adapted as components of concrete mixtures due to their outstanding performance in relation to the durability. However, we don't have much information how much these materials influence the durability performance of concrete. Therefore, this study has explored the influence of supplementary cementitious materials on the service life of concrete structures.

Keywords: *Durability; Service life; Chloride, Concrete*

1. Introduction

A large number of concrete structures have been constructed in many countries for the past several decades. However, these structures have suffered from safety and serviceability problems due to the deterioration of concrete. Therefore, concrete durability has received a great amount of attention. Although concrete is believed to be a durable material, concrete structures have been degraded by severe environmental conditions such as exposure to chloride and harmful chemical, abrasion, and other deterioration processes. Therefore, durability evaluation has been required to insure the long-term serviceability of concrete structures located in these harmful environments, especially for chloride

Traditionally, the durability design of concrete structures is based on implicit rules for several factors such as materials, mixture proportions, material compositions, structural dimensions, environmental conditions. Usually, the requirements for a minimum concrete cover, maximum water/cement ratio, minimum cement contents, crack width limitations, air contents, cement type, coating of concrete surface have been specified in the design process. The purpose of all these rules has used to secure service life of concrete structures [1, 7, 12].

As new methods for more accurate durability design of structures have been demanded, a lot of research on concrete durability has produced reliable information on deterioration process [2, 3], which makes it possible to incorporate durability even in the mechanical design of concrete structures. Recently, new methods based on diffusion and probability theories have been established to overcome the above problems in durability design of concrete structures. With them, the service life of concrete structures can be predicted rationally.

To obtain a controlled durability and long-term performance of concrete structures under chloride ingress environments, many parameters related to concrete material need to be selected and designed properly. One of the popular methods is to use supplementary cementitious materials (SCM). It is well known that the SCM can increase the durability performance of concrete without increasing the strength excessively. Thus, this study has explored the influence of SCM in the concrete on the service life of concrete structures. The results can be the basic information that can be used for selection of constituents of concrete mixtures.

2. Analysis Methods

There are two basic approaches for durability analysis against chloride ingress: deterministic or probabilistic approach. In the deterministic approach, only average properties are used in the prediction of service life. However, concrete structures in actual condition behave different from the assumed ideal conditions. For an example, the region where the concrete quality is the poorest is supposed to corrode earlier than elsewhere.

In order to consider the variations of properties, the probabilistic approach should be adapted in the diffusion analysis. There are several prediction methods including Monte Carlo Simulation (MCS) methods, the first-order reliability method (FORM), the second-order reliability method (SORM) (Ang and Tang 1984), and the other (Bentz 2003).

The probabilistic approach is better to simulate the realistic behavior of diffusion in concrete. However, the deterministic approach is still a good tool for parametric study about the chloride diffusion phenomena. In this study, the deterministic approach has been used.

2.1 Serviceability Limit States

In the durability design, serviceability limit states can be determined such as corrosion due to chloride penetration, corrosion due to carbonation, surface deterioration, frost attack, etc. For concrete structures located near seashore, the most significant factor influencing the durability of structure is the chloride ingress, which results in a corrosion of reinforcing steel embedded in concrete. In reality, it may take several years before any visual sign of deterioration such as cracking and spalling will occur after depassivation or onset of steel corrosion. In addition, it may still take a very long time before the structural capacity or integrity becomes significantly reduced.

However, since the time to depassivation, that is when the chloride ion concentration at steel reaches the critical value and the corrosion may start, represents both a reasonable and well defined stage of deterioration process, it is appropriate to define this stage as the serviceability limit state in the durability analysis [2, 4]. With this definition, the limit state function of concrete structure exposed to chloride can be written as equation (1).

$$g(\mathbf{X},t) = R(t) - S(t) \quad (1)$$

in which, X is the design variable vector defining limit state function g, t is time, R(t) and S(t) are time dependent variables representing resistance and load, respectively. In chloride penetration problems, resistance and load are defined as a depth of steel cover and a depth of chloride ion penetration whose concentration reaches critical value, respectively.

2.2 Durability Model

The rate of chloride penetration into concrete can be modelled as a function of depth by using Fick's Second Law of Diffusion.

$$\frac{\partial C(x,t)}{\partial t} = D(t)\frac{\partial^2 C(x,t)}{\partial x^2} \quad (2)$$

where, C(x, t) is chloride ion concentration at a distance x from the concrete surface after being exposed for a time t, and D(t) is the chloride diffusion coefficient dependent on the time t. Because the diffusion coefficient varies with ages, the aging effect can be modeled as follows,

$$\frac{\partial C(x,t)}{\partial T} = \frac{\partial^2 C(x,t)}{\partial x^2}, \quad T = \int_0^t D(\tau)d\tau \quad (3)$$

Generally, the time dependent function D(t) can be written as equation (4) [6].

$$D(t) = D_0\left(\frac{t_0}{t}\right)^n \qquad (t < t_c) \quad (4a)$$

$$D(t) = D_0\left(\frac{t_0}{t_c}\right)^n = const. \qquad (t > t_c) \quad (\quad 4b)$$

where $D(t)$ is the diffusion coefficient at time t, and D_0 is the diffusion coefficient at the reference time t_0 that is usually 28 days. In order to prevent the diffusion coefficient decreasing with time indefinitely, the relationship shown in equation (4) is valid only within the limit time t_c (= 30 years). Beyond this time, the value at time t_c calculated from equation (4b) is assumed to be constant throughout the rest of the analysis period. By substituting equation (4) into equation (3), T is obtained as follows

$$T = D_m t = \frac{D_0}{1-m}\left(\frac{t_0}{t}\right)^m t \qquad (t < t_c) \quad (5a)$$

$$T = D_m t = D_0\left[1 + \frac{t_c}{t}\left(\frac{m}{1-m}\right)\right]\left(\frac{t_0}{t_c}\right)^m t \qquad (t < t_c) \quad (5b)$$

where, D_m is the average diffusion coefficient from initial time 0 to analysis time t. From appropriate initial and boundary conditions and by substituting equation (5) into equation (3), an expression is obtained that permits the prediction of chloride levels based on time-dependent diffusion coefficient.

$$C(x,t) = C_s\left[1 - erf\left(\frac{x}{2\sqrt{D_m t}}\right)\right] \quad (6)$$

where C_S is the chloride ion concentration on the concrete surface and *erf*() is the error function.

3. Durability Analysis

3.1 Overview of Parametric Analysis

Parametric studies are conducted in this section in order to investigate the relations between mixture proportions and service life of concrete structures. For the simplicity of the service life prediction, analytic solution based on error function for 1-D diffusion was adopted. It should be noted that this error function approach has been widely used and proven that it can describe well the chloride diffusion phenomena.

ACI 318-08 recommends a 40 or 50mm of cover depth for reinforced concrete structures exposed to earth or weather. When concrete is in corrosive environments or other severe exposure conditions, the amount of concrete protection can be suitably increased in order to provide sufficient protection against chloride ingress. Assuming typical concrete is used without any other protections, 50 mm of concrete cover depth is not suitable for the concrete structure exposed to chloride environment in order to insure more than 50 years of service life. Here in this section, the influence of mixture proportions including water-binder ratio, fly-ash, slag, and silica fume are investigated on the service life of concrete structures. For this objective, the models proposed in Life-365 have been adopted.

The model proposed in Life-365 defines the diffusion coefficient in terms of water-binder ratio and the level of silica fume (%SF)

$$D_0 = 1 \times 10^{(-12.06 + 2.40w/b)}\, e^{-0.165 \cdot SF}\ (m^2/s) \quad (7)$$

It should be noted that this relationship is only valid up to replacement levels of 15 percent silica fume.

In this model, neither fly ash nor slag are assumed to affect the early-age diffusion coefficient, D_0. However, both materials influence the rate of reduction in diffusivity and hence the value of m. The following equation is used to modify m based on the level of fly ash (%FA) or slag (%SG) in the mixture:

$$m = 0.2 + 0.4(\%FA/50 + \%SG/70) \quad (8)$$

The relationship is only valid up to replacement levels of 50 percent fly ash or 70 percent slag and m itself cannot exceed 0.60 (which would occur if fly ash and slag were used at these maximum levels), that is, m must satisfy $m \le 0.60$.

The properties used in the analysis are listed in Table 1. 75 mm of cover depth is assumed for these parametric studies. The surface and critical chloride concentrations used in Table 1 can represent the conditions of majority region in the US and a marine splash zone [14]. The relationship is only valid up to replacement levels of 50 percent fly ash or 70 percent slag and m itself cannot exceed 0.60 (which would occur if fly ash and slag were used at these maximum levels), that is, *m* must satisfy $m \leq 0.60$.

The properties used in the analysis are listed in Table 1. 75 mm of cover depth is assumed for these parametric studies. The surface and critical chloride concentrations used in Table 1 can represent the conditions of majority region in the US and a marine splash zone [14].

3.2 Effect of Fly-Ash or Slag

Figure 1 and 2 show the corrosion initiation time estimated based on the models and parameters assumed in this study. As modeled in the Eq. (8), the effect of fly ash and slag on the aging coefficient is similar except 50% of fly ash replacement is equivalent to 70% replacement of slag. Figure 1 shows that, as the replacement ratio of fly ash increases, the corrosion initiation time increases, too. This delaying effect is more prominent for the low water-binder ratio mixtures. It can be observed that that the mixture with 0.40 of water-binder ratio and a 50% replacement of fly-ash can achieve about 60 years of service life against chloride induced corrosion.

3.3 Effect of Silica Fume

Figure 3 and 4 show the influence of silica fume on the corrosion initiation time. Since the diffusion coefficient decreases with an increase in the silica fume contents, as described in Eq. (7), the time to corrosion initiation increases with an increase in the silica fume contents. When we compare the results shown in Figures 1, 2, and 3, it can be observed that silica fume is more effective material for delaying the corrosion initiation time than other supplementary materials.

Table 1: Parameters used in the analysis

Parameters	**Values**
Surface chloride concentration, C_s(%)	0.8
Critical chloride concentration, C_{cr} (%)	0.05
Cover depth, x	75 mm
Initial chloride concentration (%)	0.0
Water-binder ratio (W/B)	0.3 - 0.6
Fly-ash	0 - 50 %
Slag	0 - 70 %
Silica fume	0 - 12 %
Time to build up (yrs)	0
Time to propagate (yrs)	0

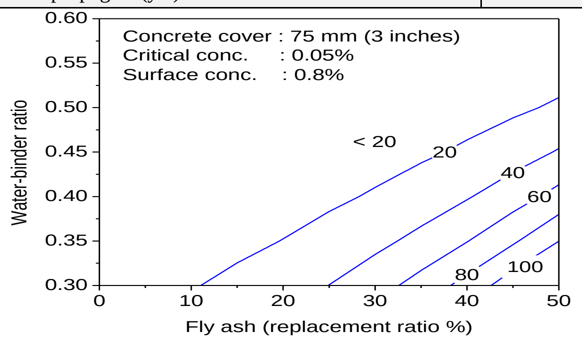

Figure 1: Corrosion initiation time with respect to the water-binder ratio and fly ash contents

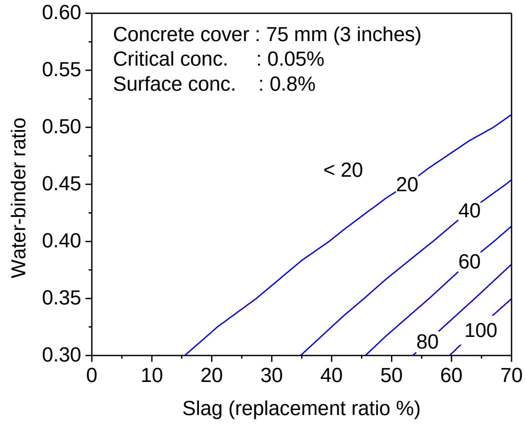

Figure 2: Corrosion initiation time with respect to the water-binder ratio and slag contents

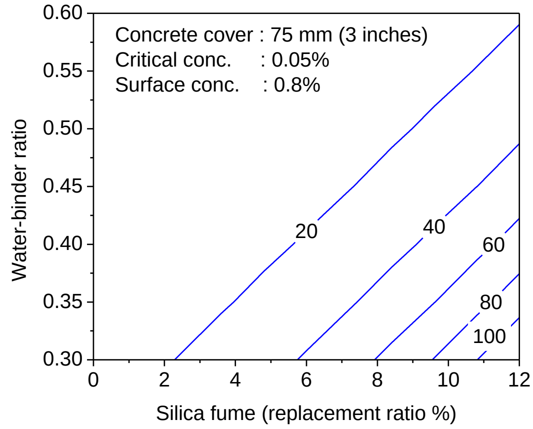

Figure 3: Corrosion initiation time with respect to the water-binder ratio and silica fume contents

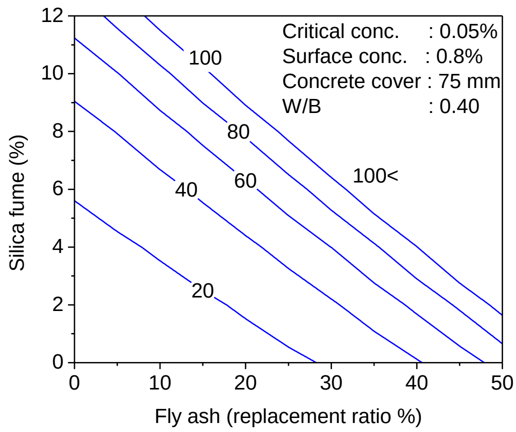

Figure 4: Corrosion initiation time with respect to the contents of silica fume and fly ash (W/B=0.4)

Figure 4 shows the corrosion initiation time with respect to silica fume and fly ash replacement ratios when the water-binder ratio is fixed as 0.40. As expected, the corrosion initiation is delayed when the replacement ratio of fly-ash or silica fume increases. According to the Model, the use of silica fume delay the corrosion by decreasing the diffusion coefficient, meanwhile the use of fly-ash or slag by increasing the aging coefficient.

3.4 Use of Ternary Binders

Even though the model proposed in Life-365 can consider the combined effect of slag and fly-ash, the prediction tends to overestimate the effect of supplementary materials. Moon et al. [11] eported that the diffusion coefficient of concrete using ternary binders is similar to that of concrete using slag cement. In their research, the chloride diffusion coefficient does not vary significantly when the mixture with 60% GGBF and the mixture with 30% FA and 40% GGBF are compared.

4. Conclusion

This paper shows the influence of supplementary cementitious materials on the service life of concrete structures under chloride exposing condition.

(1) Using the analytic solution for the chloride ingress into concrete, corrosion initiation time has been investigated with respect to the mixture proportions. Analysis results show that lower diffusion coefficient (high diffusion resistivity) and higher aging coefficient delay the corrosion initiation. The parametric study shows that the diffusion coefficient can be reduced with the use of silica fume while the aging coefficient can be increased with the replacement of fly-ash or slag.

(2) The analysis results show the importance of the diffusion properties in the service life prediction. Small changes of diffusion properties influence significantly the service life of concrete structures under chloride environment. Therefore, precise information and measurement of the diffusion properties should be obtained in order to predict better the service life.

Acknowledgement

This work was supported by research fund of Chungnam National University.

References

[1] ACI Committee 318, Building code requirements for reinforced concrete (ACI 318-08) and commentary, American Concrete Committee, 2014
[2] Ang, H.-S. and Tang, W., Probability Concepts in Engineering Planning and Design – Decision Risk and Reliability, John Wiley & Sons, New York, 1984
[3] Bamforth, P. B., Spreadsheet Model for Reinforcement Corrosion in Structures Exposed to Chlorides, Concrete under Severe Conditions 2: Environment and Loading, E&FN SPON, London, 1, pp. 64-75, 1998
[4] Bentz, C. Probabilistic Modeling of Service Life for Structures Subjected to Chlorides, ACI Journal of Materials, Vol. 100, No. 5, pp.391-397, 2003.
[5] Collepardi, M., Marcialis, A. and Turriziani, R., Penetration of chloride ions into cement pastes and concrete, J. Am. Ceram. Soc., Vol. 55, No. 10, pp. 534-535, 1972.
[6] Crank, J., The mathematics of diffusion, London: Arrowsmith:, pp. 11-24, 104, 1975.
[7] Edvardsen, C., Kim, Y. J., Park, S. J. Jeong, S. K., and Im, H. C., Busan-Geoje Fixed Link Concrete Durability Design for Bridges and Tunnels, Proceedings of the ITA-AITES 2006 World Tunnel Congress and 32nd ITA General Assembly, 22-27 April 2006, Seoul, Korea.
[8] Luping, T. and Gulikers, J. On the mathematics of time-dependent apparent chloride diffusion coefficient in concrete, Cement and concrete research, Vol. 37, No. 4, pp. 589-595, 2007.
[9] Mangat, P. S. and Molloy, B. T. Chloride Binding in Concrete Containing PFA, GBS or Silica Fume under Sea Water Exposure, Magazine of Concrete Research, Vol. 47, No. 171, pp. 129-141, 1995.
[10] Mehta, P. K. and Monteiro, P. J. M., Concrete: Microstructure, Properties, and Materials, McGraw-Hill, 2006.
[11] Moon, H. Y., Kim, H. S., and Choi, D.S., Relationship between average pore diameter and chloride diffusivity in various concretes, Concstuction and Building Materials, Vol. 20, No. 9, pp. 725-732, 2006.
[12] Sarja, A., and Vesikari, E., Durability Design of Concrete Structures, E & FN Spon, London, UK, 1996.
[13] Schiessl, P., New Approach to Service Life Design of Concrete, Asian Journal of Civil Engineering (Building and Housing), Vol. 6, No. 5, pp. 393-407, 2005.
[14] Thomas, M. D. A. and Bentz, E. C., Life-365 Manual, Silica Fume Association, 2000.