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Probabilistic Analysis of the Durability of Piles with Microcracks Under Chloride Attack

Wei Shao^{1,2*} and Danda Shi¹

Abstract

A probabilistic analysis approach for estimating the durability of piles with microcracks under chloride attack is presented. The chloride ingress model is obtained by considering the time-dependent diffusion process. The equivalent diffusion coefficient is derived to investigate the crack effect by introducing the crack effect factor. The fitting formula between the chloride diffusion coefficients and crack widths is established through experimental results, and the proposed equivalent diffusion coefficient is verified by comparison with the experimental results. The probabilistic evaluation of durability of piles with microcracks is performed, and then the parametric analysis is performed to study the effect of main parameters on the failure probability and durability life. The results indicate that the chloride concentration increases rapidly as the crack width increases at the same number of cracks. The durability life greatly reduces with increasing crack density of pile. The durability life predicted by probabilistic method is always less than those by deterministic method at the same condition. The deterministic approach may underestimate the threat of reinforcement corrosion induced by chloride attack, owing to the omission of probabilistic nature of main influencing parameters.

Keywords: probabilistic analysis, durability life, piles, microcracks, chloride attack

1 Introduction

Corrosion caused by chloride ions is accepted as the significant deterioration mechanism of reinforced concrete piles. Once the corrosion initiation is activated, the bearing behavior of piles can seriously be deteriorated, thereby severely threatening the serviceability and safety of piles (Liu et al., 2021; Shi et al., 2012). Therefore, the significance of evaluating the durability has been highlighted to ensure the reliability of piles subjected to chloride attack.

The appearance of microcracks in piles can be induced by many factors such as shrinkage, expansive degradation reactions, weathering processes and mechanical loading (Li et al., 2021; Meng et al., 2021; Poursaeed & Hansson, 2008). The existing cracks can

dramatically accelerate the chloride penetration and aggregation in pile concrete and reduce the durability of pile foundations, thus manifesting the significance of the study for the behavior of chloride penetration in piles with microcracks. Based on experimental, theoretical and numerical approaches, some analysis models have been developed to investigate the influence of cracking on the chloride diffusion behavior and durability in reinforced concrete structures in the recent researches (Bentz et al., 2013; Du et al., 2015; Park et al., 2012; Peng et al., 2019; Wang et al., 2016). These previous researches can provide the significant guidance and valuable reference for evaluating the behavior of chloride ingress. However, these previous models are proposed within a deterministic framework, without considering the uncertainties of influencing factors associated with the chloride penetration. There are significant uncertainty associated with these influencing parameters used in modeling the chloride penetration and predicting the durability life of reinforced

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concrete structures (Ryan & O'Connor, 2013; Val & Trapper, 2008). In view of the significant uncertainty concerning these factors, the probabilistic approaches have been proposed as an attractive alternative to complement a large margin of error of the deterministic methods by considering these parameters as random variables. To incorporate the uncertainty of influencing parameters into the durability analysis, many probabilistic approaches and techniques have recently been proposed to represent chloride penetration and subsequent reinforcement corrosion in reinforced concrete structures (El Hassan et al., 2010; Kirkpatrick et al., 2002; Nogueira & Leonel, 2013; Saassouh & Lounis, 2012; Strauss et al., 2013; Zhu et al., 2016). However, the probabilistic studies in these literatures mainly focus on the sound concrete without taking into account crack effect, and relatively few studies have examined the chloride diffusivity in cracked reinforced concrete structures and the durability assessment using the probabilistic approaches (Papakonstantinou & Shinozuka, 2013).

In this study, a probabilistic analysis approach is presented for the durability assessment of piles with microcracks under chloride attack. The equivalent diffusion coefficient is derived by considering the time-varying process of chloride penetration and the effect of microcracks. To consider the effect of microcracks on chloride ingress, the chloride concentration profiles in piles in artificially simulated seawater were measured. The fitting expression between the chloride diffusion coefficients and crack widths is established. The proposed equivalent diffusion coefficient is verified based on the established fitted relationship. The durability life of piles with microcracks is estimated by the probabilistic method based on the proposed equivalent diffusion coefficient. The deterministic and probabilistic results of durability life are compared and the parametric analysis of main influencing factors is performed.

2 Probabilistic Analysis of Durability Life

2.1 Modeling Chloride Penetration

The model for modeling chloride penetration in reinforced concrete pipe pile can be expressed as (Shao & Li, 2014)

$$\frac{\partial C(r, t)}{\partial t} = D(t) \left(\frac{\partial^2 C(r, t)}{\partial r^2} + \frac{1}{r} \frac{\partial C(r, t)}{\partial r} \right) \quad (1)$$

in which $C(r, t)$ is the chloride concentration at diffusion depth r and time t (kg/m^3), and $D(t)$ is the time-varying chloride diffusion coefficient due to the hydration

process of concrete (m^2/s), and which is given as (Aude-naert et al., 2010; Boddy et al., 1999; Mangat & Molloy, 1994)

$$D(t) = D_{\text{ref}} \left(\frac{t_{\text{ref}}}{t} \right)^m \quad (2)$$

where D_{ref} is the diffusion coefficient at reference time t_{ref} ($t_{\text{ref}}=28$ days), m is the aging factor. Though the above model accounts for the variation of concrete pore structures with time, this model fails to consider the hysteretic change of chloride diffusion coefficient for a specific exposure period. To modify the drawback, the mean value D_m of diffusion coefficient is used in this study, and is expressed as

$$D_m = \frac{1}{t} \int_0^t D(\tau) \cdot d\tau. \quad (3)$$

Defining $I(t) = D_m t$, and by introducing $dI = D(\tau) d\tau$, Eq. (1) can be rewritten as

$$\frac{\partial C(r, t)}{\partial I} = \left(\frac{\partial^2 C(r, t)}{\partial r^2} + \frac{1}{r} \frac{\partial C(r, t)}{\partial r} \right). \quad (4)$$

Assuming that the internal and external radii of pipe pile are $r=a$ and $r=b$, and at the initial condition, no chlorides exist in the pile concrete. The analytical solution of Eq. (4) can be derived using Bessel function as

$$C(r, t) = C_s \left[1 - \sum_{n=1}^{\infty} \frac{\pi J_0(\alpha_n a) U_0(\alpha_n r)}{J_0(\alpha_n a) + J_0(\alpha_n b)} e^{-D_m \alpha_n^2 t} \right] \quad (5)$$

where α_n is the positive root of

$$U_0(\alpha_n a) = 0 \quad (6)$$

where

$$U_0(\alpha_n r) = J_0(\alpha_n r) Y_0(\alpha_n b) - J_0(\alpha_n b) Y_0(\alpha_n r) \quad (7)$$

where C_s is the surface chloride concentration, J_0 and Y_0 are the first and second class of zeroth order Bessel functions. Assuming that the hydration process of concrete has finished after 30 years, D_m in Eq. (3) can be derived as follows (Kwon et al., 2009):

$$D_m = \frac{1}{t} \int_0^t D_{\text{ref}} \left(\frac{t_{\text{ref}}}{\tau} \right)^m d\tau = \frac{D_{\text{ref}}}{1-m} \left(\frac{t_{\text{ref}}}{t} \right)^m \quad (8a)$$

$(t < t_R = 30 \text{ years})$

$$D_m = D_{\text{ref}} \left[1 + \frac{t_R}{t} \left(\frac{m}{1-m} \right) \right] \left(\frac{t_{\text{ref}}}{t} \right)^m \quad (8b)$$

$(t \geq t_R = 30 \text{ years}).$

2.2 Equivalent Diffusion Coefficient

The total flux of chloride ions (J_{tot}) contains two parts: the flux of chloride ions through the sound concrete (J_0) and cracked concrete (J_{cr}), and which can be described as (Gérard & Marchand, 2000; Jang et al., 2011)

$$A_{tot}J_{tot} = A_0J_0 + A_{cr}J_{cr} \tag{9}$$

where A_{tot} is the total sectional area, and A_0 and A_{cr} are the sectional areas of sound and cracked concrete, respectively. The ionic flux can be represented as

$$D_{eq}\nabla c = \frac{A_0}{A_{tot}}(D_m\nabla c) + \frac{A_{cr}}{A_{tot}}(D_{cr}\nabla c) \tag{10}$$

where D_{eq} is the equivalent diffusion coefficient, D_{cr} is the diffusion coefficient of cracked concrete, and ∇c is the concentration gradient. Since $A_0/A_{tot} \approx 1$, and defining the crack density α_{cr} as $\alpha_{cr} = A_{cr}/A_{tot}$, Eq. (10) can be rewritten as

$$D_{eq} = D_m + \alpha_{cr}D_{cr}. \tag{11}$$

For the reinforced concrete pipe pile, the crack effect factor can be expressed as

$$\alpha_{cr} = \frac{A_{cr}}{A_{tot}} = \frac{\sum_{i=1}^n w_i}{\pi(a+b)} \tag{12}$$

where n is the number of crack, w_i is the crack width of number i th. The empirical formulas for D_{cr} is given as (Djerbi et al., 2008)

$$\begin{cases} D_{cr} = (0.16w_{cr} - 3) \times 10^{-10} & 30 \mu\text{m} \leq w_{cr} \leq 100 \mu\text{m} \\ D_{cr} = 13 \times 10^{-10} & w_{cr} > 100 \mu\text{m} \end{cases} \tag{13}$$

2.3 Probabilistic Approach

As mentioned above, the chloride penetration behavior is associated with some uncertain parameters, thus the probabilistic approach is supposed to be more reasonable and reliable to evaluate the durability life. For the probabilistic approach, the ultimate state equation of durability life is formulated as

$$g(x, t) = C_{th} - C(x, t), \tag{14}$$

where C_{th} is the chloride threshold value. Based on the probability density function $f(x)$, the failure probability p_f is estimated as

$$p_f = \int_{g(x,t) \leq 0} f(x) dx. \tag{15}$$

The durability life can be evaluated by the probabilistic approach:

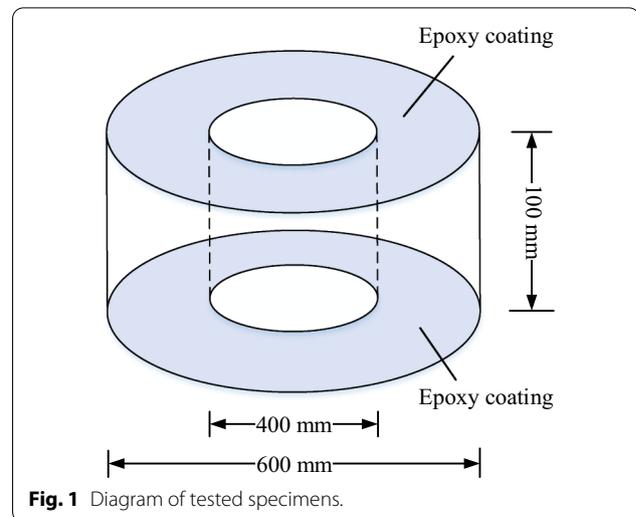


Table 1 Mixture proportions of concrete (kg/m³).

w/c	Cement	Water	Sand	Gravel
0.30	420	126	684	1217

$$T_f = [p_f \geq p_{fmax}], \tag{16}$$

where T_f is the durability life, and p_{fmax} is the intended maximum failure probability.

3 Experimental Program

In this experimental study, 36 model piles were casted with dimensions of outer diameter 600 mm, inner diameter 400 mm and height 100 mm (Fig. 1). The mix design of tested model piles is given in Table 1. After 24 h of casting, the model piles were demolded and cured in the standard conditions. After that, the splitting tests were performed on the model piles to generate the pre-existing cracks (Fig. 2a). After unloading, the crack widths in model piles at the unloaded state were measured by the measurement device. The model piles with different crack widths were coated with epoxy resin except for the internal and external surfaces (Fig. 2b). This is to ensure that the chloride ions diffuse into the concrete piles mainly by one-dimensional radial diffusion. After the epoxy resin dried, the model piles with pre-existing cracks were immersed in the artificial simulated seawater for 180 days. The artificial simulated seawater was prepared, whose chemical composition is shown in Table 2. After the immersion period, core samples were extracted, pulverized, and sieved into fine powder at incremental depths of 5 mm from the exposed surface (Fig. 2c), and then the powder samples were stored in plastic bottles

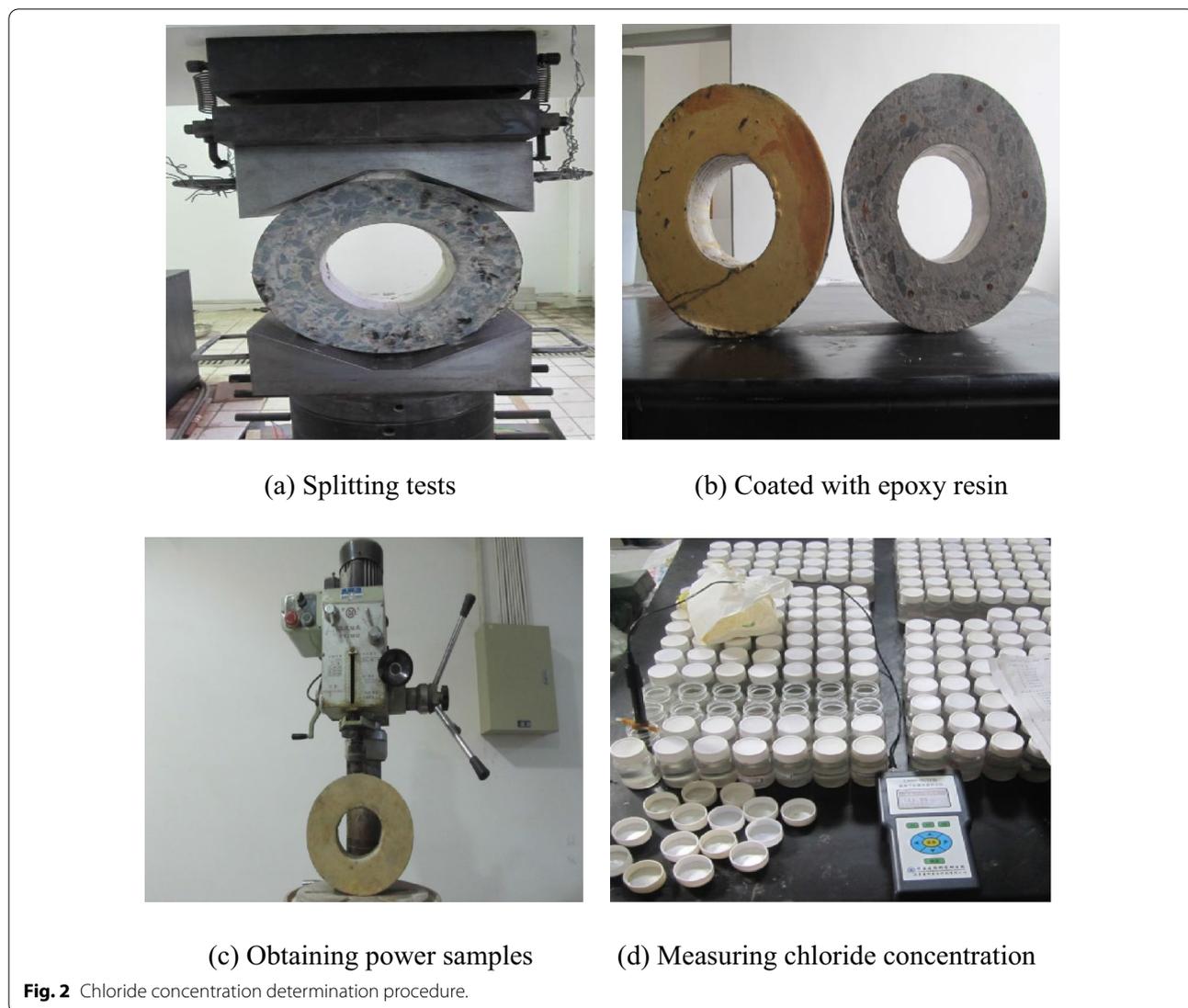


Fig. 2 Chloride concentration determination procedure.

filled with the extraction solution for 48 h, the chloride concentration was then determined by potentiometric titration (Fig. 2d).

The chloride concentration profiles in the core samples for different crack widths are presented in Fig. 3. The chloride concentration at the same diffusion depth tends

to increase gradually as the crack width increases due to increasing diffusion coefficient. The surface chloride concentration (C_s) and apparent diffusion coefficient (D_a) can be obtained by Eq. (5) to fit the chloride concentration profiles, and the corresponding calculated results are given in Table 3. Based on the experimental results, the changing trend of normalized diffusion coefficient (D_a/D_m) with crack width can be expressed in Fig. 4. The function $f(w)$ is required to be introduced to modify the diffusion coefficient, and which is achieved from regression analysis:

$$D_a = f(w) \cdot D_m \tag{17}$$

$$f(w) = 32.55w^2 + 12.34w + 1 \quad (w \leq 0.3 \text{ mm}, R^2 = 0.997). \tag{18}$$

Table 2 Chemical composition of artificial simulated seawater (kg/m³).

NaCl	MgCl ₂	Na ₂ SO ₄	CaCl ₂	KCl	NaHCO ₃
24.53	5.20	4.09	1.16	0.70	0.20

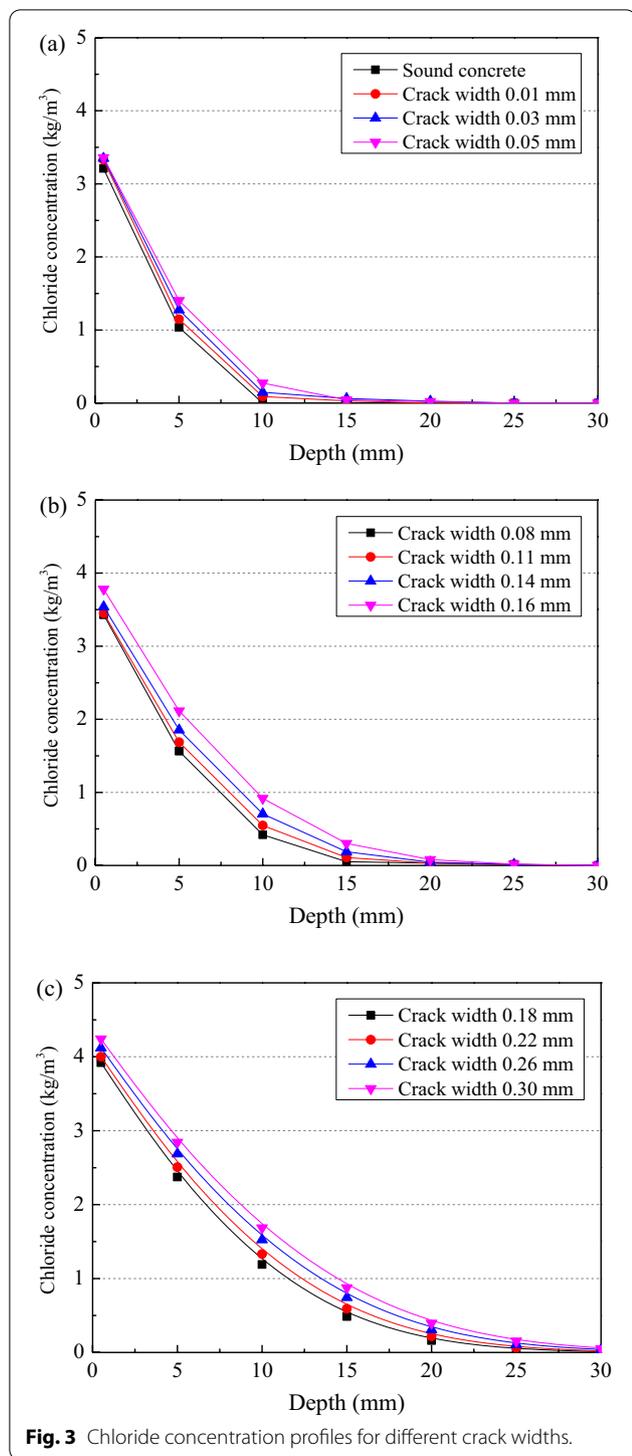


Fig. 3 Chloride concentration profiles for different crack widths.

According to the given parameter values in Table 4, the equivalent diffusion coefficient derived in Sect. 2.2 can be calculated and compared with the experimental results. From Fig. 4, it can be observed that the proposed

Table 3 Experimental results for apparent diffusion coefficient and surface chloride concentration.

Crack width (mm)	Averaged diffusion coefficient (m^2/s) $\times 10^{-12}$	Surface chloride concentration (kg/m^3)
0	0.64	3.21
0.01	0.74	3.33
0.03	0.92	3.35
0.05	1.13	3.36
0.08	1.39	3.43
0.11	1.65	3.45
0.14	1.98	3.54
0.16	2.39	3.78
0.18	3.09	3.92
0.22	3.50	4.00
0.26	4.10	4.12
0.30	4.62	4.24

analytical method for the equivalent diffusion coefficient agrees well with the experimental data, thus the validity of proposed analytical model for chloride penetration can be verified.

4 Probabilistic Analysis Results and Discussion

4.1 Probabilistic Analysis of Durability Life

The ultimate state of intended maximum probability has been suggested in several published references as indication of durability life. Some previous studies have defined a failure probability of 10% as the intended failure probability of the durability life of reinforced concrete structures (Kwon et al., 2009; Lu et al., 2011; Pack et al., 2010). In this study, 10% of failure probability is applied as limit state for the durability of piles under chloride attack. It is assumed that $a = 200$ mm and $b = 300$ mm. The statistical parameters used for the probabilistic analysis of durability life are shown in Table 4. To obtain the durability life based on deterministic method, the chloride concentration is calculated from Eq. (5) using the means of random variations. As previously mentioned, the durability limit state can be determined by Monte-Carlo simulation method. In this probabilistic analysis, different crack widths ($w = 0, 0.1, 0.2$ and 0.3 mm) are considered to demonstrate the effect of cracks on chloride ingress and durability life. In addition, different number of cracks ($n = 1, n = 5$ and $n = 10$) is also considered in the probabilistic analysis. To obtain the accurate analysis results, the random samples of 10^6 are used in the probabilistic analysis.

The variations of failure probabilities for different crack widths and different number of cracks are presented in Fig. 5. The growth rate of failure probability tends to be

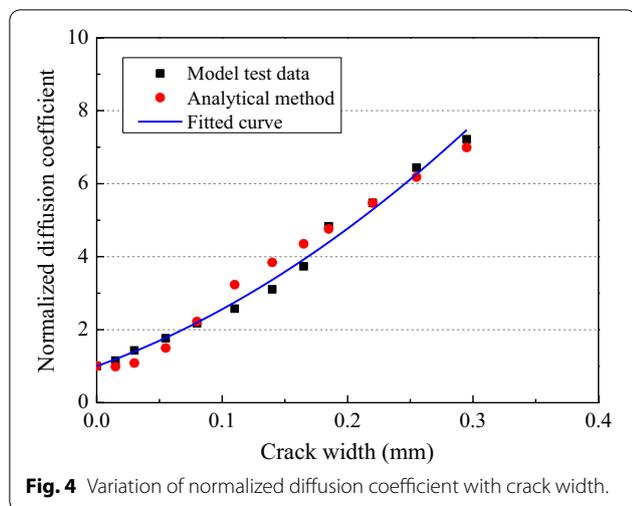


Fig. 4 Variation of normalized diffusion coefficient with crack width.

faster with the increase in crack width. Compared with different number of cracks, the failure probability builds up significantly with the increasing number of cracks, which indicates the durability life greatly reduces with the increase of crack density of pile.

Fig. 6 shows the variations of chloride concentration at steel surface for different number of cracks. The induced chloride concentration increases rapidly with the increase of crack width at the same number of cracks. From Fig. 6, the deterministic durability life may be obtained when the induced chloride concentration exceeds the chloride threshold value.

The durability life for deterministic and probabilistic methods is given in Fig. 7. For the probabilistic method, when the crack width increases from 0.0 to 0.3 mm, the durability life decreases from 50.5 years to 26.3, 8.2 and 4.2 years, respectively, for $n=1$, $n=5$ and $n=10$. For the deterministic method, the predicted durability life reduces from 108.0 years to 46.0, 13.5 and 7.3 years, respectively, under the same condition. Compared with two different prediction methods, the durability life predicted by probabilistic method are always less than those by deterministic method at the same condition. This indicates that the deterministic approach may underestimate

the threat of reinforcement corrosion induced by chloride attack, owing to the omission of probabilistic nature of main influencing parameters.

4.2 Parametric Analysis

In this section, the effects of C_s , C_{th} , m and c on the failure probability are discussed, respectively, for the case of $n=5$. The influence of C_s on the failure probability is depicted in Fig. 8a–c and corresponding probabilistic durability life is also plotted in Fig. 8d. The failure probability gradually increases and the durability life rapidly decreases with the increase of C_s at the same condition, which indicates that it is an effective method to isolate the piles from erosion environments by epoxy coating, so as to delay the time to chloride-induced corrosion initiation.

The influence of cover depth on failure probability is shown in Fig. 9a–c and the predicted durability life is also given in Fig. 9d. The durability life increases with increasing cover depth. The durability life in sound pile increases from 55.0 years to 120.8 years when the cover depth is raised from 50 to 70 mm. However, it is worth noting that although the cover depth is raised, the durability life decreases obviously once the pile concrete exists some microcracks. Therefore, piles used in chloride-dominated environments should be carefully checked to ensure no cracks existing in the pile shaft.

The influence of m on the failure probability is given in Fig. 10a–d and the related durability life is also given in Fig. 10e. In this study, the probabilistic evaluation for time independent model ($m=0$) is also discussed. For the time independent model, the growth rate of failure probability is the largest by comparison with the time-dependent model. The time-dependent model indicates the longer durability life than the time independent model. The increasing aging factor extends the time of failure probability reaching target probability. The greater value of aging factor is associated with the lower rate of chloride penetration because of the progress of cement hydration. This demonstrates that the omission of time dependency of chloride ingress can significantly

Table 4 Statistical parameters of the random variables.

Variable	Description (Source)	Mean	COV	Distribution
C_s (kg/m ³)	Surface chloride concentration (Model test)	3.64	0.12	Lognormal
C_{th} (kg/m ³)	Chloride threshold value (Kwon et al., 2009)	1.2	0.20	Uniform
c (mm)	Concrete cover depth (Model test)	45	0.18	Normal
D_{ref} (m ² /s)	Effect diffusion coefficient (Model test)	0.93×10^{-12}	0.20	Lognormal
m	Aging factor (Kwon et al., 2009)	0.20	0.20	Normal

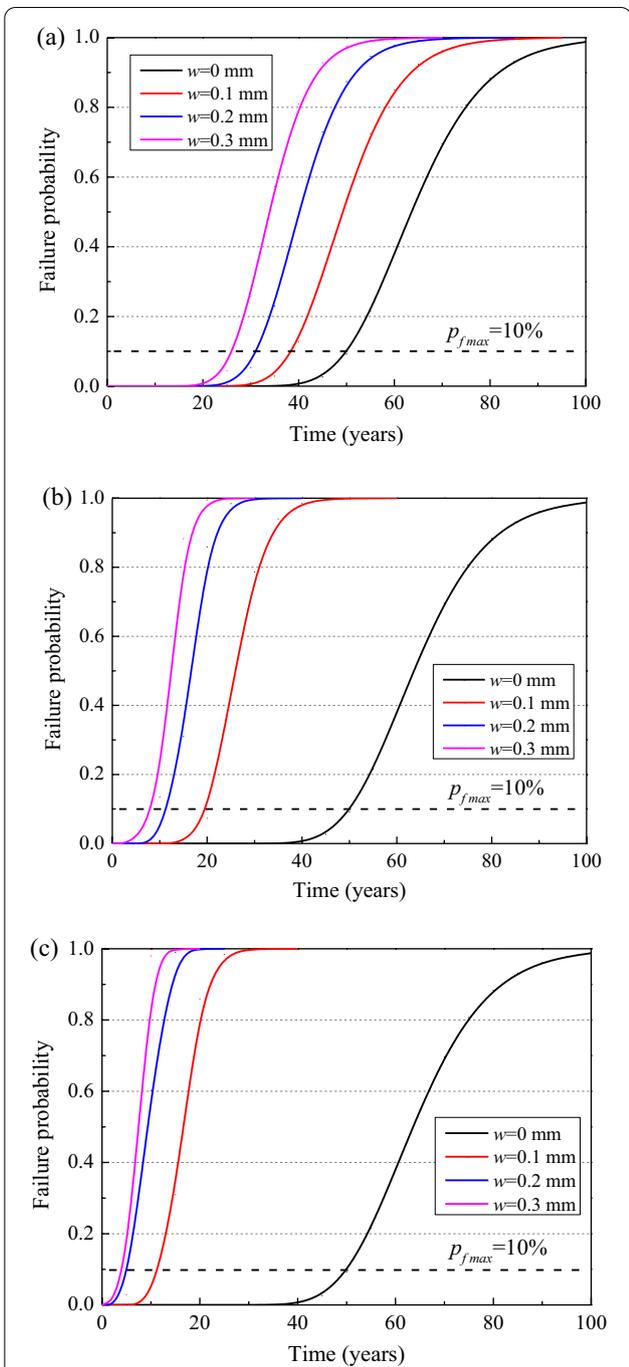


Fig. 5 Variations of failure probabilities with exposure time for different number of cracks: **a** $n=1$, **b** $n=5$ and **c** $n=10$.

underestimate the danger of reinforcement corrosion in the piles. From Fig. 10e, the durability life significantly increases as the aging factor increases. The durability life in sound pile increases from 24.5 years to 93.0 years as

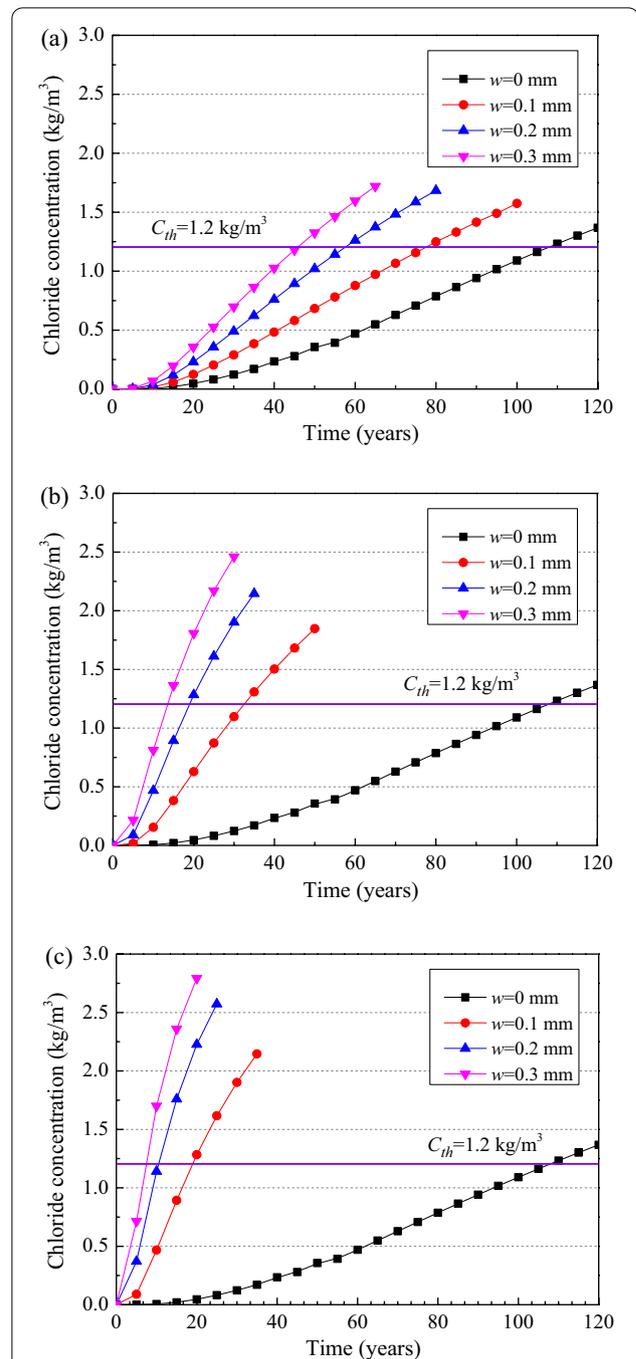
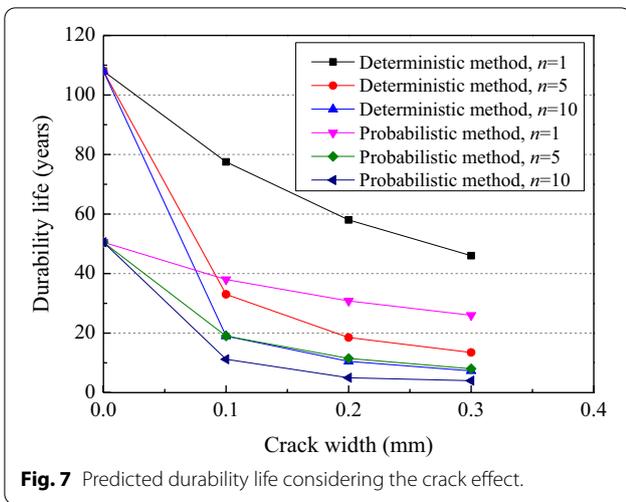
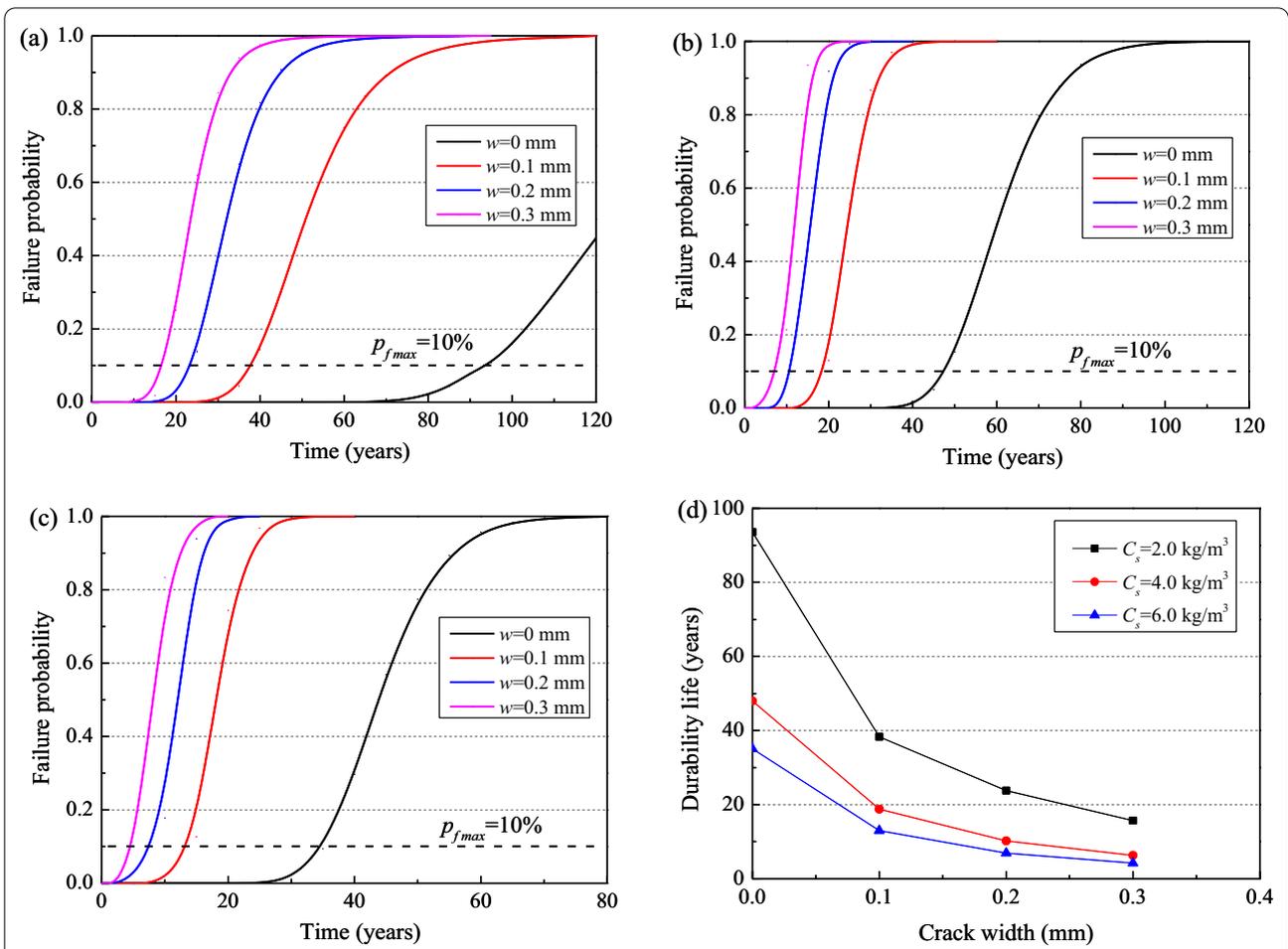


Fig. 6 Variations of chloride concentration at the depth of reinforcement with exposure time for different number of cracks: **a** $n=1$, **b** $n=5$ and **c** $n=10$.

the aging factor is changed from 0 to 0.3. However, the growth of durability life is dramatically damped with the increase of the crack width.



The effect of C_{th} on the failure probability is depicted in Fig. 11a–c, and corresponding probabilistic durability life is also given in Fig. 11d. The variation of C_{th} can cause a striking difference in evaluating the durability life. For the larger chloride threshold value, the failure probability tends to require much longer time to reach target failure probability of 10%. From Fig. 11d, the durability life increases from 45.0 years to 85.0 years for $w=0$, and from 17.1 years to 35.2 years for $w=0.1$ as C_{th} changes from 1.0 to 2.0 kg/m³. This indicates that raising the chloride threshold value is a valid way to prolong the durability life, and corrosion inhibitor has become a representative approach to raise the chloride threshold value by inhibiting and mitigating corrosion of reinforcement.



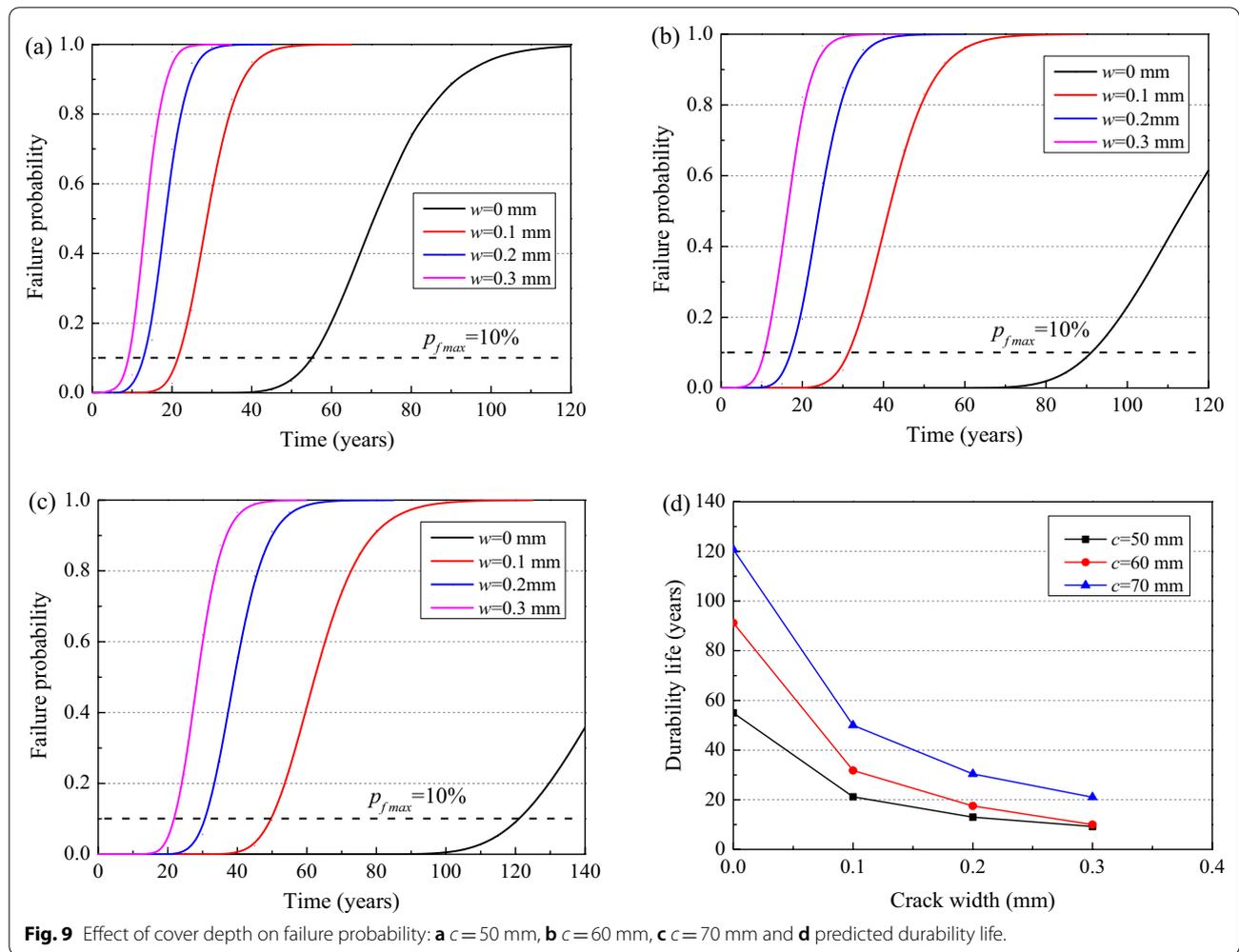


Fig. 9 Effect of cover depth on failure probability: **a** $c = 50$ mm, **b** $c = 60$ mm, **c** $c = 70$ mm and **d** predicted durability life.

5 Conclusions

The equivalent diffusion coefficient is derived by introducing the crack effect factor and is verified by comparison with the experimental results. The durability life of piles with microcracks subjected to chloride attack is evaluated based on the probabilistic approach. The following conclusions can be addressed:

1. The growth rate of failure probability tends to be faster with the increase in crack width. The induced chloride concentration increases rapidly with the increase of crack width at the same number of cracks. The durability life predicted by probabilistic method are always less than those by deterministic method at the same condition.
2. The time-dependent model indicates the longer durability life than the time independent model. The increasing aging factor extends the time of failure probability reaching target probability. The omission of time dependency of chloride ingress can significantly underestimate the danger of reinforcement corrosion in the piles.
3. The durability life significantly increases with the increase in cover depth. It is also worth noting that although the cover depth is raised, the durability life decreases obviously once the pile concrete exists some microcracks.
4. The variation of chloride threshold value can cause a striking difference in evaluating the durability life. For the larger chloride threshold value, the failure probability tends to require much longer time to reach target failure probability.

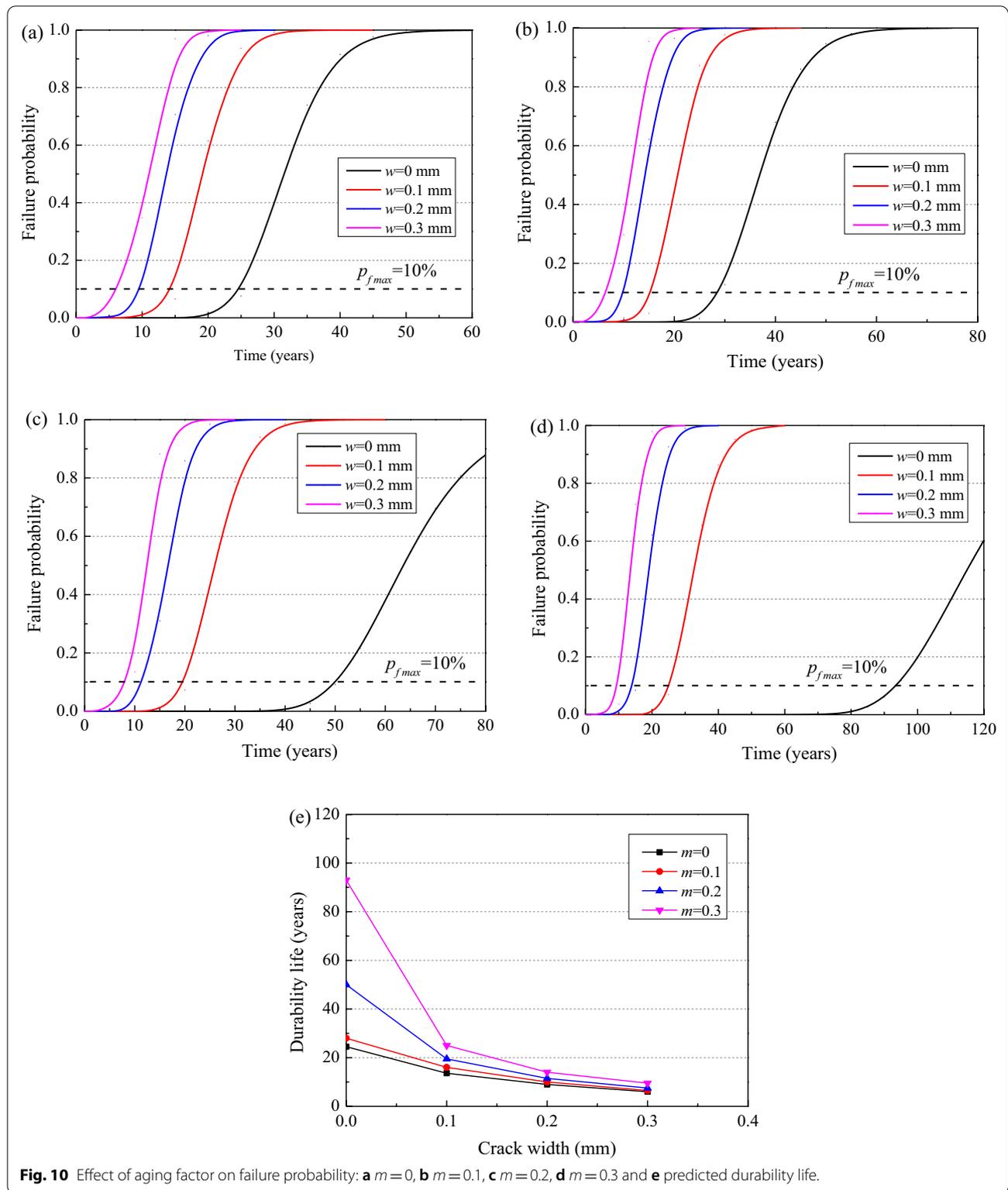
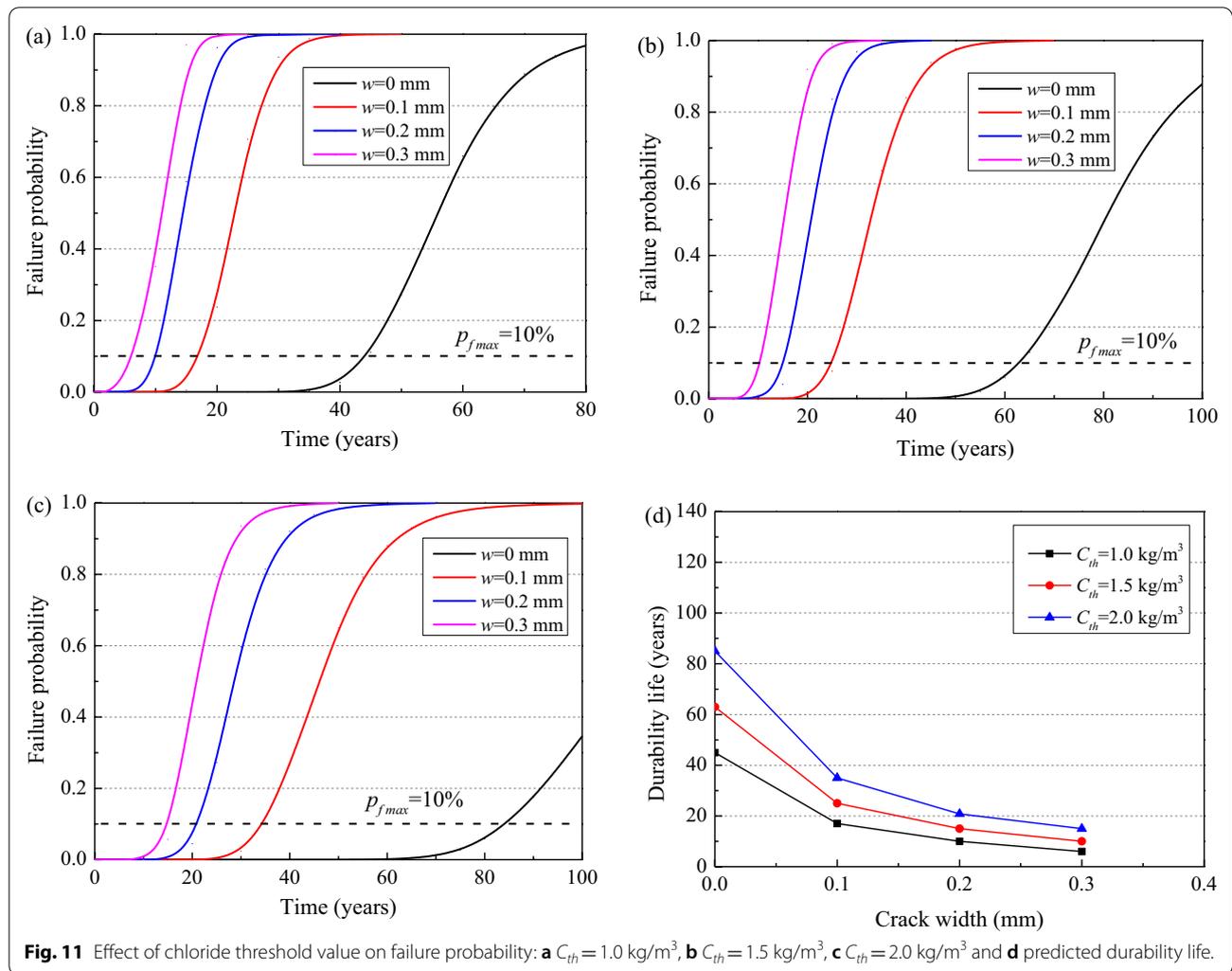


Fig. 10 Effect of aging factor on failure probability: **a** $m=0$, **b** $m=0.1$, **c** $m=0.2$, **d** $m=0.3$ and **e** predicted durability life.



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Authors' contributions

WS and DS designed and performed the experiments, and analyzed the experimental data and drafted the paper. Both authors read and approved the final manuscript.

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Availability of data and materials

The data in the paper will be supplied upon request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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