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Characteristic service life for concrete exposed to marine environments

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Abstract

A statistical treatment has been applied to a deterministic service life model of concrete structures in marine environments. The chloride ingress model based on Fick's second law of diffusion was assumed. The quality of concrete was quantified in terms of three factors, namely, an apparent diffusion coefficient at 1 year (D_a), surface chloride concentration (C_s) and a critical chloride level (C_{cr}). The standard deviation of service life can be estimated from standard deviations of the four factors, namely, C_s, D_a, C_{cr} and cover depth. The effect of the severity of environment on service life was also demonstrated. With data from the literature and an approximation of the inverse error function, sensitivity analyses were carried out. Service life was found to be more sensitive to cover depth than the diffusion coefficient, and more sensitive to surface chloride concentration than the critical chloride level. Characteristic service life of a range of normal Portland cement (NPC) concrete grades was evaluated as a function of 28-day strength and cover depths for a nominated confidence level. Such characteristic service life can be readily used and appreciated by design engineers.

Keywords: Chloride; Concrete; Standard deviation; Service life; Stochastic model

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1. Introduction

The stochastic nature of service life has been very well established [1–4]. Service life is not a fixed value as calculated by a deterministic model, but instead, it is a range of values for a range of material characteristics, cover depth and severity of service environment. Service life in this study has been defined as the period of initiation or the time required for the chloride concentration at the reinforcement to reach the critical chloride level (C_{cr}).

The first source of scatter in service life is the variation in material characteristics. In any structure or building, there is bound to be variation in the quality of concrete due to variation in water/binder ratio, different levels of compaction, variation in extent of curing or the variation in the hydration of cement due to changes in temperature. The second variation is due to the deviation in the thickness of the coating on the concrete or some of the coating could be damaged, and also due to the variation in the cover depth values. Variation in the service environment is another source of scatter in service life. A part of the structure could be in the tidal zone and another part could be in the splash zone. Also, some portion of a structure could be continuously immersed in the seawater and some portion could be exposed to airborne chloride.

The abovementioned three factors will affect service life, however, more importantly the variation in the three factors will affect the variation in service life. The deterministic model, due to its inherent nature, assumes the quality of concrete and cover depth to be constant and the surrounding environment to remain unchanged. For this single value of quality of concrete, single value of cover depth and single environment, it calculates and gives a single value of service life. However, there is always variation in the three factors which will lead to a variation in the service life. Some of the variations in these three factors could be very high and in turn could cause significant variation in the service life. Thus, the single value of service life measured from the deterministic model must be supplemented with some statistical parameter to be able to truly reflect the service life and its variation. This would give a realistic and practical service life.

In this study, the single value of service life calculated from the deterministic model was supplemented with a statistical parameter—standard deviation. The standard deviation in service life was evaluated from the standard

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deviation in the four variables. Subsequently, the standard deviation of service life was used to calculate the characteristic service life at a nominated confidence level of 90%. All engineers are well familiar with the concept of characteristic values, as it is used extensively for the characteristic compressive strength or grade of concrete. Thus, the concept of characteristic service life should be easily understood and appreciated by all engineers.

Service life in this study is considered to be the period of initiation or the time required for the chloride concentration at the reinforcement to reach the critical chloride level (C_{cr}). The variation in service life due to the variation in material characteristics and cover depth was calculated. The material characteristics included concrete properties [surface concentration (C_s), diffusion coefficient (D_a) and C_{cr}]. The deterministic model used in this study for the calculation of the service life was based on Fick's second law [5], and the service life is a function of the abovementioned four variables (C_s, D_a, C_{cr} and cover depth). Apart from material characteristics and cover depth, variation in service life also arises due to variation in service environments. The variation in service life due to the variation in the severity of the environment was not calculated, but instead it was demonstrated how it affects the variations in service life. More work would be required to calculate the variation in service life due to variation in service environment.

2. Combination of statistical and deterministic models

According to Clifton [1], there are five approaches to predict the service life of construction materials, viz.:

1. Estimate based on experience;
2. Deductions from the performance of similar materials;
3. Accelerated testing;
4. Mathematical modeling based on the chemistry and physics of degradation processes; and
5. The application of probability concepts.

Strictly, the fifth method is a combination of more than one method as, due to its inherent nature, it would need data from another method so that the statistical treatment can be carried out. In this study, a combination of a statistical and a deterministic model is used to calculate service life. Such a methodology has been used by Siemes et al. [2,6].

To calculate the variation in service lives due to variation in material characteristics, cover depth and the aggressiveness (severity) of environments, two steps are essential. In the first step, the variation in these factors should be evaluated. In the second step, the relationship between the variations in these factors and service lives should be established. Subsequently, the variation in service life due to variation in these three factors can be determined.

The first step in this process is beyond the scope of the present study, and the variation values (variation in material characteristics, cover depth and severity of service environment) obtained from either previous studies or the literature will be relied upon. This study will concentrate on the second step, and thus, a relationship will be obtained between the variation in service life due to the variation in material characteristics, cover depth and severity of service environment. It should be noted that the variation in service life due to changes in the severity of the environment has not been quantified. However, the importance of the severity of the service environment on the service life was demonstrated.

The standard deviation of service life is expected to give good statistical information about the service life, and hence the standard deviation ($\sigma_{T_{SL}}$) was used to indicate variation in service life. The standard deviation of a variable (T_{SL}), which is a function of many variables (Y_i), is given by Eq. (1), provided the various variables Y_i are not interdependent [1,7]:

$$\sigma^2_{T_{SL}} = \sum_{i=1}^{n} \left[\frac{\partial T_{SL}}{\partial Y_i} \sigma(Y_i) \right]^2 \tag{1}$$

A deterministic model based on Fick's second law was used in this study. Fick's second law of diffusion has been used extensively by many researchers/engineers to calculate the chloride concentrations for various cover depths at different exposure time intervals [8–11]. The basic assumption is that chloride ions are transported through the concrete by a concentration gradient. Fick's second law is valid only for nonionic diffusants through inert homogeneous medium. Chloride solution is an ionic solution and concrete is an inhomogeneous and dynamic medium chemically and physically. Despite its shortfalls, Fick's second law is considered to be the most practical and elegant method available.

According to Fick's law, the concentration $C_t(x,t)$ at depth x and time t can be given by Eq. (2) [5], where erfc is a complementary error function. C_i or the initial concentration of chloride ions in concrete was assumed to be zero:

$$C_t(x,t)/C_s = \mathrm{erfc}(x/2\sqrt{D_a t}) \tag{2}$$

From Eq. (2), t can be derived as follows:

$$t = \frac{x^2}{4D_a} \left(\mathrm{erfc}^{-1} \left[\frac{C_t(x,t)}{C_s} \right] \right)^{-2} \tag{3}$$

where x = cover depth (m); $C_t(x,t)$ = chloride concentration at cover depth (% by mass of concrete); C_s = surface chloride concentration at time t (% by mass of concrete); erfc^{-1} = inverse of complementary error function; D_a = apparent diffusion coefficient at time t (m^2/s); t = time for chloride to reach $C_t(x,t)$ at cover depth x (s).

In Eq. (3), when $C_t(x,t)$ becomes C_{cr}, x becomes X_{cover}, and t will become T_{SL} or service life. X_{cover} is the cover depth value. It can be seen from Eq. (3) that T_{SL} is a function of D_a, X_{cover}, C_s and C_{cr}. Eq. (1) can be used to calculate the standard deviation of service life, provided D_a, X_{cover}, C_s and C_{cr} are not interdependent. The cover depth is part of the construction process and is not a property of concrete. Hence, the cover depth is an independent variable. An extensive literature search was carried out to ascertain whether the remaining three factors are interdependent. It has been very well established that D_a decreases with decreasing water/binder ratio and also by the addition of supplementary cementitious materials (SCM) [12–14]. Also, D_a has been found to decrease with time [9,15,16]. Numerous studies have been carried out on D_a, and its dependence on water/binder ratio, the addition of SCM and its variation with time has been clearly established. On the other hand, relatively fewer studies have been carried out on C_s and C_{cr}, and the findings of the studies are conflicting. According to Thomas and Matthews [17], C_{cr} was found to decrease with increasing fly ash content and it appears that C_{cr} and D_a are interdependent. However, many other researchers either found C_s and C_{cr} to be constant or could not establish any trend with confidence [18–21]. Uji et al. [22] and Bentz et al. [9] found C_s to increase with time, however, Bamforth [20] and Collins and Grace [18] found C_s to remain constant.

In view of the conflicting outcomes from the various studies reported in the literature, it was concluded, albeit with some reservations, that the three variables are not interdependent. Thus, Eq. (1) can be expanded into Eq. (4):

$$\sigma_{T_{SL}}^2 = \left[\frac{\partial T_{SL}}{\partial D_a}\sigma(D_a)\right]^2 + \left[\frac{\partial T_{SL}}{\partial X_{cover}}\sigma(X_{cover})\right]^2 + \left[\frac{\partial T_{SL}}{\partial C_s}\sigma(C_s)\right]^2 + \left[\frac{\partial T_{SL}}{\partial C_{cr}}\sigma(C_{cr})\right]^2 \quad (4)$$

where $T_{SL} = f(D_a, X_{cover}, C_s, C_{cr})$.

3. Variation in the four variables governing service life

As mentioned earlier, to evaluate the variation in service lives due to the variation in the four factors, namely, D_a, X_{cover}, C_s and C_{cr}, two steps are necessary. Firstly, the variation in these four factors in terms of the standard deviation should be evaluated. Secondly, the partial differential component of service life with respect to the four factors, such as $(\partial T_{SL}/\partial D_a)$, etc., should be evaluated. Thus, by using Eq. (4), the standard deviation of service lives due to the standard deviation of the four factors can be evaluated.

3.1. Variation in D_a

The level of compaction and the degree of curing is expected to vary from site to site, and hence, it is difficult to be estimated or quantified. Thus, the variation in D_a due to the variation in the degree of compaction and curing was not evaluated. It was assumed that the variation in D_a is solely due to the variation in the quality of supplied concrete, and hence, the variation in D_a due to the variation in the compressive strength of supplied concrete was evaluated.

According to ACI Report ACI 214-77 [23], the standard deviation of concrete in general construction with "fair" control standard has been given as 4–5 MPa. For this study, the standard deviation was assumed to be the average value of 4.5 MPa. The next step was to calculate the standard deviation in D_a, which corresponds to the standard deviation in strength of 4.5 MPa. In a previous study [16], the variation of diffusion coefficient with 28-day strength was established for a range of concrete prepared from four binder systems. Such data will be used to calculate the standard deviation in D_a. Fig. 1 illustrates the methodology used for the calculation of the standard deviation of D_a for a normal Portland cement (NPC) concrete of mean strength 47 MPa (grade 40 concrete), which has the standard deviation of strength as 4.5 MPa. NPC concretes were prepared from NPC or a general purpose Portland cement conforming to Australian Standard AS 3972 and similar to ASTM Type I. The standard deviation in the diffusion coefficient for the grade 40 NPC concrete was found to be 1.65×10^{-12} m^2/s. The standard deviation in diffusion coefficient is expected to depend on the value of diffusion coefficient. However, a similar procedure can be followed for any particular structure to calculate standard deviation of diffusion coefficient for a known standard deviation in compressive strength.

3.2. Variation in X_{cover}

Similar to compressive strength, cover values are also expected to vary within a structure. The standard deviation of the cover values was based on a study carried out by Sirivivatnanon and Cao [24]. For rectangular slabs at five major office building sites in Melbourne in 1979, four

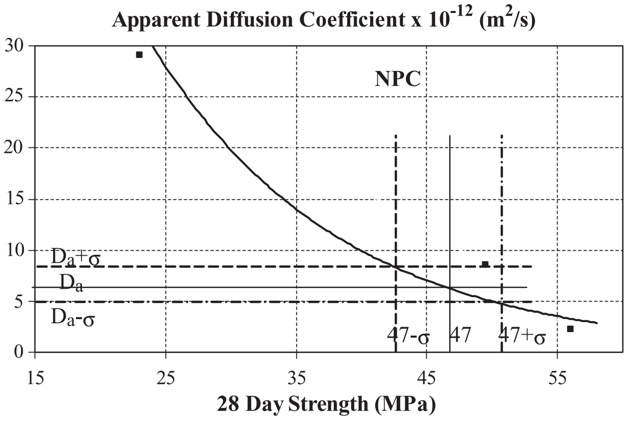

Fig. 1. Estimation of standard deviation in D_a in an NPC concrete from the standard deviation in compressive strength.

building sites in Sydney in 1980, and three building sites on the Gold Coast in 1980 (all sites are in Australia), for a mean cover value of 25 mm, the standard deviation was found to be 4 mm. For concrete walls in 40 buildings in Japan from 1924 to 1974, a standard deviation of 6.8 mm was observed for a mean cover of 30 mm. Also, for concrete columns in Japan, the standard deviation was observed to be 6 mm for a mean cover of 30 mm. All these studies are about 20 years old or older, however, they give a fair estimate of the standard deviation in cover values found on site.

3.3. Variation in C_s and C_{cr}

An extensive literature search was carried out to determine the variation in the values of C_s and C_{cr}. There is some information available about the individual values of C_s and C_{cr} for various grades of concretes prepared from different binders. Most of the values were determined experimentally, whereas some values were calculated theoretically. However, only limited information was available about the variation in these values, and hence, the variation in the service life due to variation in C_s and C_{cr} was not evaluated [25].

4. Rate of change of service life with respect to changes in the four variables

As mentioned earlier, in Eq. (3), when x becomes X_{cover}, C_t becomes C_{cr}, and t will become T_{SL}, as shown in Eq. (5):

$$T_{SL} = \frac{1}{4D_{aT_{SL}}}\left(\frac{X_{cover}}{\mathrm{erfc}^{-1}[C_{cr}/C_s]}\right)^2 \tag{5}$$

Since it is difficult to calculate D_a at the end of service life, diffusion coefficient calculated at time T_c is correlated to the diffusion coefficient at time T_{SL} by the correlation (shown in Eq. (6)) given by Maage et al. [11]. In Eq. (6), α is a maturity coefficient and a value given Maage et al. [11] of .7 was used.

$$D_{aT_{SL}} = D_{aT_c}(T_c/T_{SL})^{\alpha} \tag{6}$$

The diffusion coefficient at service life given in Eq. (6) was used to calculate T_{SL} and the equation developed by Maage et al. [11] is shown in Eq. (7):

$$T_{SL} = T_c\left(\frac{X_{cover}}{\xi\sqrt{T_c D_{aT_c}}}\right)^{(2/1-\alpha)} \quad \text{and } \xi = 2\mathrm{erfc}^{-1}(C_{cr}/C_s) \tag{7}$$

The second step in calculating the standard deviation of service life is the calculation of the partial differential component of service life with respect to the four factors (D_a, X_{cover}, C_s and C_{cr}), such as ($\partial T_{SL}/\partial D_a$) etc. The partial differential component is essentially the rate of change in service life due to change in the four factors, or in other words indicates the sensitivity of service life with respect to the four variables. A high value of partial derivative indicates high sensitivity, which implies that a small variation in that variable would lead to significant changes in the service life. A similar sensitivity study has been carried out by Boddy et al. [26], and the sensitivity study was based on a model which took into consideration diffusion, permeation, sorptivity, wicking and chloride binding. The results of the sensitivity study will be compared to the results of the study carried out by Boddy et al. [26].

4.1. Sensitivity of D_a and X_{cover}

Eq. (5) was used to calculate the partial differential component of service life with respect to diffusion coefficient and cover values as it reflects the Fick's second law of diffusion:

$$\frac{\partial T_{SL}}{\partial D_{aT_c}} = \frac{-T_{SL}}{D_{aT_c}} \tag{8}$$

$$\frac{\partial T_{SL}}{\partial X_{cover}} = \frac{2T_{SL}}{X_{cover}} \tag{9}$$

As expected, increasing D_a leads to a reduction in service life, whereas an increase in cover depth leads to an increase in service life. Eqs. (8) and (9) give the rate of change of service life due to changes in D_a and cover depth. Eqs. (8) and (9) are graphically illustrated in Fig. 2. Increasing the diffusion coefficient by 10% leads to about a 10% reduction in service life, whereas increasing the cover depth by 10% leads to about a 20% increase in service life.

Boddy et al. [26] also found that decreasing D_a from 2.53×10^{-12} m^2/s to 0.33×10^{-12} m^2/s (87% decrease) led to an increase in service life of about 84%. Also, increasing the cover depth from 30 to 60 mm (100% increase) increases the service life by about 230%.

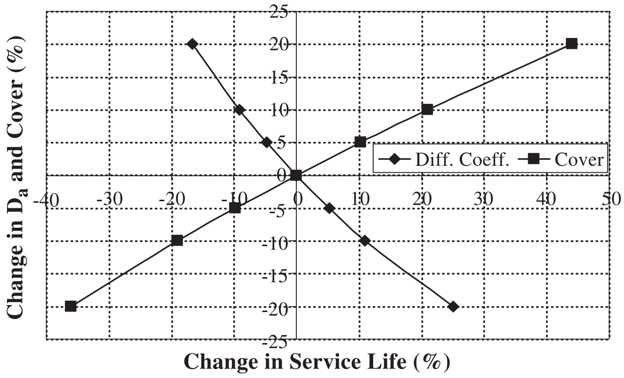

Fig. 2. Variation in service life due to changes in cover values and apparent diffusion coefficients.

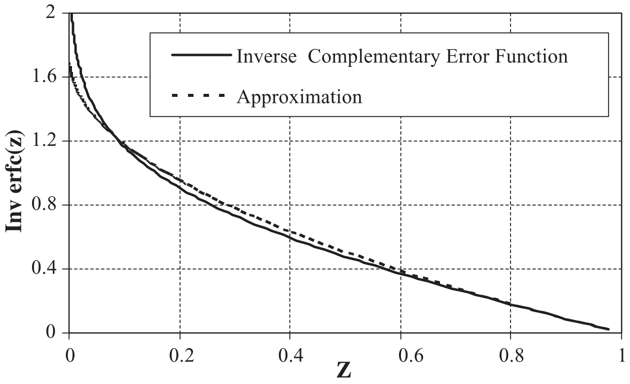

Fig. 3. Inverse complementary error function and the approximation used in this study.

4.2. Sensitivity of C_s and C_{cr}

Eq. (5) can be used to calculate the partial differential component of service life with respect to C_s and C_{cr}. Mathematically, it is difficult to take the partial derivative of service life with respect to C_s and C_{cr}, and both these variables are inside the inverse complimentary error function. There are a few approximations to the complimentary inverse error function and Eq. (10) gives one such approximation, which was used in the study and is plotted in Fig. 3:

$$\mathrm{erfc}^{-1}(Z) = \sqrt{3}\left[1 - \sqrt{z}\right] \tag{10}$$

The approximation of Eq. (10) was used to calculate the partial differential component of service life with respect to C_s and C_{cr}. The value of C_{cr} was obtained from the study of Cao et al. [27] and was 0.2% by weight of the concrete. C_s was obtained experimentally from chloride profiles after immersion in 3% NaCl solution, and was found to be 0.7% by weight of concrete [16]. Using these value of C_s and C_{cr}, the partial differential components of service life were calculated and are shown in Eqs. (11) and (12).

$$\frac{\partial T_{SL}}{\partial C_s} = -1.75 T_{SL} \tag{11}$$

$$\frac{\partial T_{SL}}{\partial C_{cr}} = 6.13 T_{SL} \tag{12}$$

It can be seen that increasing C_s leads to a decrease in the service life and vice versa. A high value of C_s would cause the chloride concentration at cover depth to reach C_{cr} earlier, and thus, would lead to lower service life. Also, it can be seen that an increase in C_{cr} would lead to an increase in the service life. A higher C_{cr} would imply that the chloride concentration has to exceed that value before corrosion can initiate, and it would take longer for the chloride concentration to reach that high value. Thus, a high value of C_{cr} would lead to higher service life. The partial derivatives suggest that service life is more sensitive to changes in C_{cr} than C_s.

5. Standard deviation of service life

After evaluating the sensitivity of service life with respect to C_s and C_{cr}, the contribution to the standard deviation of service life due to their standard deviations can be calculated, as shown in Eqs. (13) and (14), respectively:

$$\left[\frac{\partial T_{SL}}{\partial C_s}\sigma(C_s)\right]^2 = 3.07 T_{SL}^2 \sigma^2(C_s) \tag{13}$$

$$\left[\frac{\partial T_{SL}}{\partial C_{cr}}\sigma(C_{cr})\right]^2 = 37.58 T_{SL}^2 \sigma^2(C_{cr}) \tag{14}$$

C_s is expected to be much greater than C_{cr} and, in most cases, C_s would be about 3–10 times C_{cr}. For a similar coefficient of variation (COV), the standard deviation in C_s would also be about 3–10 times greater than that of C_{cr}. By comparing Eqs. (13) and (14), it is clear that the contribution from the standard deviation of C_{cr} would be significantly greater than the contribution from the standard deviation of C_s.

Since no information was available on the standard deviation of C_s and C_{cr}, their contribution to the standard deviation of service life was not included. The standard deviation of the service life can be calculated from Eq. (4) and, after incorporating the sensitivities of D_a and X_{cover}, Eq. (4) becomes:

$$\sigma_{T_{SL}} = T_{SL}\sqrt{\frac{\sigma(D_{aT_c})^2}{D_{aT_c}^2} + \frac{4\sigma(X_{cover})^2}{X_{cover}^2}} \tag{15}$$

In Section 3.1, the diffusion coefficient and standard deviation was observed to be 5.9×10^{-12} and 1.65×10^{-12} m^2/s for NPC concrete. Thus, the COV for the diffusion coefficients was 28%. Also, in Section 3.2 the COVs for cover depth values were found to be 16%, 20% and 22%. For these values of COV of cover depth and diffusion coefficients, the COV for service life was calculated from Eq. (15) and is shown in Table 1. Eq. (7) was used to calculate the service life, and for these calculations the values of C_s and C_{cr} were 0.7% and 0.2% by weight of the concrete, respectively. For service life calculation, D_{aT_c} measured after 1 year of immersion was used. It can be seen from Table 1 that the COV for service life is generally quite high, and could be as high as 52%.

Table 1
COV of service life

COV D_a (%)	COV cover depth (%)	COV T_{SL} (%)
28	16	43
28	20	49
28	22	52

6. Characteristic service life

It has been very well established that service life follows a log-normal distribution [1,3,28]. If a random variable is a product of a large number of independent positive random variables, then the resulting random variable will tend towards log-normal distribution [29]. Some examples of log-normal distributions are heights of annual floods on a river, the size of a species of insect and the distribution of incomes in a certain population [29]. Since service life follows a log-normal distribution, the natural logarithm of service life will follow the normal distribution. Thus, a concept of characteristic service life was introduced and the characteristic service life for natural logarithm service life was calculated, because it follows a normal distribution. Subsequently, by taking an exponential value, the characteristic values of actual service life were calculated. The standard deviation and mean values of actual service life were used to calculate the standard deviation and mean of the logarithmic service life, and these values were in turn used to calculate characteristic logarithmic service life [29,30]. The characteristic logarithmic service life was calculated for a confidence level of 90% or 10% rejection (10% of the values of logarithmic service life is less than the characteristic logarithmic service life). Finally, as mentioned earlier, the characteristic logarithmic service life was converted back into the actual characteristic service life.

In this study, the characteristic service life of NPC concrete of different grades (20, 32, 40 and 50) and exposed to two types of exposures were calculated. The two types of exposures were simulated submerged zone (concrete continuously immersed in 3% NaCl solution) and simulated tidal zone (concrete in cyclic immersion in 3% NaCl solution). D_a was experimentally measured after 1 year of immersion for both exposures and the mean service life was calculated using Eq. (7) [11,31]. For these calculations, the values of C_s and C_{cr} were 0.7% and 0.2% by weight of concrete, respectively. For characteristic service life calculations, the COV for diffusion coefficient was considered as 28% for NPC concrete (calculated in Section 5), and for cover was assumed as 16% (value from Sirivivatnanon and Cao [24]). The characteristic service life was calculated for a nominated confidence level of 90%. Figs. 4 and 5 show the characteristic and mean service life for simulated submerged zone and simulated tidal zone, respectively.

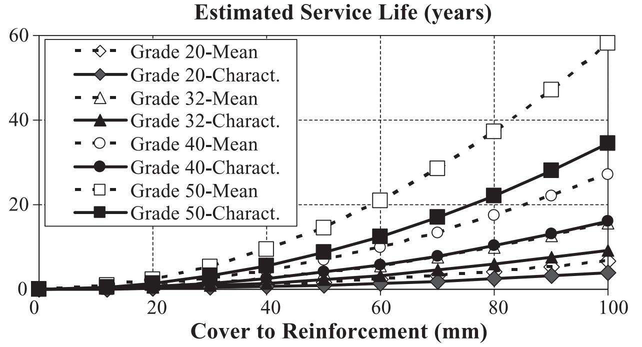

Fig. 4. Characteristic and mean service life of NPC concrete in a simulated submerged zone or continuous immersion condition.

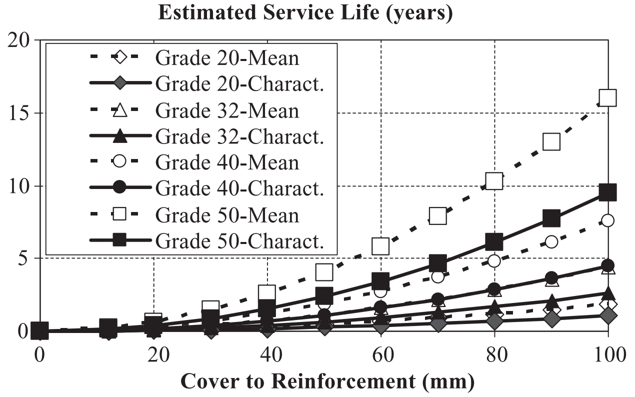

Fig. 5. Characteristic and mean service life of NPC concrete in a simulated tidal zone or cyclic immersion condition.

It can be seen from Figs. 4 and 5 that the characteristic service life is significantly lower than mean service life. As mentioned earlier, various researchers have also found huge scatter in service life [4,32].

By comparing Fig. 4 with Fig. 5, it can be seen that the service life for simulated tidal zone is lower than that for simulated submerged zone. This emphasizes the importance of the service environment. In this study, the variation in service life due to variation in material characteristics and cover depth was evaluated. Similarly, the variation in service life due to variation in the surrounding environment or service environment should also be evaluated. The difficulty arises in the quantification of the severity of the environment. It is well established that tidal zone or cyclic immersion is more severe than submerged zone or continuous immersion, however, it is difficult to quantify the severity or aggressiveness of the environment. Thus, the variation in service life due to variation in service environment was not calculated, and Figs. 4 and 5 were used to illustrate the importance of the variation of service environment and emphasize the need for further work.

7. Discussion

The service life calculations from the deterministic model were subjected to probabilistic treatment. It is well known that for any structure or building, there will be variations in material characteristics, cover depth and service environments. The variation in these factors will affect the variation in service life. In this study, the variation in service life due to variation in material characteristics and cover depth was evaluated. Also, the variation in service life due to variation in service environment was demonstrated.

Service life follows a log-normal distribution and hence the probability density function of service life follows a log-normal pattern. Thus, the probability density function of logarithmic service life would follow a normal distribution. For such a normal distribution, the characteristic values can be easily calculated and thus the characteristic logarithmic service life was calculated. This characteristic logarithmic was converted back to the characteristic service life. This appears to be a roundabout way for the calculation of characteristic service life. Since service life follows a log-normal distribution, characteristic service life cannot be directly calculated and such an indirect method is the only option. Furthermore, characteristic service life is an important concept as it can be easily appreciated by engineers, designers and specifiers, and such a concept can be readily used by them. Engineers and designers have been using the concept of characteristic compressive strength or grade of concrete for many years and are very familiar with this concept. Thus, it would be relatively easier for them to put it into practice. Such a "user-friendly" approach is highly desired even at the expense of a roundabout method of calculation. However, the procedure has been established, and by following the procedure, characteristic service life can be easily calculated.

8. Conclusions

A statistical method has been used to estimate the characteristics service life of concrete in marine environments with a nominated confidence level. The variation in service life due to variation in quality of concrete (diffusion coefficient), cover depth and service environment was quantified. The influence of service environment is reflected in the value of diffusion coefficient. The characteristic service life of different grades of NPC concrete was calculated for simulated submerged and tidal zone. It was found that service life is more sensitive to cover depth than diffusion coefficient and more sensitive to surface chloride concentration than critical chloride level.

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