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Service life of buildings subject to carbonation-induced corrosion in Hong Kong: field investigation, case studies and recommendations

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ABSTRACT

This paper investigates the service life modelling of Hong Kong buildings subject to carbonation-induced corrosion. The provisions on the design parameters of carbonation-induced corrosion in Hong Kong standards at different periods are summarised. Data from field investigations concerning carbonation-induced corrosion are presented, including in relation to cover thickness, cement content, chloride content, carbonation coefficient and deterioration state. Two case studies concerning residual service life modelling and performance-based service life design are presented using practical equations proposed by a novel service life model, CECP-SAM. To achieve service lives of 50 years and 75 years, deemed-to-satisfy limitations on design parameters, considering the partial replacement of ordinary Portland cement with supplementary cementitious materials (SCMs), are provided. The results indicate a decreasing year-on-year trend in the carbonation coefficients of existing buildings. It is unnecessary to consider the chloride effect for the internal components of buildings constructed after 1965. Rather, additional attention should be paid to carbonation-induced corrosion, especially in old buildings with a high water/cementitious ratio and new buildings with PFA and GGBS substitutions.

KEYWORDS Service life modelling; carbonation-induced corrosion; supplementary cementitious materials; performance-based service life design; carbonation coefficient
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1. Introduction

In recent decades, the corrosion of steel in reinforced concrete (RC) structures has attracted increasing attention among researchers and practitioners. The corrosion of reinforcing steel can be initiated by the carbonation of concrete (CO_2 ingression), chloride attack (seawater ingression, mixed seawater, de-icing salt and air-borne chloride) and a combination of the two. Chloride-induced corrosion has long been a well-known problem for marine and coastal RC structures (Shah and Bishnoi, 2018). However, there remains a lack of understanding surrounding carbonation-induced corrosion. The service life of RC structures can be significantly shortened by the carbonation of concrete, especially for those blended with supplementary cementitious materials (SCMs). There is a worldwide tendency for durability standards to move from being prescriptive to performance-based (Li et al., 2016; Wally et al., 2022).

Service life modelling can support the decision-making process in the maintenance of existing RC structures and provide a scientific basis for the design of new RC structures. The service life of an RC structure consists of corrosion initiation and corrosion propagation. At the corrosion initiation stage, the concrete carbonation front has not reached the depth of the steel, and the steel remains passive. Corrosion propagation commences with the corrosion of the steel due to the carbonation of the concrete surrounding it, resulting in a loss of alkalinity. The Fib model code for service life design (Schiessl et al., 2005) proposed a service life model for carbonation-induced corrosion, but corrosion propagation was neglected. Another service life model for carbonation-induced corrosion was the Portuguese model of LNEC E465, in which corrosion propagation was highly simplified as a uniform process. To fill this research gap, the authors of this paper proposed a novel service life model, CECP-SAM, for carbonated SCM concrete, considering early corrosion propagation (Chen, 2022; Chen and Su, 2024). In CECP-SAM, progressive carbonation following corrosion onset, the semi-carbonation zone and the macrocell zone are fully considered. This model has been verified by field investigations in Hong Kong. Practical equations are also proposed to facilitate a performance-based service life design.

This paper aims to introduce the use of CECP-SAM for conducting performance-based service life modelling in Hong Kong and other regions with similar environmental conditions, and present the field data concerning carbonation-induced corrosion in Hong Kong buildings. A summary of changes made in the durability regulations of Hong Kong's concrete codes is firstly presented in order to gain a greater understanding of the evolution of durability design in Hong Kong. Field investigations on the data related to the carbonation-induced corrosion of Hong Kong's RC buildings are also presented. Two case studies are used to illustrate the use of CECP-SAM to perform the residual service life modelling of existing RC structures and facilitating the service life design of new RC structures. Design provisions on the parameters necessary to achieve service lives of 50 years and 75 years are provided.

2. Summary of the changes in durability regulations in Hong Kong's concrete codes

For carbonation-induced corrosion, service life is significantly affected by cover thickness, water/cementitious ratio and SCM replacement. Table 1 summarises the changes in the limits of the related design parameters in Hong Kong standards. Provisions for SCM replacement are not included since they are unavailable in the relevant standards.

The water/cementitious ratio is a critical concrete mix design parameter, and is directly related to the compressive strength and durability performance of concrete. A higher water/cementitious ratio generally leads to reduced durability performance. However, Table 1 reveals that no restrictions existed on the maximum water/cementitious ratio until 1985. This indicates that the corrosion performance of Hong Kong's buildings constructed before 1985 may be poorly controlled since a high water/cementitious ratio of 0.70 and 0.75 could be used. By introducing the maximum water/cementitious ratio of 0.65 in 1985 (BS 8110 1:1985 and Code of Practice for the Structural Use of Concrete 1987), the service life of buildings constructed after 1985 is expected to be prolonged, as compared with that of buildings constructed in the 1960s and 1970s (B(C)R 1975 & 1976).

Table 1 also presents the minimum concrete cover thickness in Hong Kong standards. Whilst limits on the cover thicknesses of beams and columns have remained somewhat stable, the minimum cover thickness of slabs has increased from 12 mm to 25 mm. Indeed, it should be noted that the minimum cover thickness of slabs was just 15 mm during the period 19751984. Compared with the minimum cover thicknesses of 25/40 mm for beams/columns during this period, it can be postulated that the slabs are prone to carbonation-induced corrosion as compared with beams and columns.

3. Field investigation on Hong Kong's buildings subject to carbonation-induced corrosion

3.1. Cover thickness

Figure 1 presents the distributions of cover thicknesses of different RC components for a number of Hong Kong's RC buildings constructed from 1950 to 1967. After conducting the K-S test, the cover thicknesses were found to be well fitted by normal distribution (p-value: 0.71, 0.16 and 0.88 for slabs, beams and columns, respectively). The mean cover thicknesses (standard deviations) are 17.9 (7.7) mm, 30.4 (18.3) mm and 42.2 (13.7) mm for slabs, beams and columns, respectively. It can be observed that the minimum cover thicknesses of slabs and beams/columns during 1956 and 1974, as required by the design standards, are higher than the minimum values but lower than the mean values of the field data during 1950 and 1967. This indicates that one can consider cover thickness as a stochastic variable with a mean value of the minimum cover thickness (Angst, 2019; Wally et al., 2021), as required by the design standards and an appropriate coefficient of variation.

Table 1. Changes in the minimum cover thickness and maximum water/cementitious ratio in the design standards of Hong Kong.

Period	Standard	Minimum cover thickness (mm)		Maximum water/cementitious ratio
		Slab	Beam/column	
1956-1974	Building Ordinance, B(C)R, London County Council Bylaws 1938 and 1952	12	25	N.A.
1975-1984	B(C)R	15	25/40	N.A.
1985-2003	B(C)R and Code of Practice for the Structural Use of Concrete 1987 or BS 81101:1985	20	20	0.65
2004-now	Code of Practice for the Structural Use of Concrete 2004 and 2013	25	25	0.65

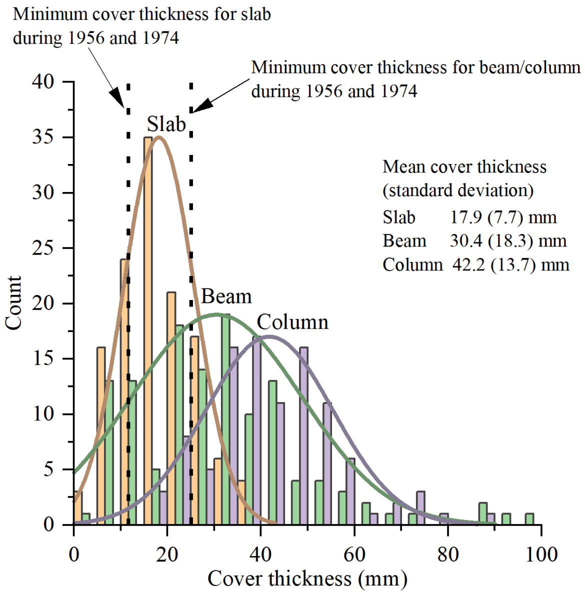

Figure 1. Distribution of cover thicknesses of RC structures constructed from 1950 to 1967.

3.2. Cement content

Figure 2 presents the changes in cement content as a weight percentage of collected powders for buildings constructed from 1957 to 1985. The cement content was obtained by analysing the collected concrete powder based on CEDD CS1:1990 Section 21.6. There is a trend in which cement content percentages increased from 1957 to 1985, despite the large deviations. One may postulate that the water/cementitious ratio for the buildings constructed within this period also declined with the construction time period, as the water content would be relatively stable.

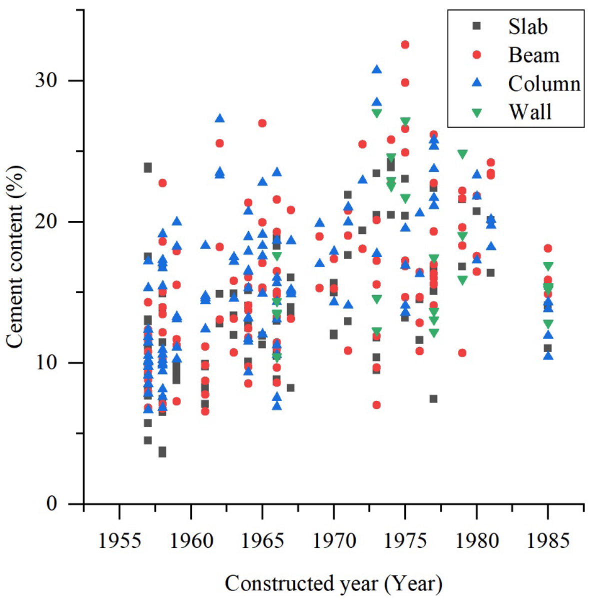

Figure 2. Cement content as a weight percentage of drilled powder of RC structures.

3.3. Chloride content

Figure 3 presents the chloride content by weight of cement for 55 buildings constructed from 1957 to 1985, 53 of which are located in Kowloon, Hong Kong. In the year of testing, the distances of the buildings away from the sea ranged from 247 m to 5 km with 49 buildings located within 1.5 km of the sea. The chloride content was obtained by analysing the collected concrete powder based on CEDD CS1:1990 Section 21.10.2, which is a potentiometric titration method. It can be observed that the chloride content declined with the construction time period. For some buildings constructed between 1957 and 1965, the chloride content is quite high. This could have been induced by the use of seawater during concrete casting or the effect of airborne chloride for coastal buildings. For buildings constructed after 1965, most of the chloride content levels lie below the chloride threshold defined by EN 206:2013.

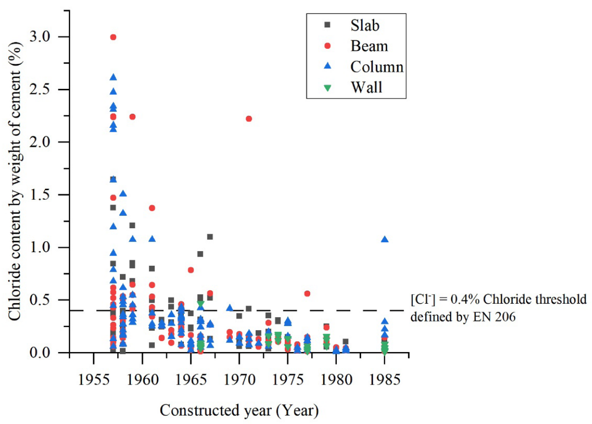

Figure 3. Chloride content by weight percentage of cement of RC structures.

The coupling effect of chloride attack and concrete cover carbonation is an interesting topic. For buildings without direct contact with underground water, seawater and de-icing salts, there are two sources of chloride ions: mixed-in chloride ions in seawater during concrete mixing and air-borne chloride ions. The first case can be found for old buildings built in a period without explicit limitation on the use of seawater during concrete casting in construction codes, and the second case can be found for the external components of buildings nearby the coast. The data shown in Figure 3 indicate two circumstances in which the effect of chloride attack may be considered for carbonation-induced corrosion:

(a) Buildings constructed before 1965, due to the inclusion of seawater; and

(b) External components of buildings nearby the coast.

For the internal components of buildings constructed after 1965, there is no need to consider the effect of chloride attack on carbonation-induced corrosion.

3.4. Carbonation depth and coefficient

Figure 4 presents the tested carbonation coefficients with different component types for buildings constructed from 1950 to 2015. The carbonation coefficients decrease with the construction time period. It should be noted that, although a maximum water/cementitious ratio of 0.65 was implemented in 1985, the carbonation coefficients before 1985 still show a declining trend with the construction time period. This can be explained by the increased content of cement, as found in Figure 2. Figure 4 also shows that there are insufficient data for buildings constructed after 1985.

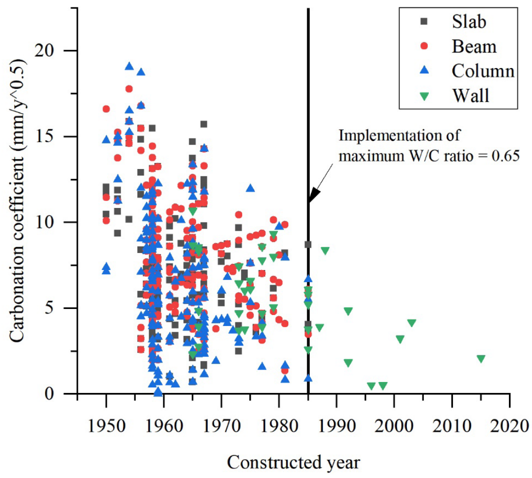

Figure 4. Carbonation coefficient of RC structures.

Table 2 shows the average values and standard deviations of the carbonation coefficients for buildings constructed during different periods of time, which can be used to conduct the performance-based design of carbonation-induced corrosion for Hong Kong's buildings.

Table 2. Statistics of carbonation coefficients of Hong Kong's buildings.

Build year	Type of component	Number of tests	Average carbonation coefficient ($mm/y^{0.5}$)	Standard deviation ($mm/y^{0.5}$)
1950-1959	Slab	126	7.54	3.14
	Beam	117	9.01	3.72
	Column	101	7.44	4.46
1960-1969	Slab	75	7.18	3.23
	Beam	77	7.86	3.15
	Column	71	5.79	3.29
	Wall	8	6.27	2.96
1970-1979	Slab	6.30	1.86	
	Beam	36	7.18	1.93
	Column	17	4.79	2.31
	Wall	16	6.14	1.70
1980-1990	Slab	4	6.19	2.28
	Beam	10	5.57	2.28
	Column	8	4.98	3.22
	Wall	7	5.12	1.76
1992-2015	Wall	7	2.47	1.58

3.5. Deterioration state

Ninety-one residential buildings in Hong Kong, built between 1952 and 2020, were visually inspected in 2021 and 2022. The observations showed carbonation-induced damage mainly to have occurred within the slabs. Figure 5 presents the deterioration states of 334 RC slabs in relation to building age upon inspection. Carbonation-induced damage - narrow cracks, wide cracks, local spalling and widespread spalling - was found in 50 slabs, representing a total of 15% of all inspected slabs. Figure 5 shows the locations of those RC slabs in which carbonation-induced damage was found, from which it can be concluded that damage was mainly found in washrooms, which may be related to the room's high moisture content. Nevertheless, it should be noted that a substantial proportion of damaged slabs were also found in other rooms, such as living rooms and bedrooms. Figure 6 presents photos of typically damaged slabs found during the field investigation.

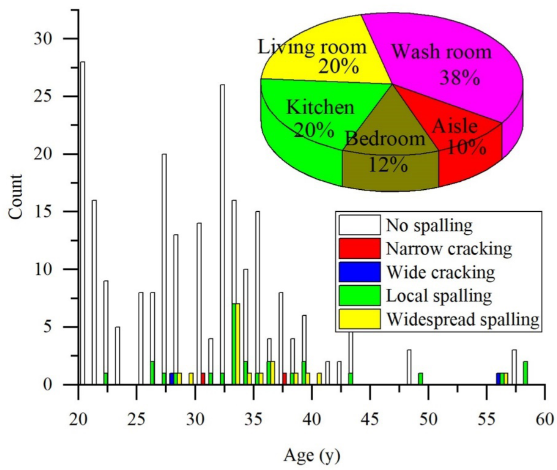

Figure 5. Deterioration state of slabs at 91 residential buildings in Hong Kong.

Hong Kong is a coastal city. The chloride-induced corrosion of coastal RC structures is well known by local engineers and practitioners. However, insufficient attention has been directed towards the carbonation-induced corrosion of RC buildings located away from the coast, regarding which the consequences are also serious. The main reason for the deterioration of the components of old buildings is the high carbonation coefficients associated with a high water/cementitious ratio. For new buildings, the use of supplementary cementitious materials should be carefully considered, which will be illustrated in Section 5.1.

(a)

(b)

(c)

Figure 6. Examples of carbonation-induced damage. (a) Wide cracking in a bedroom; age of building = 28 years; (b) local spalling in a bedroom; age of building = 28 years; and (c) widespread spalling in a washroom; age of building = 38 years.

4. Case studies for service life modelling using CECP-SAM

An experimental study was conducted to investigate the effects of SCMs on the carbonation coefficient and corrosion performance of carbonated RC structures. Three types of SCMs, namely silica fume (SF), pulverised fly ash (PFA) and ground granulated blast furnace slag (GGBS), were studied using two replacement levels. A traditional ordinary Portland cement (OPC)-based concrete mix without SCM replacement was also studied for reference. Based on the experimental data, a novel Carbonation-induced Early Corrosion Propagation-based Service-life Assessment Model (CECP-SAM) was proposed and compared with field data in Hong Kong. In CECP-SAM, various variables are considered including exposure condition, binder type, water/cementitious ratio, cover thickness, rebar diameter, cathode/anode ratio and length of the semi-carbonation zone. End of service life is defined as surface cracking width = 0.5 mm prior to the spalling of concrete, which is a threat to pedestrians. In CECP-SAM, by considering the design parameters as stochastic variables with given mean values, coefficients of variation and modes of probabilistic distribution, Monte-Carlo simulations were conducted 10,000 times. Service life results corresponding to a failure probability of 2.3% (or reliability index of 2.0) were used. Further details can be found in (Chen, 2022; Chen and Su, 2024).

This section illustrates the residual service life modelling and performance-based service life design using practical equations given by CECP-SAM (Chen, 2022; Chen and Su, 2024). Here, the assumptions of the cathode/anode ratio (CA) = 10 and length of semi-carbonation zone (X_{s-d}) = 10 mm are adopted. The assumed values are deemed representative if no data are available. One should use the equations in (Chen, 2022; Chen and Su, 2024) if the cathode/anode ratio and length of semi-carbonation zone are different from the assumed values.

4.1. Residual service life modelling for existing RC buildings

Practical equations have been proposed for service life modelling by CECP-SAM:

$$t_s = (3354d + 191371c^2 - 633c - 0.9) K_a^{0.35d-6..}, \quad (1)$$

$$t_s = (4300d + 221499c^2 - 2781c + 45) K_a^{2.49d-7.20c-1.39}, \quad (2)$$

where t_s denotes service life (year), d denotes rebar diameter (m), c denotes cover thickness (m) and K_a denotes carbonation coefficient (mm/y$^{0.5}$). Equation (1) is used for exposure condition 1 while Equation (2) is used for exposure condition 2, as defined by the Code of Practice for the Structural Use of Concrete 2013 (2020 Edition) (CoP_SUC2013 [2020e]) (Building Department of HKSAR, 2020) in Table 3.

One can estimate the residual service life using Equations (1) and (2). The following are the parameters of an RC component whose residual service life needs to be estimated.

Construction year:	*1986*
Inspection year:	*2022*
Type of component:	*beam*
Location:	*living room*
Cover thickness:	*0.03 m*
Rebar diameter:	*0.02 m*
Type of binder:	*OPC without SCM*
Water/cementitious ratio:	*0.65*

In accordance with Table 3, the exposure condition of the beam is 1 (internal concrete surface). Equation (1) should be used. The carbonation coefficient to be used can be obtained via field tests, or Table 4 and Table 5, according to the exposure condition, binder and water/cementitious ratio. This case study used a carbonation coefficient of 2.31 mm/y$^{0.5}$, in accordance with Table 4. By substituting K_a = 2.31 mm/y$^{0.5}$, d = 0.02 m and c = 0.03 m into Equation (1), the service life is 55 years with a reliability index of 2.0 (or failure probability of 2.3%) as described above. The age of the building was 36 years at the time of inspection and therefore the remaining service life was 19 years.

4.2. Performance-based service life modelling for new RC buildings

The following equations can be obtained in accordance with the equations in (Chen, 2022, Chen and Su, 2024):

$$K_a = \left(\frac{t_s}{3354d + 191371c^2 - 633c - 0.9}\right)^{\frac{1}{0.35d - 6.58c - 1.46}}, \quad (3)$$

$$K_a = \left(\frac{t_s}{4300d + 221499c^2 - 2781c + 45}\right)^{\frac{1}{2.49d - 7.20c - 1.39}}, \quad (4)$$

$$\alpha_k = -118.2c^2 + 13.8c - 0.221 \qquad \alpha_k \in [0, 1], \quad (5)$$

$$t_i^{num} = \alpha_k \left(\frac{c - 0.01}{K_a}\right)^2, \quad (6)$$

where α_k denotes the empirical factor that correlates the probabilistic value with the theoretical value of the corrosion initiation stage and t_i^{num} denotes the corrosion initiation stage (year) with 2.3% failure probability. Equation (3) is used for exposure condition 1 while Equation (4) is used for exposure condition 2, as defined by CoP_SUC2013 (Building Department of HKSAR, 2020) (Table 3).

One can conduct a performance-based service life design using Equations (3) to (6). The following are the parameters of an RC component whose concrete mix design needs to be determined.

Type of component:	*slab*
Location:	*washroom*
Cover thickness:	*0.02 m*
Rebar diameter:	*0.012 m*
Expected service life:	*50 years*

In accordance with Table 3, the exposure condition of the beam is 2 (internal concrete surface exposed to high humidity). Equation (4) should be used. By substituting t_s = 50 years, c = 0.02 m and d = 0.012 m into Equation (4), the required carbonation coefficient is 1.88 mm/y$^{0.5}$. In accordance with Table 5, the following combinations of binder and water/cementitious ratio can be selected:

C00-0.50, S05-0.45, S10-0.50, G25-0.40, G50-0.40.

G25-0.40 was selected for further calculations. The carbonation coefficient would be 1.75 mm/y$^{0.5}$. By substituting K_a = 1.75 mm/y$^{0.5}$ and c = 0.02 m into Equations (5) and (6), the corrosion initiation stage is 0.2 years. This indicates that the steel may start to corrode within a short time under the assumption of a cathode/anode ratio of 10 and length of semi-carbonation zone of 0.01 m. This is in accordance with the findings in (Chen, 2022; Chen and Su, 2024), in which corrosion propagation plays a dominant role in the service life of an RC component under high humidity indoor exposure, with a low cover thickness and rebar diameter. The role of corrosion initiation in service life is mainly dependent on the exposure condition, length of the semi-carbonation zone, water/cementitious ratio and cover thickness. One may consider an increase in cover thickness or a decrease in water/cementitious ratio to ensure that the corrosion initiation stage is sufficiently long, in cases where a high safety level is needed.

Table 3. Exposure conditions as defined by CoP_SUC2013 (Building Department of HKSAR, 2020).

Exposure condition	Type of exposure
1	Mild - Internal concrete surfaces. - External concrete surfaces protected from the effects of severe rain or cyclic wetting and drying (e.g., concrete finish with mosaic tiles, painting or rendering). - Concrete surfaces continuously under water, or rarely dry-not sea water. - Concrete in contact with non-aggressive soil.
2	Moderate - Internal concrete surfaces exposed to high humidity (e.g., bathrooms and kitchens). - External concrete surfaces exposed to the effects of severe rain or cyclic wetting and drying (e.g., fair faced concrete, concrete with cladding secured by dry or mechanical fixing, curtain walling).

Table 4. K_a with different W/B ratios under Condition 1 of CoP_SUC2013 (Building Department of HKSAR, 2020) (Unit: mm/$y^{0.5}$).

W/B ratio	C00	S05	S10	P12	P25	G25	G50
0.80	4.48	-	-	-	-	-	-
0.75	3.65	-	-	-	-	-	-
0.70	2.93	-	-	-	-	-	-
0.65	2.31	-	-	-	-	-	-
0.60	1.80	1.93	1.70	3.69	5.66	3.17	2.74
0.55	1.35	1.44	1.28	2.82	4.34	2.43	2.10
0.50	1.00	1.07	0.95	2.13	3.26	1.83	1.58
0.45	0.73	0.78	0.69	1.56	2.39	1.34	1.16
0.40	0.49	0.53	0.47	1.11	1.71	0.96	0.83

* C00: OPC without SCM replacement, S05: 5% of OPC replaced by SF, S10: 10% of OPC replaced by SF, P12: 12% of OPC replaced by PFA, P25: 25% of OPC replaced by PFA, G25: 25% of OPC replaced by GGBS and G50: 50% of OPC replaced by GGBS.

Table 5. K_a with different W/B ratios under Condition 2 of CoP_SUC2013 (Building Department of HKSAR, 2020) (Unit: mm/y0.5).

W/B ratio	C00	S05	S10	P12	P25	G25	G50
0.80	8.17	-	-	-	-	-	-
0.75	6.66	-	-	-	-	-	-
0.70	5.35	-	-	-	-	-	-
0.65	4.22	-	-	-	-	-	-
0.60	3.29	3.52	3.11	6.73	10.33	5.79	5.00
0.55	2.47	2.64	2.33	5.16	7.92	4.44	3.83
0.50	1.83	1.95	1.73	3.88	5.96	3.34	2.88
0.45	1.33	1.42	1.25	2.85	4.37	2.45	2.12
0.40	0.90	0.96	0.85	2.03	3.12	1.75	1.51

* C00: OPC without SCM replacement, S05: 5% of OPC replaced by SF, S10: 10% of OPC replaced by SF, P12: 12% of OPC replaced by PFA, P25: 25% of OPC replaced by PFA, G25: 25% of OPC replaced by GGBS and G50: 50% of OPC replaced by GGBS.

5. Recommendations according to CoP_SUC2013 (Building Department of HKSAR, 2020)

Section 4 introduces the use of CECP-SAM for conducting performance-based service life modelling. Although it is believed that the performance-based service life design approach will be an important option in the future, the deemed-to-satisfy design approach is adopted in most current international and local design standards. This section introduces a prescriptive design approach based on the format of CoP_SUC2013 (Building Department of HKSAR, 2020).

5.1. Use of supplementary cementitious materials

The beneficial effects of SCM substitution in increasing chloride diffusion resistance and chloride binding ability have been widely accepted (Papadakis, 2000; Riding et al., 2013; Thomas et al., 2012) and adopted in design standards. On the other hand, the harmful effects of SCM substitution on the service life of carbonated concrete have not been widely recognised, especially by practitioners and engineers. The carbonation coefficient of RC structures can be significantly increased by the partial replacement of OPC with SCMs, as a result of reduced alkalinity (Chen and Su, 2022; von Greve-Dierfeld et al., 2020). Moreover, the corrosion rate of steel in carbonated concrete has also been found to increase due to SCM substitutions (Chen and Su, 2022; Stefanoni et al., 2018). As a result, SCM replacements can lead to significant service life reduction, especially for PFA and GGBS concretes (Chen, 2022; Chen and Su, 2024). Although it is necessary to restrict the SCM substitutions for buildings subject to carbonation-induced corrosion, there are no such provisions in CoP_SUC2013 (Building Department of HKSAR, 2020).

Herein, Table 7 and Table 9 present the limits on the maximum replacement level, minimum cover thickness and maximum water/cementitious ratio for SCM blended concrete mixes to achieve service lives of 50 years and 75 years, respectively.

5.2. Design parameters according to the Code of Practice of the Structural Use of Concrete

Based on CECP-SAM, preliminary limits on the design parameters can be given for a specific service life. One can find the recommended design parameters in Table 6 to Table 9 for the 50- and 75-year service life designs of OPC concrete and SCM concrete under different exposure conditions, as defined by CoP_SUC2013 (Building Department of HKSAR, 2020) (Table 3). It should be noted that the results in Table 6-Table 9 were calculated under the assumptions of a cathode/anode ratio (*CA*) = 10 and length of semi-carbonation zone ($X_{s\text{-}d}$) = 10 mm. The assumed values are deemed to be representative if no data are available. One should use the equations in (Chen, 2022; Chen and Su, 2024) if the cathode/anode ratio and length of semi-carbonation zone are different from the assumed values.

Table 6. Recommendations for the design parameters for a service life of 50 years, OPC.

Conditions of exposure	Nominal cover (mm)						
Lowest grade of concrete	C20/C25	C30	C35	C40	C45	C50	>C55
Condition 1	35	30	30	30	25	25	25
Condition 2	--	50*	40*	35	30	30	30
Maximum free water/ cementitious ratio	0.65	0.65	0.60	0.55	0.45	0.40	0.35
Minimum cementitious content (kg/m^3)	290	310	330	350	375	400	400

* Stricter limits as compared with CoP_SUC2013 (Building Department of HKSAR, 2020).

Table 7. Recommendations for the design parameters for a service life of 50 years, SCM.

Conditions of exposure	Condition 1			Condition 2		
Allowable SCM	SF	PFA	GGBS	SF	PFA	GGBS
Maximum replacement level (%)	10	25	50	10	25	50
Minimum cover thickness (mm)	30	30	25	40	35	30
Maximum free water/cementitious ratio	0.60	0.40	0.45	0.60	0.35	0.40
Minimum cementitious content (kg/m^3)	290	420	395	290	420	420

Table 8. Recommendations for the design parameters for a service life of 75 years, OPC.

Conditions of exposure	Nominal cover (mm)						
Lowest grade of concrete	C20/C25	C30	C35	C40	C45	C50	>C55
Condition 1	--	35	30	30	25	25	25
Condition 2	--	--	55	40	30	30	30
Maximum free water/ cementitious ratio	0.65	0.65	0.60	0.55	0.45	0.40	0.35
Minimum cementitious content (kg/m3)	300	320	340	360	385	410	410

Table 9. Recommendations for the design parameters for a service life of 75 years, SCM.

Conditions of exposure	Condition 1			Condition 2		
Allowable SCM	SF	PFA	GGBS	SF	PFA	GGBS
Maximum replacement level (%)	10	25	50	10	25	50
Minimum cover thickness (mm)	30	35	30	35	40	35
Maximum free water/cementitious ratio	0.60	0.40	0.45	0.50	0.35	0.40
Minimum cementitious content (kg/m3)	300	430	405	380	430	430

6. Conclusions

In this study, field investigations, case studies of performance-based service life modelling and prescriptive recommendations for the design parameters for achieving service lives of 50 years and 75 years are presented for the carbonation-induced corrosion of Hong Kong's buildings. Based on the results of this study, the following conclusions can be drawn:

(a) A maximum water/cementitious ratio of 0.65 was implemented in the Hong Kong standards in 1985. For buildings constructed prior to 1985, a high water/cementitious ratio may have been used.
(b) There is a trend in which the carbonation coefficient of buildings constructed after 1950 decreases with the construction time period. The average carbonation coefficient decreases from 9 mm/y$^{0.5}$ to 2.5 mm/y$^{0.5}$.
(c) It is not necessary to consider the coupling effect of chloride attack for buildings constructed after 1965, especially in relation to internal RC components.
(d) Residual service life estimation and performance-based service life modelling can be implemented using the novel service life model CECP-SAM.
(e) Deemed-to-satisfy limitations on the design parameters for achieving service lives of 50 years and 75 years are provided for carbonated RC structures, considering the SCM substitutions. The partial replacement of OPC by GGBS and PFA can lead to a significant decline in service life.

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