PROBABILISTIC APPROACH FOR TIME-BASED CORROSION COST ASSESSMENT: CHLORIDE-EXPOSED CONCRETE STRUCTURE

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ABSTRACT

International accounting standards significantly serves as a guideline for recognition and measurement of assets. Organizations, thus, is suggested to put a group of cross-disciplinary experts together with different approaches for specific purposes of making assumptions in reassessment of the values of assets, and inferring appropriate accounting numbers via a wide variety of estimation methods such as engineering or statistical approach. This paper attempts to apply a probabilistic approach to the application of time-based corrosion to suggest a model for accounting treatment on measurement of the infrastructure from the perspectives of engineering and statistical disciplines. Researchers principally undertake this study in combination of Crank-Nicolson finite difference scheme with the Latin Hypercube algorithm. A model with four-random variables, including surface chloride, diffusion coefficient, concrete cover depth, and critical chloride value, is constructed. On the probabilistic analysis, the CDF of critical time, or the probability that the content of chloride ions at the cover depth appears more than or equal to the critical chloride value while normal concrete is found to be effectively identical with that for FA concrete despite certain diversity in mean and standard deviation respectively. Still and all, the expected cumulative cost for critical time of reinforcement corrosion occurrence of normal concrete indicates obviously lower than that of FA concrete. A possible explanation for this might be that higher cover depth of FA concrete leads to higher expected cost. The results from this study provide a substantial framework for decision-makers toward measuring assets value and prioritizing annual budget allocations for management of concrete structures exposed to chloride environment.

Keywords: Cost Assessment, Time-based Corrosion, Chloride, Concrete, Probabilistic

INTRODUCTION

The methods for determining its values after initial recognition, simply for most of the organizations, property, plant, and equipment including lands, buildings, computers, furniture and the like, would remain uncomplicated. Differently, infrastructure such as bridges, local highways and roads require detailed engineering and construction supervision methodology. This paper aims to shed light on the applications and implications of the engineering and statistical approach to accounting treatment for fair value considerations on infrastructure regarding a bridge with a concrete structure.

Costs of bridge infrastructure corrosion are considerably high due to corrosion damage from environments such as sea salts and climate. Concrete deterioration appears highly relevant to the diffusion of chloride ions. Accordingly, corrosion of reinforcement is considered as one of the significant deteriorations phenomena because it enables to reduce reinforcement cross-sectional area, which potentially could lead to the cracking of concrete. This would eventually spark off severe loss of structural safety and shorten service life (Petcherdchoo & Chindaprasirt, 2019). The corrosion initiates whenever a critical quantity of diffused chloride ions in reinforcement is reached leading to breaking down the thin oxide layer known as the

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"passivation film" (Page, 1975). In practice, the severe loss is disallowed due to the risk of human life. To remedy this issue, three main approaches have been put forward— (Petcherdchoo & Chindaprasirt, 2019) production of durable concrete for reinforcement protection (Petcherdchoo, 2015) design of proper concrete cover depth (Frangopol, 1997); (Petcherdchoo, 2015) application of appropriate maintenance (Petcherdchoo, 2018). Similarly, several existing research recognize these approaches as critical roles along with relevant studies conducted as follows. Farahani, et al., (2020) proposed a model to predict the chloride diffusion coefficient for Portland Cement (PC) reinforced concrete under long-term exposure in the tidal zone of southern Iran. A finite-element model was utilized to assess the time-dependent capacity of corroded RC structures using nonlinear analysis and the impact of corrosion on inelastic buckling of reinforcements. In comparison with the case of unrepair, the corrosion percentage of longitudinal bars of PC concrete increased with water-to-cement ratios. Cusson, et al., (2010) found that internal curing was able to prolong the service life of high-performance concrete bridge decks by more than 20 years, mainly on account of reducing early-age shrinkage cracking and chloride diffusion with a significant reduction in chloride penetration rate through the concrete. Compared to normal concrete, high-performance concrete with internal curing increased the service life of bridge decks in severe environmental conditions by more than 40 years. Moreover, life-cycle cost reductions of 40% and 63% were approximately estimated when conventional and internally cured high-performance concretes were used in bridge decks instead of normal concrete respectively. This result is likely to be attributed to low-permeability high-performance concrete bridge decks having a longer service life and less maintenance actions required.

In the real world, uncertainty is unanimously inevitable. This can also occur with chloride-attacked concrete structures mainly due to chloride environment and materials properties. On the other hand, in spite of similar design and chloride-exposures, the chloride environment (surface chloride) of concrete structures the material property (diffusion coefficient and critical chloride value), and even the quality of workmanship (concrete cover depth), are all presumably diverse. This may bring about uncertain deterioration of concrete structures. Notably, the uncertainty seems also significantly weighty in case of a group of concrete structures. As a result, the probabilistic assessment can be necessarily indispensable over determining chloride diffusion through concrete structures. Publications that concentrate on this domain have been readily available as follows. O'Connor, et al., (2013) developed a Markov chain model for maintenance management to deal with two types of deterioration phenomena, *i.e.*, initiation and propagation of corrosion. In the case of their model, owners/managers of bridges were allowed to differentiate various maintenance strategy efficiencies. This was used to determine the optimal maintenance strategy for a structure or groups of structures. Their study research have found that when repairing a structure, it was worth designing a more durable mix with lowered permeability or increasing concrete cover in order to increase the time to initiation of corrosion. It might be optimal considering the lifetime cost of a structure in spite of a higher repair cost. Frangopol, et al., (1997) employed the Monte Carlo simulation method to present a reliability-based approach in the design of RC bridge girders under corrosion attack based on the American Association of State Highway and Transportation Officials (AASHTO). As noted by Frangopol, et al., (1997), they have attempted to pinpoint out a reliability-based design approach based on minimization of expected lifetime cost including corrosion effects and cost of failure consequences. Based on the Monte Carlo simulation, Val (2007) examined the effect of different uncertainty sources associated with corrosion initiation and propagation modeling as well as relevant damage of structures on results of life-cycle cost analysis, and estimated cost of failure in particular. The study, thus far, has indicated that in life-cycle cost analysis, collecting more data and improving models for the prediction of corrosion initiation had higher priority than modeling crack initiation and propagation. Aslani & Dehestani (2020) performed reliability analyses on the concrete structural performance considering serviceability and structural capacity, using the finite element method in calculating the probability of capacity reduction of beams with different percentages of corrosion. They also estimated and optimized the failure

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costs over the RC beam life cycle. Data from their study suggested that the life cycle cost for lower concrete cover generally decreased with the increase of concrete compressive strength nevertheless that for higher one decreased with increasing the concrete compressive strength. In addition, the cost started to increase with further increase in the compressive strength. For the same cover, the optimum concrete strength in the case of minimum life cycle cost increased (or at least remained identical) with increasing the severity of exposure environment.

Despite the previous research taking the service life of concrete structures into consideration by using a probability-based approach, they did not explicitly take for behaviors of chloride diffusion due to the uncertainty of four main parameters; surface chloride, diffusion coefficient, concrete cover depth, and critical chloride value. To bridge this gap, a study on probabilistic analysis for considering corrosion state of concrete structures under chloride environment is carried out in the current study. The quantitative comparison in terms of the expected cost of critical time relevant to the corrosion initiation of reinforcement in concrete structures under chloride attack is accordingly estimated. These are of interest because a deterministic analysis may hinder some pivotal points in the probabilistic analysis, which would be shown later. Furthermore, this study focuses on designing durable concrete for reinforcement protection and designing proper concrete structure size, hence normal and Fly-Ash (FA) concrete materials will be determined including concrete cover depth.

Probabilistic Descriptors for Chloride Attacked Concrete

In this study, there are four random variables to be determined. They consist of chloride attack in terms of surface chloride (C_s), chloride diffusion resistance of concrete in terms of diffusion coefficient (D_0), the size of chloride diffusion resistance in term of concrete cover depth (Cover depth), and the resistance of reinforcement corrosion initiation in term of critical chloride value ($C_{Corr.}$). Here, the design value for these four variables is recommended according to the Thai standard (DPT, 2021). For jetty girders located in splash zone, there can be two types of concrete materials recommended for 20-year design service life without reinforcement corrosion, *i.e.*, normal and Fly-Ash (FA) concrete materials. The recommended design value for these two types is used as the mean value as shown in Tables 1 and 2, respectively.

Table 1
PROBABILISTIC DESCRIPTORS FOR CHLORIDE DIFFUSION IN NORMAL CONCRETE

Variables	Mean	Standard deviation	Coefficient of variation	Descriptor
C_s (% weight binder)	8.445	2.11	0.254	LN(8.445,2.11)
D_0 ($\times 10^{-12}$ m^2/s)	0.726	0.17	0.239	WB(0.726,0.17)
Cover depth (mm)	59	5.72	0.097	LN(59,5.72)
$C_{Corr.}$ (% weight binder)	0.45	0.2	0.44	$Beta_{[0,2]}$(0.45,0.2)

Table 2
PROBABILISTIC DESCRIPTORS FOR CHLORIDE DIFFUSION IN FLY-ASH (FA) CONCRETE

Variables	Mean	Standard deviation	Coefficient of variation	Descriptor
C_s (% weight binder)	8.445	2.11	0.254	LN(8.445,2.11)
D_0 ($\times 10^{-12}$ m^2/s)	0.805	0.19	0.239	WB(0.805,0.19)
Cover depth (mm)	65	6.31	0.097	LN(65,6.31)
$C_{Corr.}$ (% weight binder)	0.35	0.15	0.44	$Beta_{[0,2]}$(0.35,0.15)

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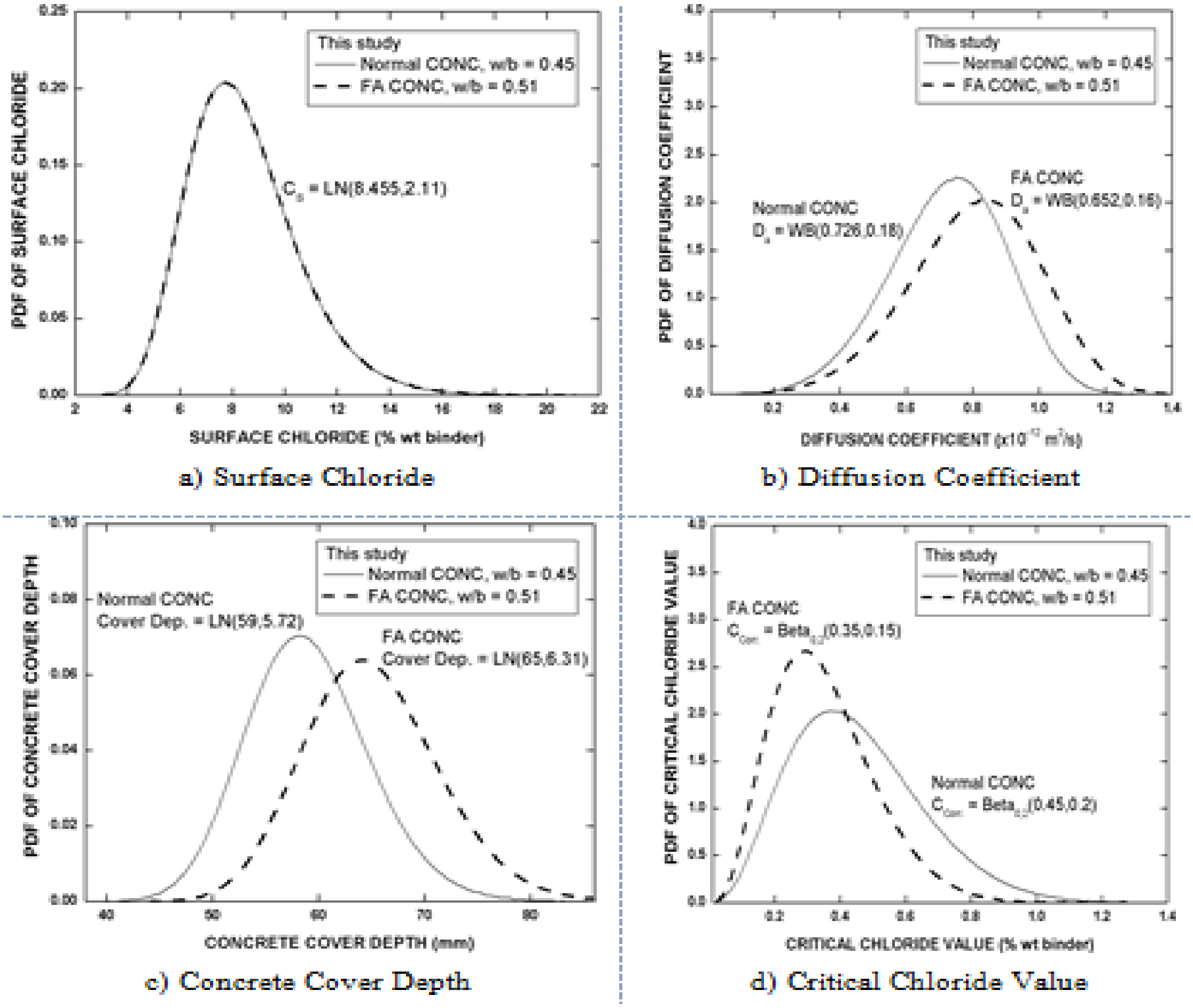

FIGURE 1
FOUR RANDOM VARIABLES

Based on the study of Song, et al., (2009), the coefficient of variations for the four random variables are adopted as indicated in Table 1 and 2. According to the mean and the coefficient of variation, the standard deviation for the four random variables can accordingly be calculated as shown in Tables 1 and 2. Song, et al., also proposed the distribution types for C_s and Cover depth as normal, however this study instead proposed them as log-normal in order to ensure their positive value. In addition, the distribution type for D_0 is directly adopted from Song & Belleghem, et al., (2017) proposed the distribution type of $C_{Corr.}$ To be Beta $_{[0,2]}$ as directly used in this study. It is noted that LN(a,b) represents the log-normal distribution having the mean of “a” and the standard deviation of “b”, while WB(p,q) represents the weibull distribution having the mean of “p” and the standard deviation of “q”. Moreover, Beta $_{[0,\ 2]}$ (x,y) represents the beta distribution for the value falling between 0 and 2 having the mean of “x” and the standard deviation of “y”.

The random variables in Tables 1 and 2 are plotted and compared in Figure 1a to d. It is noted that the water-to-binder ratio (w/b) for normal concrete and fly-ash concrete is equal to 0.45 and 0.51, respectively, as recommended in the Thai standard (DPT, 2021). This difference leads to different D_0, concrete cover depth, and $C_{Corr.}$ However, the effect of w/b does not influence C_s.

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Assessment of Chloride Diffusion in Concrete

In studying the service life of chloride attacked concrete structures, a quantitative assessment is desirable (Petcherdchoo, 2015). The Fick based theory is applicable to predict the diffusion of chloride ions through concrete structures. Basically, the one-dimensional partial differential equation (1-D PDE) of the Fick's second law can be expressed as below:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial C}{\partial x} \tag{1}$$

From a study (Crank, 1975), if both the surface chloride and the diffusion coefficient are assumed constant, the one-dimensional partial differential equation (1-D PDE) of the Fick's second law can be analytically solved and used to predict the service life.

In this study, Eq. (1) is applied, and two kinds of assessments are to be considered—deterministic and probabilistic. The deterministic assessment aims at determining the recommendations in the Thai standard (DPT, 2021), whereas the probabilistic one is to present its effect on results. Thus, they can be demonstrated in the following section.

Deterministic Assessment

In this assessment, the mean value of each variable in Tables 1 and 2 is used. Accordingly, a Crank-Nicolson based finite difference scheme was developed based on the partial differential equation (PDE) of the Fick's second law in Eq. (1) as

$$\frac{c_{i,j+1} - c_{i,j}}{\Delta t} = \frac{D}{2}\left[\frac{(c_{i+1,j+1} - 2c_{i,j+1} + c_{i-1,j+1}) + (c_{i+1,j} - 2c_{i,j} + c_{i-1,j})}{(\Delta x)^2}\right] \tag{2}$$

Where $c_{i,j}$ is defined as the content of chloride ions at the mesh point i and time j, respectively. Furthermore, D is defined as a constant diffusion coefficient. In numerical computation, Δx and Δt are the size of the mesh point (1 mm) and the incremental time step (1 week), respectively.

Using the finite difference computation based on Eq. (2), the space-dependent chloride diffusion through the normal concrete from years 1 to 50 is shown in Figure 2. The content of chloride ions at the cover depth of 59 mm reaches $C_{Corr.}$ Of 0.45% wt. binder around year 20. This is compatible with the recommended design in the Thai standard (DPT, 2021). The reach time is called corrosion-free service life because $C_{Corr.}$ is the value that the passivation film on reinforcement starts to be broken causing the initiation of reinforcement corrosion. Figure 3 shows the comparison of time-dependent chloride profile at the cover depth of 59 and 65 mm for normal and FA concrete materials, respectively. At year 20, the content of chloride ions at the cover depth of 59 mm for normal concrete reaches $C_{Corr.}$ of 0.45% wt. binder, and that of 65 mm for FA concrete reach $C_{Corr.}$ of 0.35% wt. binder. In spite of different chloride profiles, the service life of both concrete appears exactly identical. The reason for this is that both concrete materials were recommended to satisfy the corrosion-free service life of 20 years by designing the four variables as seen in Table 1 and 2 (DPT, 2021). It is also noted that although most of the mean of the four variables used for assessing normal and FA concrete materials remains dissimilar. They are both equivalent due to equivalent variables.

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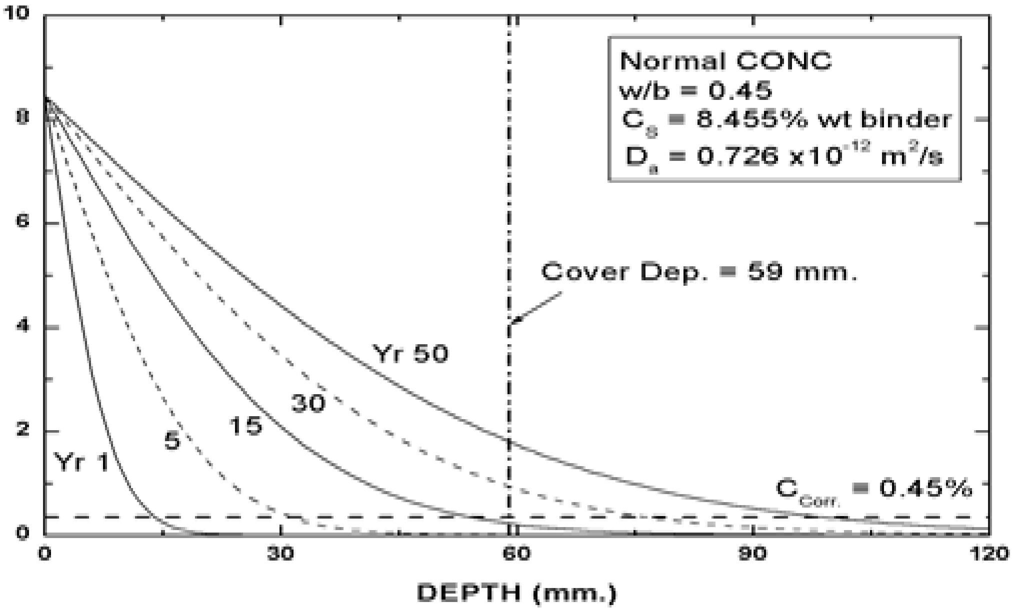

FIGURE 2
SPACE-DEPENDENT CHLORIDE DIFFUSION THOUGH NORMAL CONCRETE

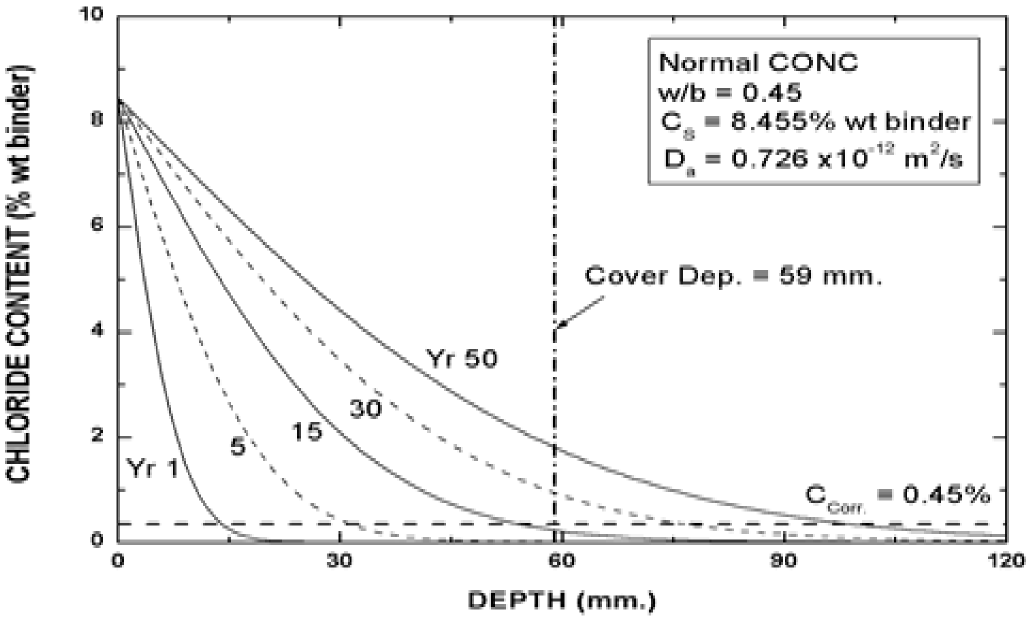

FIGURE 3
TIME-DEPENDENT CHLORIDE DIFFUSION IN NORMAL AND FA CONCRETE

Probabilistic Assessment

In this assessment, the Crank-Nicolson finite difference scheme is combined with the Latin Hypercube algorithm for calculating chloride diffusion and sampling random number, respectively. It is noted that the Latin Hypercube algorithm is used due to its potential in decreasing the number of samples while still satisfying computation accuracy. Figure 4, as example, shows the time-dependent chloride profile for normal concrete using 10 sets of random samples. The chloride profile and $C_{Corr.}$ for each set are not the same, although they have the same mean and standard deviation in Table 1. So, the probabilistic assessment is required to cover this uncertainty.

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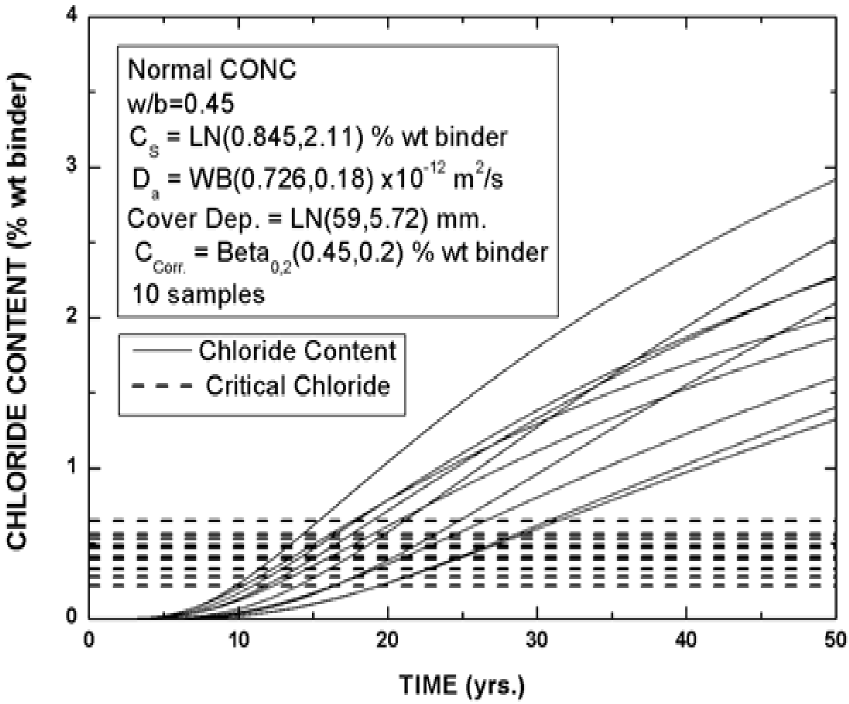

FIGURE 4
CHLORIDE PROFILE & $C_{Corr.}$ FOR NORMAL CONCRETE (10 SAMPLES)

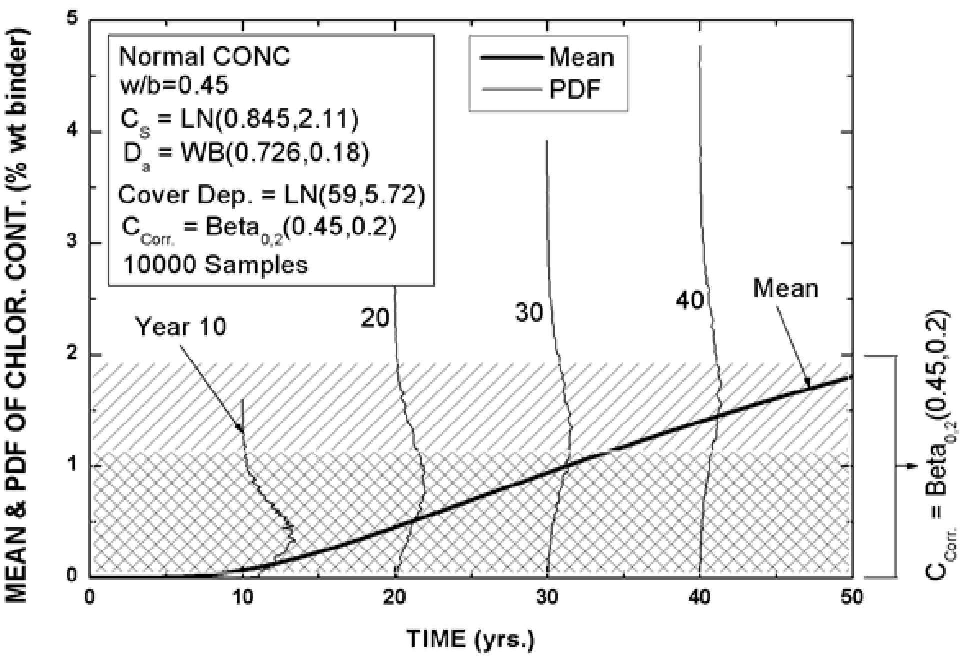

FIGURE 5
MEAN AND PDF OF CHLORIDE CONTENT FOR NORMAL CONCRETE

Figure 5 represents the expected content of chloride ions and its Probability Density Function (PDF) at years 10, 20, 30, and 40 for normal concrete monitored at concrete cover depth, using 10000 random samples. It is observed that the dispersion of chloride content increases with time, as shown by the PDF from years 10 to 40. In addition, the probability that the content of chloride ions at concrete cover depth is more than or equal to the critical chloride value ($C_{Corr.}$) also increases with time. For more explanation, let's consider the PDF at year 10 as an example. Although the PDF at year 10 totally falls within the range of the critical chloride

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value $C_{Corr.}$ (0 to 2 due to using Beta [0,2], see Table 1), the probability that the content of chloride ions at concrete cover depth is more than or equal to the critical chloride value is not zero. This is due to the fact that $C_{Corr.}$ mostly occurs within 0 to 1.2 as shown by the dense area in Figure 5 (see also Figure 1d). In the other words, the probability that $C_{Corr.}$ is more than 1.2 is quite low. As a result, there is a probability that the content of chloride ions at concrete cover depth is more than or equal to the critical chloride value at year 10. This probability is defined as the Cumulative Density Function (CDF) of critical time at year 10. As shown in Figure 6, at year 10, the CDF of critical time, or the probability that the content of chloride ions is more than or equal to the critical chloride value, is quite low. However, the CDF of critical time increases with time, and almost approaches 1 at year 50. This agrees with the PDF of chloride content in Figure 5, due to the increase of both the mean value and the dispersion of chloride content. By calculating the rate of increase of CDF of critical time, the PDF of critical time can be defined and determined as also shown in Figure 6. It is observed that the rate of increase of PDF of critical time is high between year 10 and 20, but gradually lowers after that. This shows that the probability that the content of chloride ions is more than or equal to the critical value increases more quickly between years 10 and 20.

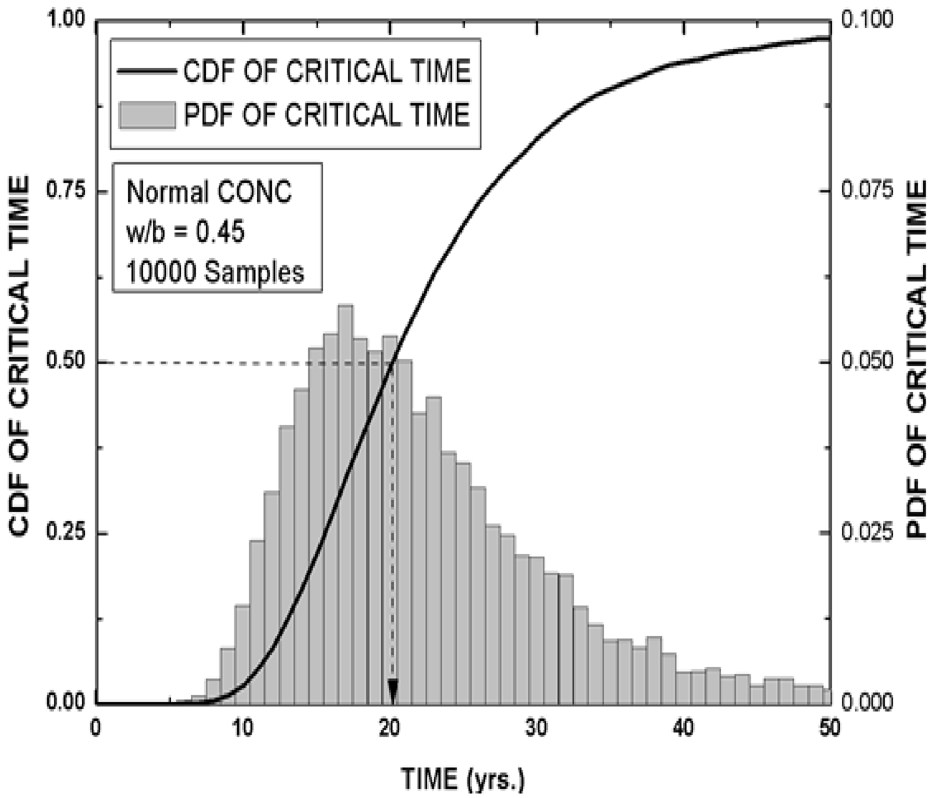

FIGURE 6
CDF AND PDF OF CRITICAL TIME FOR NORMAL CONCRETE

Figure 7 compared the CDF of critical time between normal and FA concrete materials. They are identical. To explain this, let’s consider Figure 8 which shows the mean and the standard deviation of time-dependent chloride content for normal and FA concrete. Although their mean is different, they are considered equivalent because both of them are designed to be free of reinforcement corrosion for 20 years by considering different critical chloride values (0.45 and 0.35 in Tables 1 and 2). And also, their standard deviation is not much different. So, their CDF of critical time is identical.

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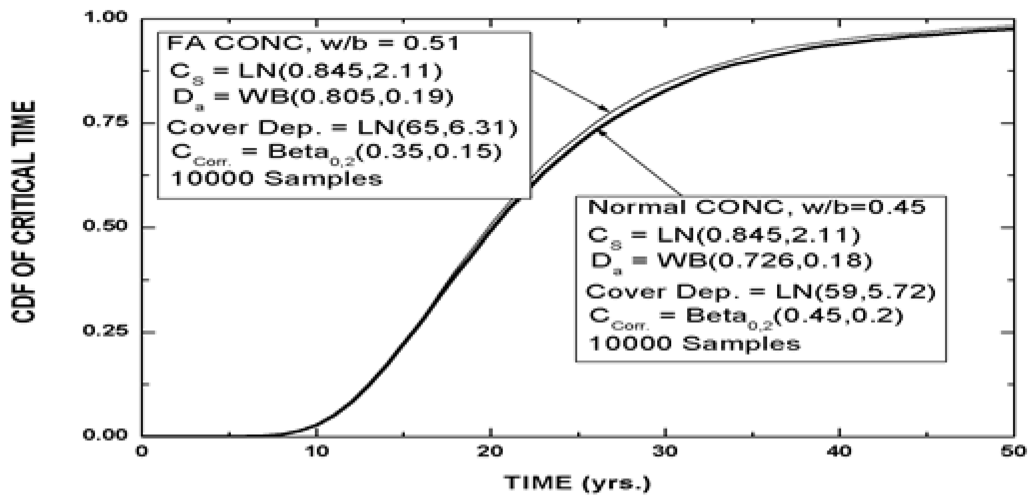

FIGURE 7
CDF OF CRITICAL TIME FOR NORMAL AND FA CONCRETE

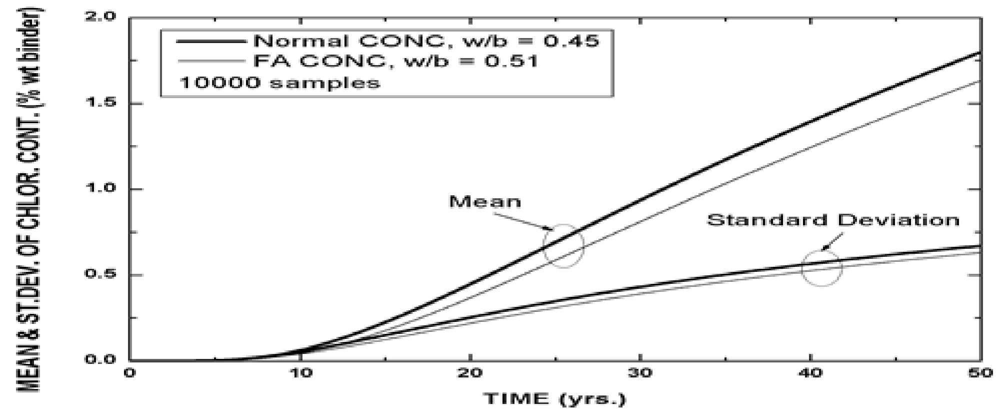

FIGURE 8
MEAN & ST. DEV. OF CHLORIDE CONTENT FOR NORMAL AND FA CONC RETE

Using only the CDF of critical time, as shown in Figure 9, is not enough to represent the difference between normal and FA concrete. To clarify the difference, lets define the expected cumulative cost for critical time as the cost equivalent to the cost of cover concrete repair (patch concrete repair). It is noted that the cost of concrete is used in comparison, because the predicted critical time of reinforcement corrosion is expectedly related to repairs, leading to the cost of concrete repairs, such as concrete patching. By this definition, the expected cumulative cost can be formulated as

$$E(Ccost) = CDF \times (Cover\ depth) \times (cost\ of\ concrete) \tag{3}$$

Where the cost of concrete is equal to 2400 Baht per m^3. The unit of the expected cumulative cost in Eq. (3) is in Baht per m^2, because of multiplication with the cover depth. Because the concrete cover depth of normal concrete is lower than that of FA concrete (see Tables 1 and 2), the expected cumulative cost of critical time for normal concrete is lower than that for FA concrete. Figure 10 compares the expected cumulative cost for critical time of normal concrete to FA concrete at years 20 and 50. For 20-year corrosion-free service life, the

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expected cumulative cost for critical time of normal concrete is lower than that of FA concrete by 11.83%. For 50-year, the difference is lower by 10.23%.

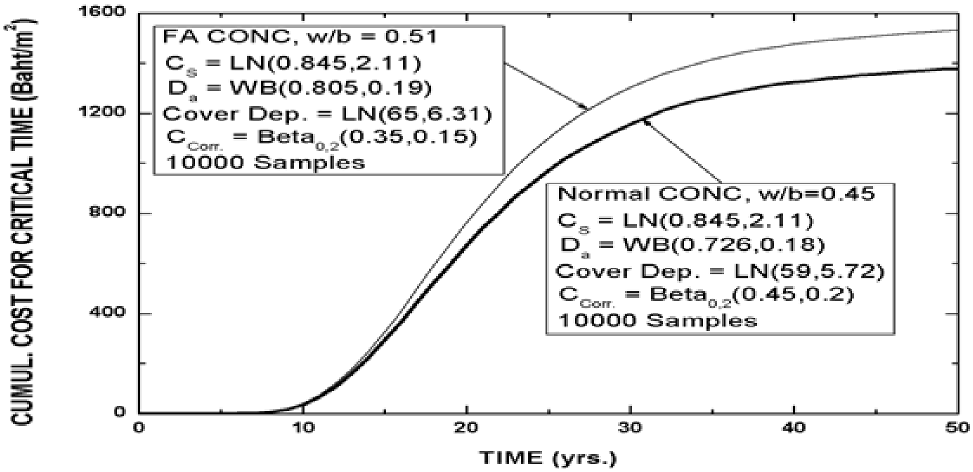

FIGURE 9
CDF OF CRITICAL TIME FOR NORMAL AND FA CONCRETE

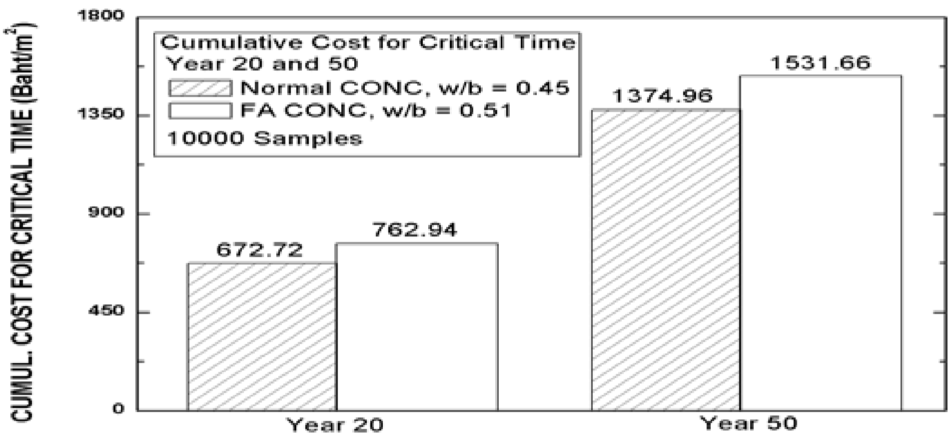

FIGURE 10
COMPARISON OF EXPECTED CUMULATIVE COST FOR CRITICAL TIME OF NORMAL CONC TO FA CONC AT YEARS 20 AND 50

CONCLUSION

From the deterministic assessment, normal concrete with w/b of 0.45 and cover depth of 59 mm is found to be equivalent to fly-ash concrete with w/b of 0.51 and that of 65 mm, satisfying 20-year corrosion-free service life as per the Thai standard (DPT, 2021). From the probabilistic assessment, the CDF of the critical time (the probability that the content of chloride ions at the cover depth is more than or equal to the critical chloride value) for normal concrete is also identical with that for FA concrete despite designing different mean and standard deviation. However, the expected cumulative cost for critical time of normal concrete is obviously lower than that of FA concrete because the cover depth of normal concrete is lower. This is judged by assuming that the predicted critical time of reinforcement corrosion is expectedly related to repairs and its cost.

The findings from this study have provided a practical framework for decision-makers to prioritize annual budget allocations to manage concrete structures exposed to a chloride environment. Moreover, based on engineering and statistical disciplines, the suggested model

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can be developed and applied for cost estimation by assuming that the predicted critical time of reinforcement corrosion is expectedly related to repairs and its cost. The model can also be serving as a guideline for revaluating assets according to international accounting standards pertaining to measuring depreciation and impairment of assets after initial recognition.

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