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SIGNIFICANCE OF SERVICE LIFE BASED CONCRETE MIX DESIGN IN MARINE ENVIRONMENT

Manzur, T.[1,7], Hasan, M. J.[2], Baten, B.[3], Torsha, T.[4], Khan, M. F. A.[5] and Hossain, K. M. A.[6]

[1,2,6]Ryerson University, Canada, [1,3,4,5]Bangladesh University of Engineering and Technology, Bangladesh

[7]tmanzur.buet@gmail.com

Abstract: Concrete mix design in many parts of the globe is still primarily based on strength requirement. One of the main reasons for strength focussed mix design is the relative simplicity and promptness of the strength measurement procedure. However, under severe exposure condition like marine environment, typical durability concept often fails to provide required serviceability of a Reinforced Concrete (RC) structure. This structural hazard is usually significant in RC structures of low to moderate strength, particularly in regions where durability is not a prime concern over strength, like Bangladesh. The impermeability of concrete is usually measured through chloride diffusion coefficient which has significant effect on corrosion initiation of reinforcement. The typical strength focussed mix design practices cannot ensure reduced diffusion coefficients since pore refinement is necessary to disconnect continuous pore system within concrete. Refinement of pores can be warranted through use of composite/blended cement that contains supplementary cementitious material like fly ash. Nevertheless, use of such composite cement could hamper the strength gain of concrete. As a result, use of Ordinary Portland Cement (OPC) is preferred over blended cements in most cases of strength-based mix design. Considering all the aforementioned aspects, an effort has been undertaken in this study to investigate the probable service life of RC structures of some common concrete mixes targeted for low to moderate strength with workable slumps. Chloride diffusion coefficients of the mixes were obtained by non-steady state rapid migration test. A probabilistic approach was followed to determine probable service life considering typical concrete covers used in marine condition. It has been found that proper choice of cement type and concrete cover has significant impact on achieving satisfactory service life of RC elements.

1 INTRODUCTION

Concrete, over the years, has attained significant acclamation as the most widely used construction materials owing to its several noteworthy benefits (Palumbo, 1991). While designing a Reinforced Concrete (RC) structure, the most preferred practice involves proportioning of concrete ingredients based on strength requirement which is known as mix design. In conventional mix design process, durability concerns are generally kept in a backseat considering better strength would result in superior durability (Torsha et al., 2019). However, this outlook has been changed notably in recent times because of the dominant influence of durability on the service life of a RC structure. Nevertheless, in developing countries like Bangladesh, the strength-based design is still most practiced (Manzur et al., 2017). Even, the prevalent mix design methods lack directives on design exercises that will primarily focus on ensuring serviceability in lieu of ensuring strength gain of the concrete mix used. Hence, it has become a key challenge to provide guidelines for safeguarding durability of RC structures so as to keep pace with the recent boom in usage of reinforced concrete in local construction industry. One of the prime factors that affects durability of the embedded reinforcement and ultimately the RC element is corrosion of the steel rebar (Wegen et al., 2012; Zhou et al., 2015). Under aggressive environment such as that surrounds a marine structure, adverse agents like chloride seep into the concrete and eventually, abolishes the protective layer around the steel rebar by diminishing the alkaline environment to an acidic one (Verma et al., 2014; Altoubat et al., 2016; Moreno et al., 2004). Such situations get aggravated further due to highly permeable concrete that results from lack of suitable material choice as well as quality control and proper workmanship (Mashrur et al., 2018; Manzur et al., 2018). Apart from lower permeability, concrete cover provided during structural design of a RC element works remarkably in ensuring desired serviceability of any particular RC element (Wang et al., 2010). This is because concrete cover defines the distance to be travelled by any corrosion inducing agents to reach the reinforcement level and thus, has an impact on their rate of accumulation to a critical level to initiate corrosion (Wang et al., 2010; Abouhussein and Hassan, 2014). The prevalent literatures and local building codes, however, suggest concrete cover limit based on tension crack criteria and typical environmental effects, hardly addressing the durability issue. Likewise, the issue of concrete permeability and its association with concrete quality as well as its serviceability have scarcely been addressed by past researches let alone by existing code directives in the country. All these aspects, thus, substantiate the necessity of reviewing serviceability of RC elements, prepared using local materials and with cover limit as suggested by native codes. Through this study, ranges of expected service life values of some indigenous concrete mixes under extreme marine exposure were determined for some typically used concrete cover values. The values of service life were calculated in terms of time required to initiate the corrosion process, following an equation as specified in fib guidelines (2006) which was initially developed by Duracrete (1998). The whole evaluation process was based on a probabilistic approach that involves choosing range of values randomly for certain parameters from their respective particular data distribution functions. The degree of permeability of selected concrete mixes were evaluated in terms of chloride diffusion coefficients. These values signify the concrete resistance towards chloride ions ingress and rate at which the concrete surface will be affected. For this evaluation purpose, concrete mixes with locally produced Ordinary Portland Cement (OPC) or ASTM Type I and Portland Composite Cement (PCC) or CEM II (EN 197-1, 2011) were considered in order to review their performance under adverse condition. Mixes were prepared following typical volumetric mixing ratio of 1:1.5:3 and w/c ratio of 0.45~0.55 in such a way that the concretes yield moderate compressive strength (20MPa to 38MPa). In case of mixes with OPC, two different aggregate types (stone and brick) were chosen for a comparative evaluation. The corrosion initiation for each mix was, then, evaluated for typically used concrete cover values of 50mm, 75mm and 100mm. The exposure condition for marine environment were chosen as per EN 206 (2013) code. The observations showed that usage of PCC over OPC in concrete improves concrete resistance to chloride penetration appreciably. Thus, it takes comparatively higher times to initiate corrosion and gives better serviceability to concrete structure with PCC than that with OPC, irrespective of the cover values and exposure conditions. As for mixes with OPC and two differentcoarse-aggregate types (stone and brick aggregates), the mixes with stone aggregates yield better corrosion resistance and therefore, relatively higher corrosion initiation time or service life. In case of severe exposure, even the maximum cover limit was observed to be inadequate to provide a considerable service life to all the mixes prepared using OPC. Despite the fact of this study being limited to some indigenous mix practices of Bangladesh, it presents significant evidences that warrant durability or service life-based mix design practices. Moreover, the study findings provide a quantitative evaluation of the service life of concrete mixes with typical and code suggested concrete cover limits. Hence, it will aid in reviewing the existing guidelines for building RC structures and be a basis for any future research and amendments incorporating the durability aspects/requirements while designing RC structures in marine exposures of Bangladesh. Furthermore, the comparative assessment of service life values, associated with different raw materials used to produce concrete, will also work as a basis for any field engineer to select the proper material and the level of quality control required to safeguard durability of RC structures.

2 SERVICE LIFE EVALUATION: A PROBABILISTIC APPROACH

The primary focus of this study is to evaluate the service life values of RC elements that were prepared based on local mix practices of Bangladesh and subjected to chloride induced corrosion. Therefore, a probabilistic approach was adopted to determine the serviceability of concrete mixes in terms of corrosion initiation time. As stated by Wang et al. (2010), this initiation time refers to the interval within which chloride ions travel through the porous media towards the reinforcement surface and accumulate to a critical content in order to initiate the corrosion phenomena. For this study, the times to initiate corrosion (t) and thus, service life of different mixes were calculated using following Equation 1 (fib 34, 2006; Duracrete, 1998):

[1] $C_{crit}= C_o+ (C_{s,\Delta x} - C_o)\ [1- \text{erf}\ (\frac{x-\Delta x}{2\sqrt{Ke.Kt.(\frac{to}{t})^{\alpha}Drcm.t}})]$

[2] $K_e= b_e[(T_{real})^{-1}-(T_{ref})^{-1}]$

The details regarding different parameters of equations 1 and 2 as well as their respective distribution functions, as per fib guidelines (2006) are presented in Table 1.

Table 1: Summary of different parameters of Equations 1 and 2

Parameter	Identification (Unit)	Probability Distribution
D_{rcm}	Diffusion Coefficient at t_o(m^2/s)	from migration test result
t	Corrosion Initiation Time/Service Life (years)	--
t_o	Reference or migration test time (years)	Constant
x	Concrete Cover (m)	--
Δx	Depth of Convection Zone (m)	Constant but varies with exposure category
C_{crit}	Limiting Chloride Level (% by weight of cement)	BetaD Distribution
C_o	Initial Chloride Concentration (% by weight of cement)	Constant
$C_{s,\Delta x}$	Chloride Concentration at surface (Δx=0) or at Δx depth (% by weight of cement)	Lognormal Distribution
α	Aging Exponent	BetaD Distribution
K_t	Time Constant	Constant
K_e	Environmental Variable	--
b_e	Regression Variable (^{o}K)	Normal Distribution
T_{real}	Temperature of the Ambient	--
T_{ref}	Temperature of the Migration Test (^{o}K)	--

The probabilistic evaluation of the service life values for different concrete mixes requires population generation by randomizing the parameters that affect the corrosion initiation time. Hence, during this study, data series for each variable were produced based on their respective probabilistic distribution, as suggested in fib 34 (2006). These data series were later combined to generate an array of different parametric values. Thereafter, about 50 random combinations were selected using MATLAB function 'randn' (MATLAB Documentation, 2012) from the population array and subsequently, used in serviceability assessment for each mix. For simplification, the assessment was conducted considering all RC elements are exposed to the severe most marine environment-XS3 (EN 206, 2013). EN 206 (2013) identifies the marine structures in tidal, splash or spray zone with cyclic wet and dry humidity to be included within this exposure category. Furthermore, the whole valuation process also involves considerations of three typically used concrete cover values of 50mm, 75mm and 100mm for each mix type.

3 EXPERIMENTAL PROGRAM

3.1 Mix Design and Sample Preparation

During this research endeavour, a total no of 11 concrete mix variations were selected. The mixes were chosen to reflect the native concrete mix practices of Bangladesh. Table 2 summarizes the details of the mix variations considered for this study. For each mix, six nos. of cylinders of diameter 100mm and height 200mm were cast and later, cured under lime water.

Table 2: Details of Mix Design

Mix Type	Mix Ratio	w/c ratio	Cement Type	Cement (kg/m3)	Aggregate Type	CA (kg/m3)	FA (kg/m^3)
M1	1:1.5:3	0.45	OPC	419	Coarse Agg. (CA)-19mm downgraded stone and Fine Agg. (FA)-Sylhet Sand	1396	685
M2		0.48	OPC	419		1396	685
M3		0.50	OPC	419		1396	685
M4		0.55	OPC	419		1396	685
M5		0.45	PCC	419		1396	685
M6		0.48	PCC	419		1396	685
M7		0.50	PCC	419		1396	685
M8		0.55	PCC	419		1396	685
M9		0.45	OPC	419	CA-19mm downgraded brick and FA-Sylhet Sand	977	685
M10		0.48	OPC	419		977	685
M11		0.50	OPC	419		977	685

3.2 Test Procedures

For this study, the degree of permeability of all concrete mixes were measured in terms of diffusion coefficient values in order to determine corrosion initiation time as suggested by fib 34 (2006). Therefore, all concrete samples were tested for their diffusion coefficient values as per the migration test specification NT BUILD 492 (1999).

The code specifies the test to be performed on preconditioned cylindrical samples of thickness 50±2 mm (Figure 1.b). Therefore, the cast cylindrical specimen were sawed to the code specified thickness and preconditioned through the code stated vacuum process in $Ca(OH)_2$ solution for 18-20 hours. After preconditioning, the sample was placed within the rubber sleeve of the setup, as shown in Figure 1(a). The glass reservoir was filled with NaCl solution and the portion of the sleeve above specimen was filled with 0.3N NaOH solution. Once power supply was on, an initial voltage of 30V was set and the respective current was measured. Depending on this initial current, the voltage was adjusted to a new value, as suggested by NT BUILD 492 (1999) and the test-run was performed for 24 hours. After the test completion, the sample was split into two halves and the diffusion coefficient was determined from the penetration depth as stated in NT BUILD 492 (1999). The penetration depths (Figure 1.b) were measured following the guidelines of the aforementioned code using colorimetric method with $AgNO_3$ as a colorimetric indicator.


(a) (b)

Figure 1: a) Migration test setup, b) Split sample with white precipitation of AgCl to identify chloride penetration depth

4 RESULTS & DISCUSSIONS

4.1 Diffusion Coefficients

Degree of permeability of a concrete mix has a significant impact on the service life of the associated RC element. The equation as stated by fib guidelines (2006) involves determination of corrosion initiation time using migration/diffusion coefficients of the concrete mixes along with other factors. Therefore, during this research program, diffusion coefficients of all the mixes considered were evaluated as per the specifications of NT BUILD 492 (1999). In Table 3 all the diffusion coefficient data are enlisted in correspondence with their mix types.

Table 3: Chloride Diffusion Coefficients of Different Types of Concrete Mixes

Mix Type	Diffusion Coefficient (m^2/s)	Mix Type	Diffusion Coefficient (m^2/s)
M1	2.3778E-11	M7	1.89844E-11
M2	2.415E-11	M8	1.80604E-11
M3	2.5E-11	M9	2.477E-11
M4	3E-11	M10	2.5E-11
M5	1.57487E-11	M11	2.7E-11
M6	1.7511E-11		

The diffusion coefficient value of a particular mix usually refers to its resistance against ingress of corrosion inducing agent, in this case chloride ions. Higher diffusion coefficient means higher permeability and thus, relatively lower resistance to chloride attack and vice versa. Concrete with PCC can be expected to perform better than that with OPC owing to the presence of fine particles (pozzolanic substances) in PCC (Hasan, 2018). This is due to the production of C-S-H gel, essential for pore refinement, from the long-term hydration of the pozzolanic substances (Das et al. 2012). The values, listed in Table 3, portray that mixes with stone and PCC (M5 to M8) yielded about 31~32% lower diffusion coefficient values, on average, as compared to those with stone and OPC (M1 to M4). As for concrete mixes with brick as coarse aggregate and OPC (M9, M10 and M11), the diffusion coefficients were found to be 3.5~8% higher and hence, lower resistance to corrosion was observed than their respective stone counterparts (M1, M2 and M3). Such trend of brick aggregate concrete can be attributed to the porosity and high absorption capacity of brick (Manzur et al., 2018). In almost all cases, the coefficients were observed to increase with increasing w/c ratio from 0.45 to 0.55 (from M1 to M4; from M5 to M8 and from

M9 to M11), eventually, substantiating the established fact of rise in permeability with higher water content.

4.2 Probabilistic Evaluation of Service Life

The prime objective of this study is to estimate service life (corrosion initiation time) of some indigenous concrete mixes by following a probabilistic approach. Hence, with the intention of achieving this goal, 50 randomized combinations from an array of data set of different parameters affecting serviceability of a certain mix were generated, as mentioned earlier. Later, these values were used for each mix type in conjunction with its respective diffusion coefficient to calculate a range of 50 different service life values. The analysis was performed considering that the RC element is with a certain cover (50mm, 75mm or 100mm) and subjected to XS3 type of exposure. Figure 2 demonstrates the frequency distribution of service life values for mix type M4 considering concrete cover to be 50mm and exposure condition to be XS3. Similar distribution pattern was observed for all other mix types as well as cover variations. Henceforth, all the mean values of service life for each mix and cover variation were calculated accordingly.

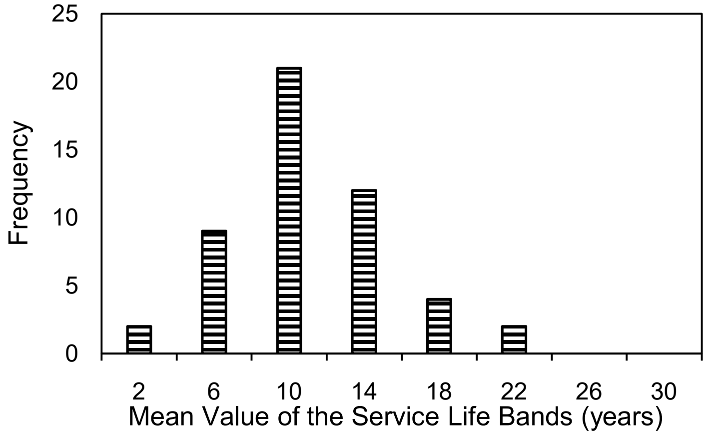


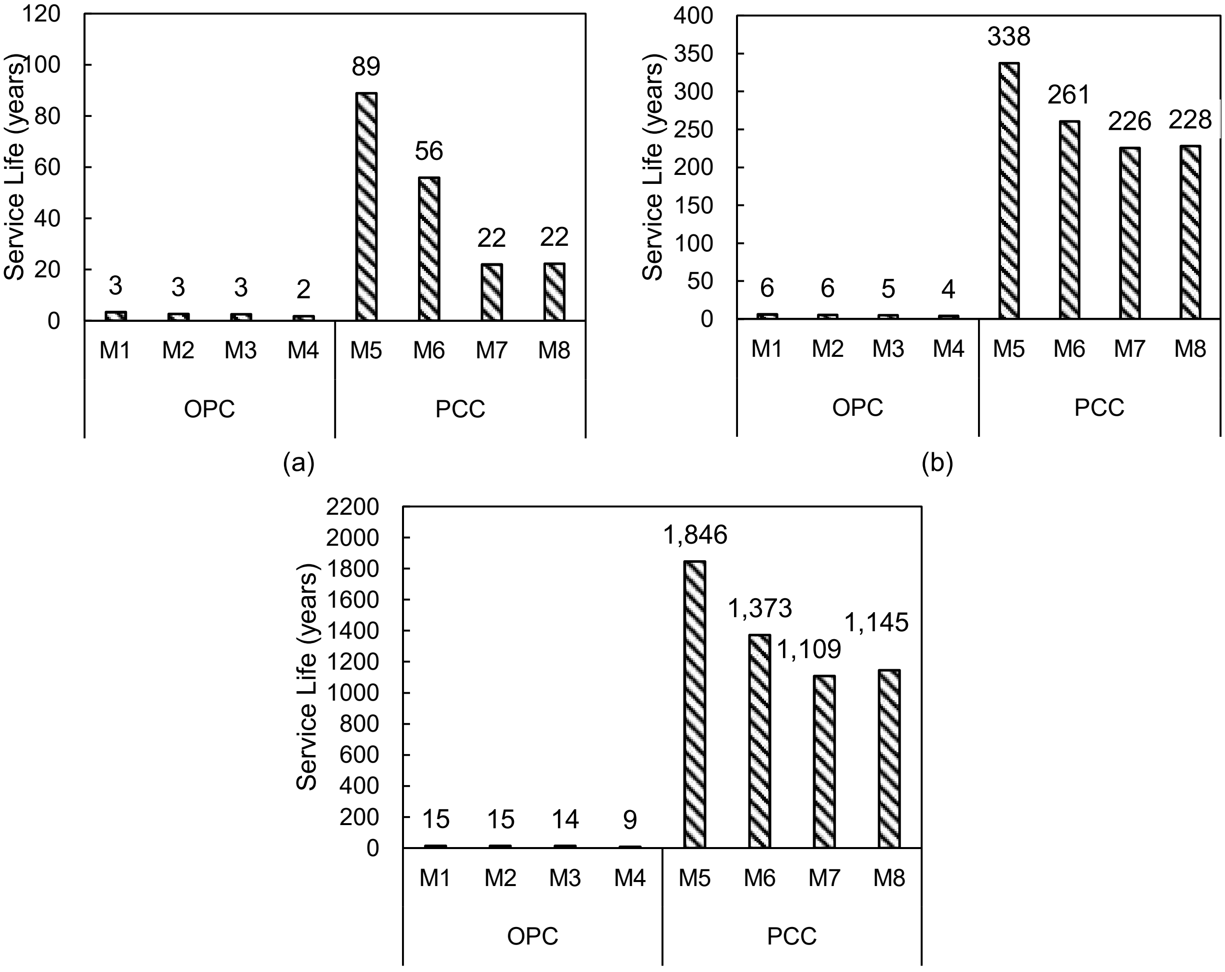
Figure 2: Frequency distribution curves for service life bands of mix M4 for a typical concrete cover of 50mm and exposure condition XS3

4.3 Effect of Mix Variations on Service Life

As mentioned in section 4.1, different types of concrete mixes yielded different diffusion coefficient values signifying their impact on corrosion susceptibility and eventually, on the service life of the particular mixes. In Figures 3 and 4, variations in mean values of the service life distributions of different mix types for typically used concrete cover of 50mm, 75mm and 100mm are presented in the form of bar charts.

Figure 3 portrays the impact of variation in cement type (OPC and PCC) on the mean service life values of the stone aggregate concrete. In case of mixes with OPC (M1 to M4) and concrete cover of 50mm, the mean values were observed to be decreasing from 3.4 years to 1.8 years for increasing w/c ratio of 0.45 to 0.55. However, for cover variation of 75mm the values are 6.3, 5.7, 5.1, 4.1 years for w/c ratio 0.45, 0.48, 0.5, 0.55, respectively. As for RC elements with 100mm concrete cover, they were observed to sustain corrosion as long as 15.4, 14.5, 14.2 and 9.2 years, on average, in case of mix variations M1, M2, M3 and M4, respectively. On the other hand, mixes with PCC (M5 to M8) demonstrated about 17, 49 and 104 times higher mean service life values for cover variations of 50mm, 75mm and 100mm, respectively, as compared to their respective OPC counterparts. The factors that can be presumed to affect such variations are relatively higher aging exponent and lower diffusion coefficient values of PCC mixes. These values indicate the effect of the pozzolanic characteristics of PCC in reducing permeability through long term hydrations which consequently, is responsible for the improvement of the corrosion resistance as well as betterment of the longevity.

The comparative assessment of the serviceability between brick aggregate concretes (M9 to M11) and stone aggregate concretes (M1 to M3) are presented in the form of bar charts, as shown in Figure 4. The valuation showed that mixes with brick as coarse aggregate exhibit, on average, 54%, 28% and 26% lower mean values of service life than that of stone aggregate, for concrete cover alternatives of 50mm, 75mm and 100mm, respectively. This, ultimately, confirms the facts of higher permeability and thus, lower longevity against chloride induced corrosion of brick aggregate concretes.

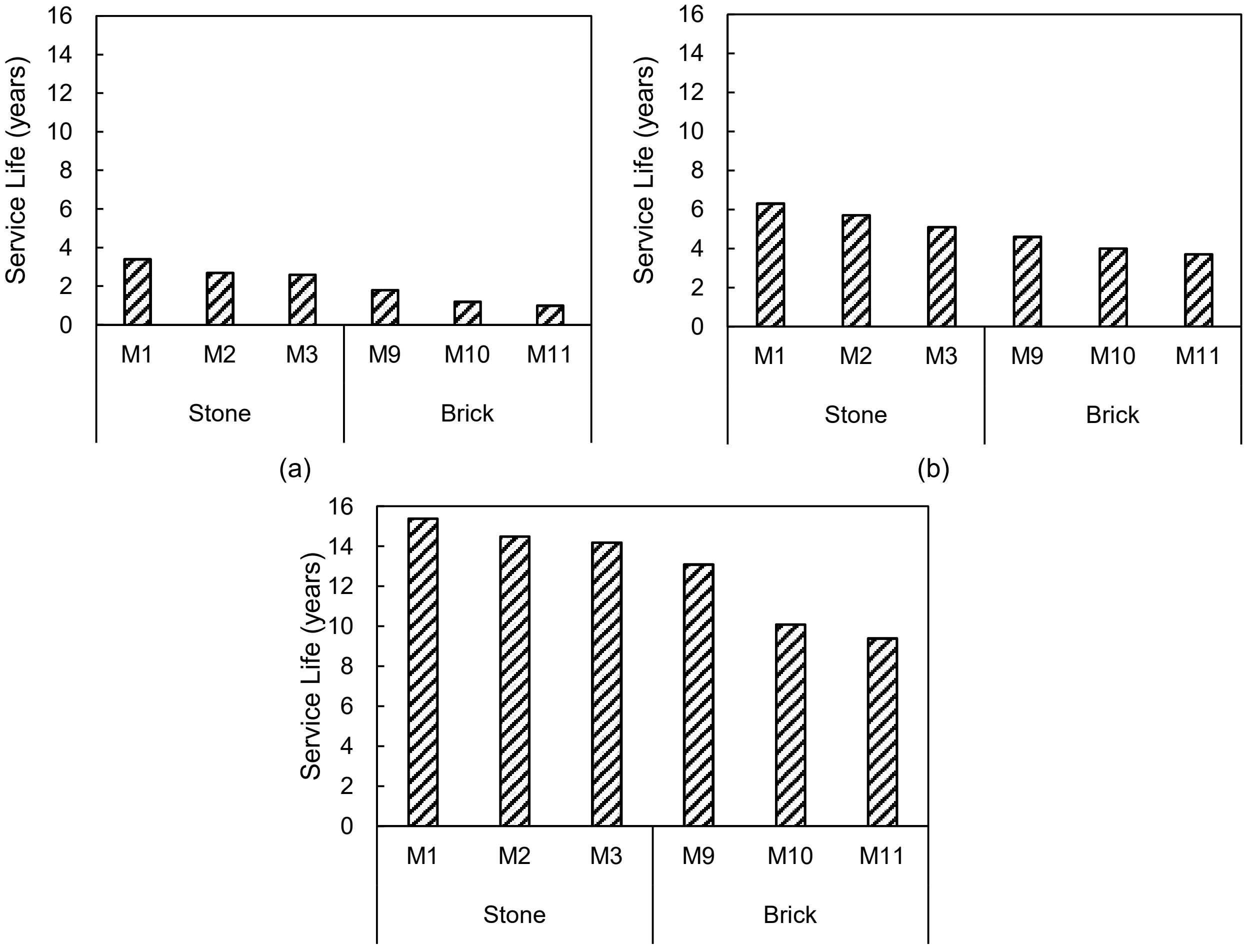


(a)

(b)

(c)

Figure 3: Effect of variations in cement type (OPC and PCC) on the mean values of the service life of RC elements with-a) 50mm concrete cover, b) 75mm concrete cover and c) 100mm concrete cover



(a)

(b)

(c)

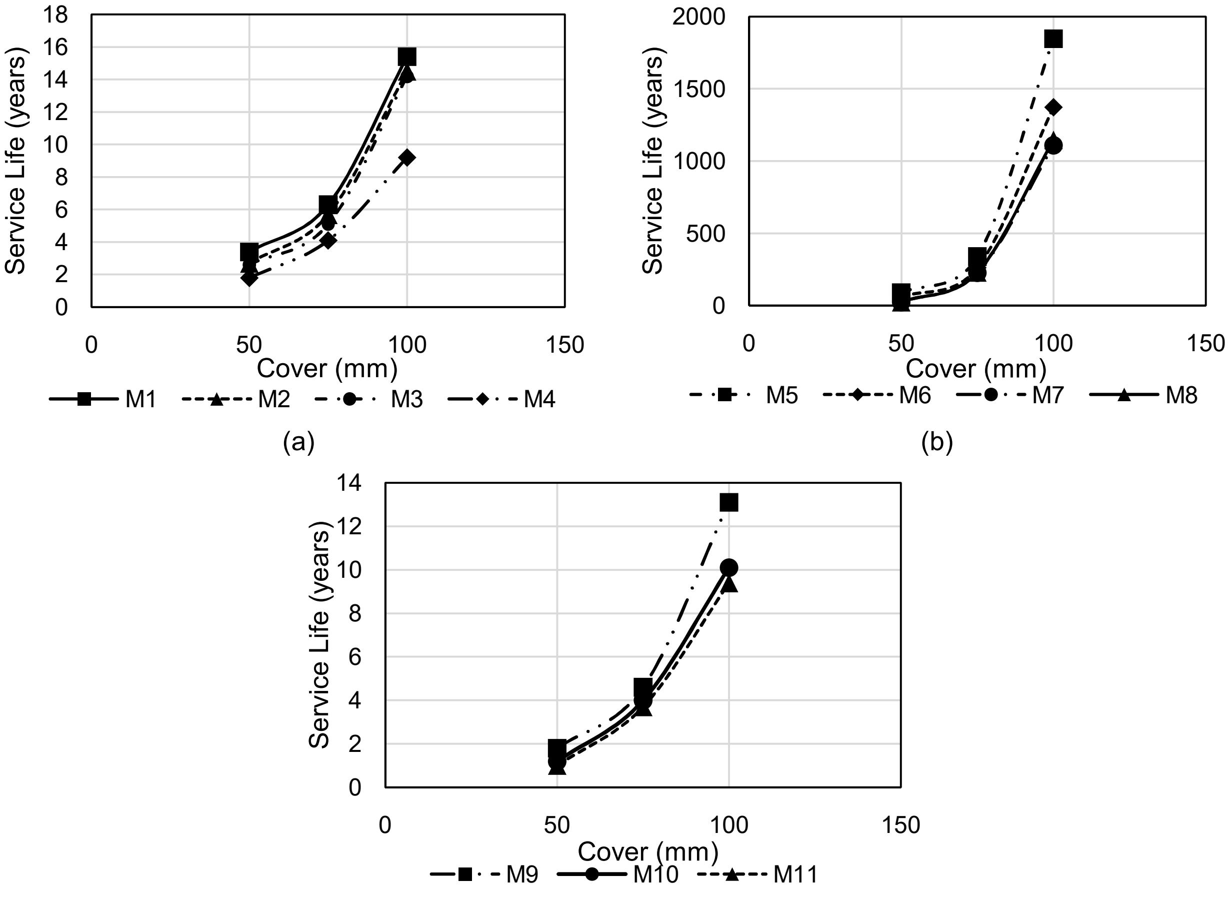
Figure 4: Effect of variations in coarse aggregate type (stone and brick) on the mean values of the service life of RC elements with-a) 50mm concrete cover, b) 75mm concrete cover and c) 100mm concrete cover

4.4 Effect of Concrete Cover on Service Life

This study comprises of the service life evaluation of different common local concrete mixes for some typically used concrete cover under extreme marine exposure. The assessments showed notable impact of concrete cover on service life values and the findings are summarized in the forms of graphical representations, as shown in Figure 5. It is evident from the figures that in all cases, mean values of service life increase exponentially with every 25mm increase in concrete cover value used.

In case of mixes with OPC and stone, all mixes show almost similar rise in service life mean values (about 2 times) with increase in cover value from 50mm to 75mm. As the cover value rises another 25mm towards 100mm, most of the mixes (M1 to M3) yield about 2.5 times or higher service life values than those associated with 75mm concrete cover. However, in case of PCC mixes, the rate of increase can be observed to be more pronounced (about 5 to 8 times). This can be owing to the combined effect of better pore refinement capability of PCC as well as longer distance to be travelled by the chloride ions to reach reinforcement level.

As for mixes with brick aggregate and OPC, similar trend of improvement in service life values were observed with increasing cover limit. Although the values are, still, lower than those of stone aggregate concretes, the rate of improvement of service life values were found to be about similar to those detected in case of mixes with OPC and stone aggregate.



(a)

(b)

(c)

Figure 5: Effect of variations in concrete cover on the mean values of the service life of RC mixes with-a) OPC and stone aggregate, b) PCC and stone aggregate and c) OPC and brick aggregate

5 CONCLUSIONS

The principal goal of this research was to discuss the importance of durability based mix design practice in marine environment through estimation of the service life of some indigenous concrete mixes under severe marine exposure. With the intention of fulfilling this objective, 11 different concrete mixes were tested for permeability and later, their respective range of service life values were determined following a probabilistic approach for concrete cover of 50mm, 75mm and 100mm. During this investigation, mixes with PCC and stone aggregate owing to their lower diffusion coefficients and higher aging exponent values, demonstrated significantly better corrosion resistance and hence, higher longevity. In case of OPC mixes, the usage of maximum cover limit of 100mm can ensure maximum average service life of 14 years whereas, PCC blended mixes can sustain chloride attack upto about 80~90 years even with the minimum cover limit considered for this study (50mm). Such evidences warrant proper selection of raw material while concrete mix design in marine environment, based on durability considerations instead of strength requirement. In addition to mix quality, concrete cover appeared to have major impact on serviceability enhancement of all concrete mixes. However, the impact was observed to be more prominent (about 5-8 times increase in service life for 25mm increase in cover value) in case of PCC blended mixes than those with OPC. Despite lowest average service life values, even the mixes with brick aggregate showed exponential increase in service life for higher concrete cover values. Nevertheless, all OPC mixes, irrespective of the aggregate type, require concrete cover value significantly higher than 100mm to ensure medium to long service life while designing RC elements to sustain extreme exposure such as that of XS3.The essence of this investigation is to introduce implication of durability based mix design practice and to provide a quantitative basis for the researchers and field engineers to work on this topic in future.

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