XVI International Conference on Durability of Building Materials and Components
DBMC 2023, China
K.F. Li and D.P. Fang (Eds)

Carbonation-induced Early Corrosion Propagation Based Service Life Assessment Model (CECP-SAM)

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Abstract. *Supplementary cementitious materials (SCMs) are widely used for sustainable concrete. However, this is challenged due to the deteriorated resistance towards carbonation-induced corrosion. This paper introduces the establishment of a novel carbonation-induced early corrosion propagation based service life assessment model (CECP-SAM). This model is characterized by considering the early corrosion propagation (incipient cracking) and the use of supplementary cementitious materials. Based on experimental and numerical methods, the effects of binders, water/binder (W/B) ratio, exposure condition, cover thickness, rebar diameter, semi-carbonation zone, cathode-anode ratio on service life are investigated by CECP-SAM. The model is justified by using the results from a field investigation in Hong Kong. Performance-based service life equations are also given based on CECP-SAM.*

Keywords: *Service Life Model, Supplementary Cementitious Materials, Carbonation-induced Corrosion Propagation, Performance-based Design.*

1 Introduction

Supplementary cementitious materials (SCMs) have been widely used to partially replace ordinary Portland cement (OPC) for reducing embodied carbon of concrete. Unfortunately, however, the resulting resistance to the carbonation of reinforced concrete was found to be significantly decreased thereby (Lye et al., 2016), which means that the propagation stage of the SCM concrete plays a more significant role in the service life of reinforced concrete (RC) structures compared with that of OPC concrete. Moreover, it has been found that corrosion initiation and propagation can be significantly reduced by the semi-carbonation zone (Liu et al., 2018) and macrocell corrosion (Chen & Su, 2022), respectively. Much uncertainty therefore exists where the effects of SCM replacement, the semi-carbonation zone and macrocell corrosion are not considered.

To satisfy this research gap, this study proposes a novel carbonation-induced early corrosion propagation-based service-life assessment model (CECP-SAM) to investigate the service life of carbonated SCM concretes with the considerations of semi-carbonation zone and macrocell corrosion. The establishment of CECP-SAM is briefly introduced, followed by the verification by experimental data and field data. The effects of SCM replacement, water/binder ratio, exposure condition, cover thickness, rebar diameter, cathode over anode ratio (microcell corrosion) and semi-carbonation zone on the service life of carbonated SCM concrete are investigated by using CECP-SAM. Performance-based service life design equations are also presented. One can find more details and results on service life modelling in (Chen, 2022; Chen & Su, 2022).

2 Service Life Modelling

The service life of an RC specimen consists of corrosion initiation and corrosion propagation as shown in Equation (1):

$$t_s = t_i + t_p \tag{1}$$

where t_s is service life, t_i is corrosion initiation time, t_p is corrosion propagation time.

2.1 Corrosion Initiation

As shown in Figure 1, the profile of concrete is divided into three zones, namely fully carbonated zone I, semi-carbonation zone II_1+II_2 and non-carbonation zone III). Considering the effect of semi-carbonation zone, the steel starts to corrode when the front with a critical pH value of 11.5 arrives at the steel. Therefore, the duration of corrosion initiation is calculated by Equation (2):

$$t_i = \left(\frac{c - X_{s-d}}{K_a}\right)^2 \tag{2}$$

where X_{s-d} is the length of semi-carbonation zone, c is cover thickness, K_a is natural carbonation coefficient.

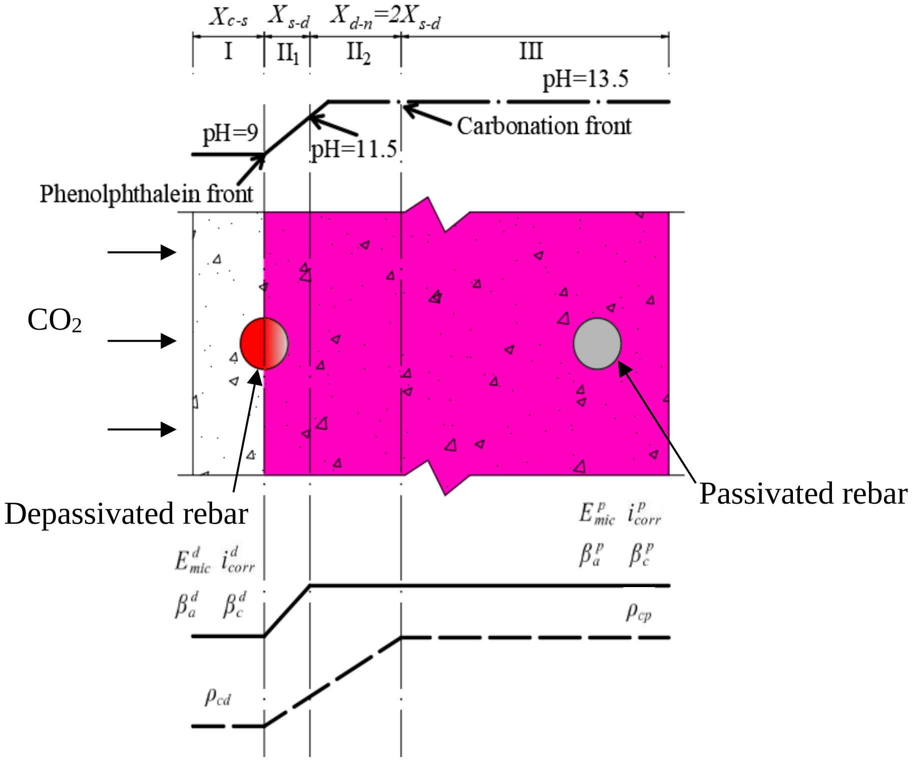

Figure 1 Profile of cross section under partial carbonation.

2.2 Corrosion Propagation

In micro-macrocell corrosion, the macrocell current density of steel is calculated by the anodic and cathodic current densities by Equation (3) (also known as Butler-Volmer equation):

$$i_{mac} = i_a + i_c = i_{corr}\left(e^{2.3\frac{E\ -E_{mic}}{\beta_a}} - e^{-2.3\frac{E\ -E_{mic}}{\beta_c}}\right) \tag{3}$$

where i_{mac} is macrocell current density. Other parameters in Equation (3) are kinetic parameters for characterizing the electrochemical behaviors of a metal.

COMSOL software was used to simulate the electrochemical behaviors of rebars by using Equation (3). The corrosion rate of depassivated rebar (namely rate of iron oxidation) can be obtained accordingly.

The end of service life in this study is defined as an early corrosion propagation with a surface crack width $CMOD_A = 0.5$ mm. Given this surface crack width, a cross-sectional loss can be calculated accordingly by the Equation (4), as proposed in a previous study of the author (Su & Zhang, 2019):

$$A_{loss} = \frac{1}{d(\beta - 1)}\left\{\left(\frac{(d+2c)\,f_t \tan\varphi}{2E_{c,ef}} + CMOD_A\right)\frac{(d+2c)\tan\varphi}{4c} + 2d_0\right\} \tag{4}$$

where A_{loss} is the cross sectional loss of rebar at the end of service life, β is the ratio of the amount of rust to corroded steel (namely, the rust expansion coefficient), f_t is the tensile strength of concrete, $E_{c,ef}$ is the effective elastic modulus of concrete, φ is the angle of the diagonal crack, $CMOD_A$ is the surface crack width (0.5 mm in this study), d is the rebar diameter, c is the cover thickness and d_0 is the thickness of the porous zone around the steel-concrete interface. A_{loss} ranges from 1% to 3% under different combinations of cover thickness and rebar diameter in this study. Based on Equations (3) and (4), one may obtain the corrosion propagation time t_p^{num} by COMSOL simulation.

2.3 Monte-Carlo Simulation

Equation (5) is proposed to correlate the result of COMSOL model t_p^{num} with a deterministic value t_p^{mic} by α_{mac}:

$$t_p^{num} = \alpha_{mac} t_p^{mic} \tag{5}$$

where α_{mac} is the macrocell corrosion coefficient and t_p^{mic} is corrosion propagation time, assuming the corrosion is uniform.

In view of the increase in corrosion rate in cracked reinforced concrete, the effect of cracking on the duration of corrosion propagation is considered by Equation (6):

$$t_p = \frac{t_p^{num}}{\alpha_c} \tag{6}$$

where α_c is the coefficient considering the decrease in corrosion propagation after cover cracking (Otieno et al., 2016).

Based on Equations (1), (2), (5) and (6), the service life of an RC specimen can be calculated by Equation (7):

$$\begin{aligned} t_s &= t_i + t_p \\ &= \left(\frac{c - X_{s-d}}{K_a} \right)^2 + \frac{\alpha_{mac} t_p^{mic}}{\alpha_c} \end{aligned} \tag{7}$$

Figure 2 presents the flow chart of CECP-SAM. Firstly, deterministic COMSOL simulations were conducted considering all combinations of the parameters. Secondly, the mean values of K_a should be determined by concrete mix, W/B ratio and exposure condition while the mean values of X_{s-d}, d, c and CA should be specified. The Monte-Carlo simulation starts by determining the values of the random variables according to their designated distributions. Equation (4) is used to calculate the cross-sectional loss at the end of service life. For a given concrete mix, exposure condition and W/B ratio, an array of α_{mac} under the random value of K_a can be easily calculated based on the corresponding deterministic numerical models. The array of α_{mac} is then fitted. The random values of X_{s-d}, d, c and CA are substituted into the fitted equation of α_{mac} to obtain the corresponding value of α_{mac}. Therefore, the corrosion initiation time, corrosion propagation time and service life can be obtained by Equations (2), (6) and (7). The iteration is repeated for ten thousand times. Finally, the cumulative failure probability of t_i, t_p and t_s under a given age can be calculated. The corrosion initiation time, corrosion propagation time and service life under a specific reliability index can be obtained.

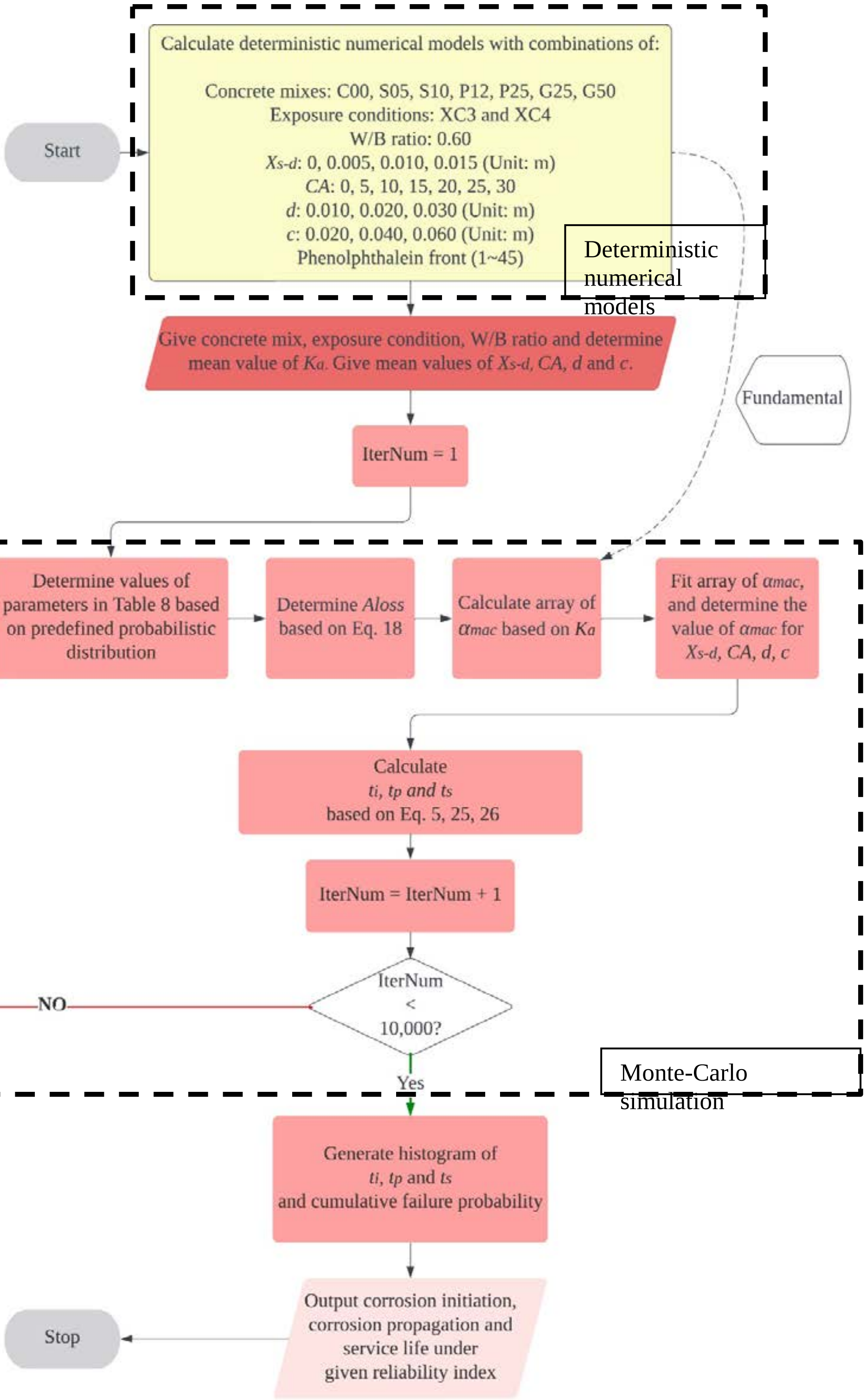

Figure 2 Flow chart of algorithm for CECP-SAM

3 Verification of Service Life Model

The proposed numerical model has been verified by using the experimental data collected in (Chen, 2022; Chen & Su, 2022).

Figure 3 presents a comparison between the field data (collected from 91 flat units in Hong Kong, built between 1952 and 2020) and a case calculated by CECP-SAM. The limit state in CECP-SAM is a crack width of 0.5 mm, while that in the field data is concrete spalling. Therefore, the lag between CECP-SAM and field data ranges from five to ten years. The trend of the case of CECP-SAM is consistent with that of field data. One can conclude that CECP-SAM is able to model the service life of carbonated concrete.

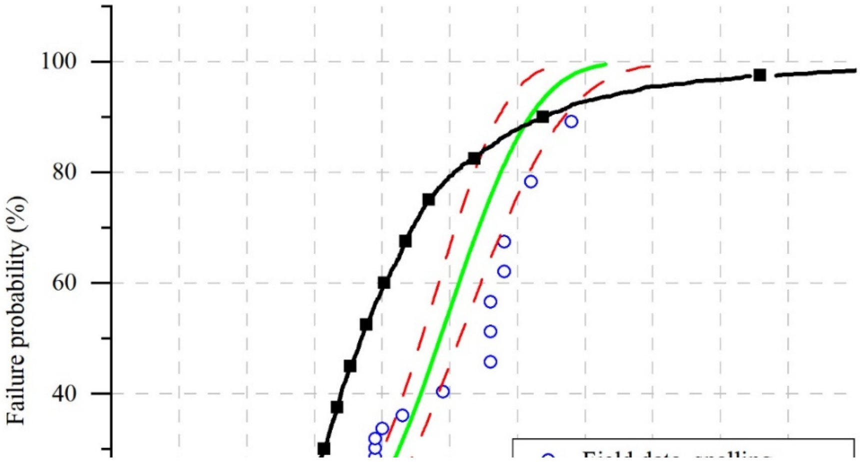

Figure 3 Comparison between field data and results of Monte-Carlo simulation. Parameters in proposed model: C00, XC3ID, W/B ratio = 0.70, X_{s-d} = 0.005 m, CA = 10, d = 0.010 m and c = 0.015 m

4 Results of Service Life Modelling

Figure 4 presents a typical example of the effects of SCM and replacement level on the total service life of all concrete mixes. Except for S05 (silica fume (SF) with 5% replacement level) at exposure condition of XC4, in which the service life is slightly decreased, most of the replacements of ordinary Portland cement (OPC) with SF appear to be beneficial, resulting in increased service life. Service life is significantly reduced when OPC is replaced with pulverized flu ash (PFA) and granulated ground blast-furnace slag (GGBS), regardless of exposure conditions. Under the exposure condition of XC4OD, the replacement of OPC with PFA and GGBS can reduce service life from 530 years to around 40 years and 100 years, respectively. Under the exposure condition of XC3ID, the replacement of PFA and GGBS can reduce service life from 66 years to 8 years and 17 years. Therefore, the partial replacement of OPC with PFA and GGBS should be considered with caution.

Figure 4 Effect of SCM replacement on service life under different exposure conditions. W/B ratio = 0.60, $X_{s\text{-}d}$ = 0.010 m, CA = 10, d = 0.020 m and c = 0.040 m

Figure 5 presents a typical result of the effect of cathode over anode ratio on corrosion propagation, while Figure 6 presents a typical result of the effect of the length of semi-carbonation zone on service life. It can be found that microcell corrosion and semi-carbonation zone can lead to substantial decreases in corrosion propagation and service life respectively, up to around -40%.

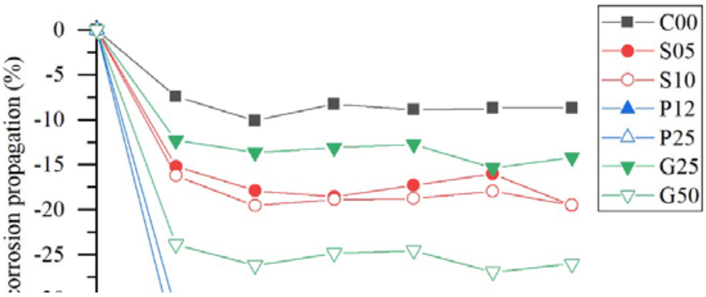

Figure 5 Effect of cathode over anode (C/A) ratio on corrosion propagation. Exposure condition: XC3ID, W/B ratio = 0.60, $X_{s\text{-}d}$ = 0.010 m, d = 0.010 m and c = 0.060 m

Figure 6 Effect of length of semi-carbonation zone X_{sd} on service life. G50, XC3OD, W/B ratio = 0.60, *CA* = 10, *d* = 0.020 m and *c* = 0.040 m

Other important effects on service life of partially carbonated concrete, including the effects of exposure conditions (by which the effect of environmental moisture content is considered), water/binder ratio, cover thickness and rebar diameter can be found in (Chen & Su, 2022). The roles of corrosion initiation and corrosion propagation in service life, and the relationship between carbonation coefficient and service life are also discussed in (Chen & Su, 2022).

5 Performance-based Service Life Design

Performance-based service life design is a promising design methodology, by which the service life of a structure can be quantified through correlation with several critical parameters. As compared with traditional deem-to-satisfy approach, performance-based service life design can provide scientific understanding of service life and support the design approach.

It is of particular interest to correlate the carbonation coefficient with the service life of an RC specimen. Based on CECP-SAM, one can calculate the service life using Equation (8) under different exposure conditions or environmental moisture contents:

$$\begin{aligned} t_s &= (4300d + 221499c^2 - 2781c + 45)K_a^{2.49d-7.20c-1.39} && \text{(XC3ID)} \\ t_s &= (3354d + 191371c^2 - 633c - 0.9)K_a^{0.35d-6.58c-1.46} && \text{(XC3OD)} \\ t_s &= (1361d + 544414c^{2.44} - 5.8)K_a^{-2.00} && \text{(XC4OD)} \end{aligned} \tag{8}$$

Equation (8) conservatively assumes the C/A ratio is 10 and $X_{s\text{-}d}$ is 0.010 m. Using Equation (8), one can easily estimate the service life of an RC specimen based on the carbonation coefficient, regardless of the concrete constituents and W/B ratio, given a certain exposure condition, cover thickness and rebar diameter. c and d in Equation (8) are in the unit of meters while K_a in Equation (8) is in the unit of mm/year$^{0.5}$.

6 Conclusions

In this paper, a novel service life model for partially carbonated concrete with supplementary cementitious materials (SCMs) is proposed with the considerations of macrocell corrosion and semi-carbonation zone. CECP-SAM is verified by experimental and field data. Effects of SCM replacement, macrocell corrosion and semi-carbonation zone on service life are presented. Equations are also proposed for performance-based service life design.

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