SERVICE LIFE PREDICTION OF REINFORCED CONCRETE TRENCHES

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ABSTRACT

Reinforced Concrete Trenches are the most common disposal modules used for the disposal of solidified Low and Intermediate Level Radioactive Wastes. During the operational and post closure phase, these structures have to encounter site-specific geo-environmental conditions which may affect their life. The desired service life of these modules is few hundred years (300 years), but having the record of modern cement life to be about 100 years, it is necessary to have some methodology to predict the service life of the reinforced concrete trenches.

In this study an attempt has been made to develop a methodology to predict the service life of reinforced concrete trenches. Durability models for chloride penetration and carbonation process has been used to predict the mean service life due to chlorination and carbonation. Effect of water cement ratio, concrete cover, water proofing (stone tile size and its joint width) and climate factor on the service life has also been studied. A computer programme has been developed to draw the probability of failure curves for a given service life for a set of environmental, design and construction parameters.

INTRODUCTION

Low and Intermediate Level Radioactive Waste (L & ILW) generated at different stages of nuclear fuel cycle are treated, conditioned and disposed off in different types of disposal modules of Near Surface Disposal Facilities (NSDF). These disposal modules consist of mainly Stone Lined Trench/Brick Lined Trench (SLT/BLT), Reinforced Concrete Trench (RCT) and Tile Hole (TH) and currently used at all the seven operating NSDF sites in India. These sites vary in their geological, hydro-geological and geo-environmental conditions and these varying geo-environmental conditions affect the service life of the disposal modules.

The integrity of these structures becomes the most important parameter for the safe disposal of solid immobilized L&ILW in NSDF modules. The history of modern cement is only 100 years old. During this period, reinforced cement concrete structures has shown good performance under different conditions, however several chemical aggressive species in the water, soil or the atmosphere may react with the cement mineralogical phase and affect its service life. Some of the predominant chemical phenomena reported are chloride diffusion and carbonation into the concrete [1, 2]. The chloride diffusion and carbonation in concrete results initiation of corrosion in the reinforcement bar, which restricts the service life.

SERVICE LIFE

Service life of the civil structures is defined in various ways depending on the service requirement of the structures [1, 2, 3]. For the present study service life is defined as the sum of two components viz (i) the corrosion initiation time (mean time from construction till the chloride or carbonation content due to diffusion at the depth of reinforcement becomes high enough to initiate corrosion), and (ii) the propagation time (time period between reinforcing steel start to corrode to spalling of concrete) for the steel reinforced bars. The deterministic formula used to calculate the service life is as follows:

$$t_L = t_0 + t_1 \tag{1}$$

where, t_L is the service life of a reinforce concrete structure (a), t_0 is the initiation time (a), and t_1 is the propagation time for steel reinforcement bar (a).

The principle used in the service life calculation is presented in Fig.1.

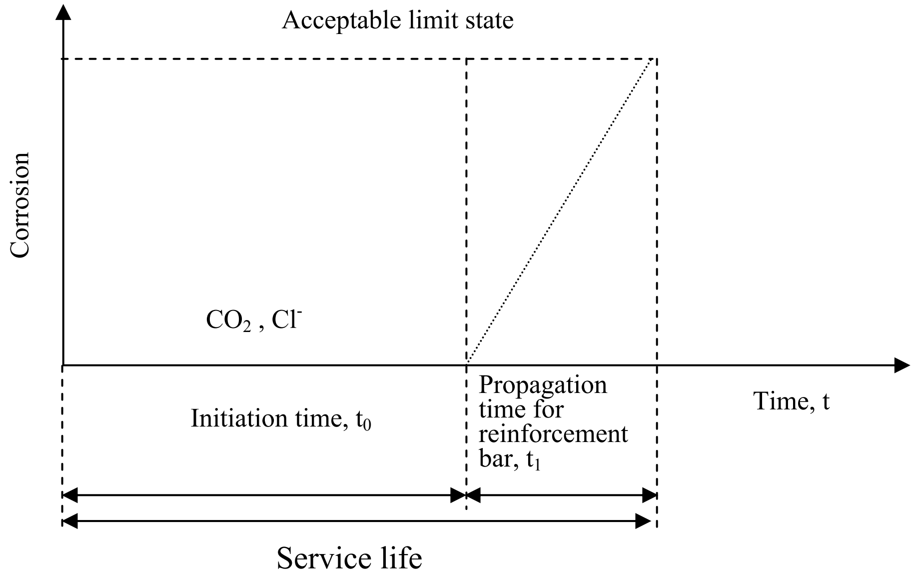


Fig. 1: Principle used in calculating the service life of reinforce concrete structure

Several researchers [1, 2, 3] have proposed different mechanisms and mathematical models for service life prediction depending upon the type of civil structures and their functional requirements. These models are usually theoretical model combined with an empirical approach. From a practical point of view, these models are difficult to apply due to too many unknown parameters employed in them.

The functional requirement for the present study is the structure should be impermeable. The RC trenches are designed as a water retaining structure, hence service life has been considered as the time from the construction of structure to the time of initiation of corrosion plus time required to corrode the reinforcement resulting into spalling of concrete [4], which will make the structure permeable.

MATHEMATICAL MODEL DEVELOPMENT

One of the principal challenges in developing a mathematical model for service life prediction of civil structures is its dependency on too many parameters, including material characteristics, climatic environment, and method of constructions. The model further gets complicated due to additional parameters associated with the nuclear waste disposal modules (e.g. use of protective coatings i.e. water proofing, frequency of maintenance etc.). In the present paper it is difficult to innumerate all the parameters and indicate their precise role in the service life of the disposal modules structure and their use in the mathematical model for service life prediction. Nevertheless the objective of this paper is to develop a usable, practical and reliable mathematical model that can be used to predict the service life of reinforced concrete trench being used for the disposal of solid L&ILW. Followings are the major steps involved in mathematical model development for service life prediction of RCTs.

IDENTIFICATION OF ENVIRONMENTAL CONDITIONS AND DEGRADATION MECHANISM FOR REINFORCED CONCRETE STRUCTURE

Environmental conditions like rain, temperature, depth of groundwater and their seasonal variation, geochemistry of soil and groundwater, proximity to sea etc., affect the service life of reinforced concrete structure. Important degradation factors responsible for degrading the reinforced concrete trench are geochemistry of soil and groundwater (e.g. pH, chloride content in the groundwater or in the soil), rainfall etc. Proper understanding of the degradation mechanisms helps in screening of mathematical models applicability.

In general the degradation mechanism of the concrete structure can be summarized as:

- degradation of ordinary concrete constructions by corrosion of reinforcement due to carbonation, chlorides etc. [5, 6]

- deterioration of concrete structures in outdoor service due to several environmental effects, e.g. corrosion, freeze-thaw, swelling-shrinkage, temperature effects etc. [6].
- deterioration of marine concrete structures due to sea water, free-thaw and ice abrasion effects [7].

SELECTION OF SERVICE LIFE PREDICTION MODELS FOR EACH DEGRADATION MECHANISM

Based on the site specific conditions of the NSDF following two degradation mechanisms have been considered which are applicable to operating RCTs in India.

Chloride Induced Corrosion

In soil and groundwater chloride is present and depending on the site condition (proximity to sea) its concentration in soil and groundwater varies to a great extent. This results in development of chloride concentration gradient between soil/groundwater and concrete structure and results into chloride diffusion into concrete. Due to the chloride diffusion, a gradient develops near the concrete surface. The time, at which the critical chloride contents (threshold values) reach the reinforcement surface and depassivate the concrete, it can be considered as the initiation time of corrosion. The gradient of chloride content is often described by an error function model, based on the Fick's law of diffusion. The mathematical equation used for chloride diffusion in concrete is described as [4, 8]

$$Cl_x = Cl_s \left[1 - \mathrm{erf}\left(\frac{x}{2(D \cdot t_0)^{1/2}}\right)\right] \tag{2}$$

where, Cl_x is the chlorine content in concrete mass at depth x (wt. %), Cl_s is the chlorine content at the concrete surface (wt. %), x is the depth from the surface of the structure (mm), D is the diffusion coefficient (mm^2/a), and t_0 is the time (a)

When chloride content at the reinforcement surface reaches to the critical chloride content Cl_{cr} corrosion in the reinforcement starts, and the initiation time of corrosion of reinforced bar can be calculated as [4, 8].

$$t_0 = \frac{1}{12 \cdot D}\left[\frac{C}{1-\left(Cl_{cr}/Cl_s\right)^{1/2}}\right]^2 \tag{3}$$

where, Cl_{cr} is the critical chloride content in concrete mass at reinforcement depth c (wt. %), and C is the concrete cover thickness (mm)

Literature [4] recommends that threshold (or critical) values should not be higher than 0.4% (Cl^-) by weight of cement for reinforcement concrete and 0.2% for prestressed concrete. This corresponds approximately to 0.05-0.07 by weight of concrete and 0.025-0.035 for prestressed concrete.

Carbonation Induced Corrosion

Carbonation is the process where carbon dioxide enters concrete and reacts with calcium hydroxide to form calcium carbonate [9]. Carbonation process is represented by the following equations:

$Ca(OH)_2\ (s) + CO_2\ (g) \Rightarrow CaCO_3\ (s) + H_2O\ (l)$
$C\text{-}S\text{-}H\ (s) + CO_2\ (g) \Rightarrow CaCO_3\ (s) + SiO_2.nH_2O\ (s) + H_2O\ (l)$

In carbonation process, carbon dioxide penetrates into concrete and neutralizes its alkaline substances. The carbon dioxide produces carbonation front which advances with time towards the interior of concrete. When this front reaches the reinforcement, the passive film on the steel becomes unstable and dissolves, enabling generalized corrosion to occur. The initiation time of corrosion is defined as the time needed for complete carbonation of the concrete cover.

A mathematical model used for service life based on carbonation of concrete, and is given by Vrouwenvelder [10] is presented in equation 4. The first term of this equation describes the actual carbonation of concrete cover without waterproofing layer. The second term describes the time after initiation of crack. The last term is increased service life due to use of protective coating i.e. waterproofing.

$$t_L = \left[\frac{(C-\Delta)}{R \cdot K} \left\{ \frac{2.7}{46 \cdot w - 17.6} \right\} \right]^2 + \frac{C \cdot c}{\varphi \cdot V_C} + \frac{C-\Delta}{180 \cdot f_0} \left\{ \frac{\frac{T}{T_0} \ln(f_0)}{1 - \exp\left(-\frac{T}{T_0} \ln(f_0) \right)} \right\} \cdot S \qquad (4)$$

where, t_L is the service life (a), C is the concrete cover thickness (mm), Δ is the difference of max and mean depth of carbonation (mm), R is the cement type parameter, K is the climate parameter, w is the water cement ratio, c is the constant, φ is the bar dia (mm), V_c is the corrosion rate (mm/a), S is the thickness of coating (mm), f_0 is the coefficient of imperfection for coating, T_0 is the durability parameter (a), and T is the maintenance period (a).

SERVICE LIFE PREDICTION USING LOGNORMAL DISTRIBUTION AND FOSM METHOD

In RCT structures the parameters involved in the durability analysis of concrete structures (i.e. environmental action, concrete deterioration and material behaviour) are random in nature. The service life prediction can be estimated if the distributions of the parameters are known.

In calculating the probability of service life being shorter than a certain target life, as the design and environmental and parameters are highly variable, the decision has to be based on maximum acceptable failure probabilities. In such cases, the probability of failure, p_f, is expressed as equation 5 [3].

$$P\{\text{Failure}\} = p_f = p\{R - S < 0\} < P_{\text{Target}} \qquad (5)$$

where p_f is the failure probability, p_{Target} is the target failure probability.

For this kind of design problems, relevant failure probability has been calculated. The probability of failure has been calculated by the method used by [3, 11] for similar studies. This procedure starts with limit state function Z = R - S, and introduces the variables R and S to the equations including their average and standard deviation. Z is the reliability of the construction. R is the resistance of the structure against the action or load (S). Assuming that the variable S and R are normally distributed, the reliability Z, the difference between the variables R and S, is a variable which itself is normally distributed. Averages and standard deviations of the parameters can be calculated according to the relationship shown in Fig. 2.

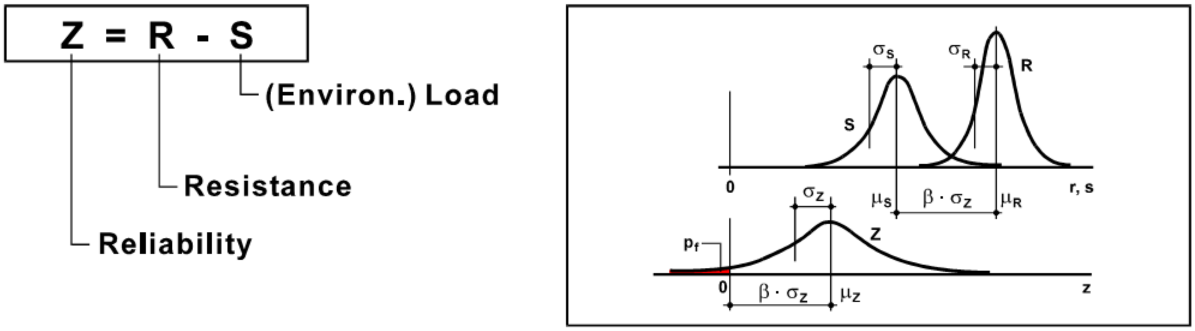


Fig. 2: Probabilistic performance based durability design, terms, safety concept

The reliability index β also shown in Fig. 2 is calculated using the average and standard deviation of Z: $\mu(z)$ and $\sigma(z)$ respectively. Reliability index is the difference between the mean values of R and S divided by the standard deviation of the variable Z or, alternatively, the mean value of Z divided by the standard deviation of Z.

$$\underbrace{p_f}_{\text{Failure probability}} = \underbrace{\emptyset}_{\emptyset\text{ (.) Normal distribution}}\left(-\frac{\mu_Z}{\sigma_Z}\right) = \emptyset(-\underbrace{\beta}_{\text{Reliability index}}),\ \text{with}\ \mu_Z = \mu_R - \mu_S,\ \sigma_Z = \sqrt{\sigma_R^{2}+\sigma_s^{2}} \quad (6)$$

A computer code has been developed to predict the service life of RCT. The code has two separate modules for prediction of service life due to carbonation and due to chloride attack. The code computes mean service life, standard deviation of service life and probability of failure for different target lives of RCTs. The computer code is based on the reliability theory. Probabilities of failure for different target lives have been calculated for different values of safety index.

SERVICE LIFE PREDICTION DUE TO CARBONATION

A typical failure probability curve for predicting the service life of RCTs due to carbonation is depicted in Fig. 3. Due to uncertainty involved in the parameters, the result depicted here is with conservative value of parameters. To visualize the effect of parameters, failure probability curves have been generated for varying parametric values and their effects has been studied. Fig. 3 shows that, the major contribution in service life is due to concrete cover (318 years) and stone cover (72 years). Stone cover is used as a waterproofing system in the RCTs wall from outside. Contribution in service life due to reinforcement is minimal (3years).

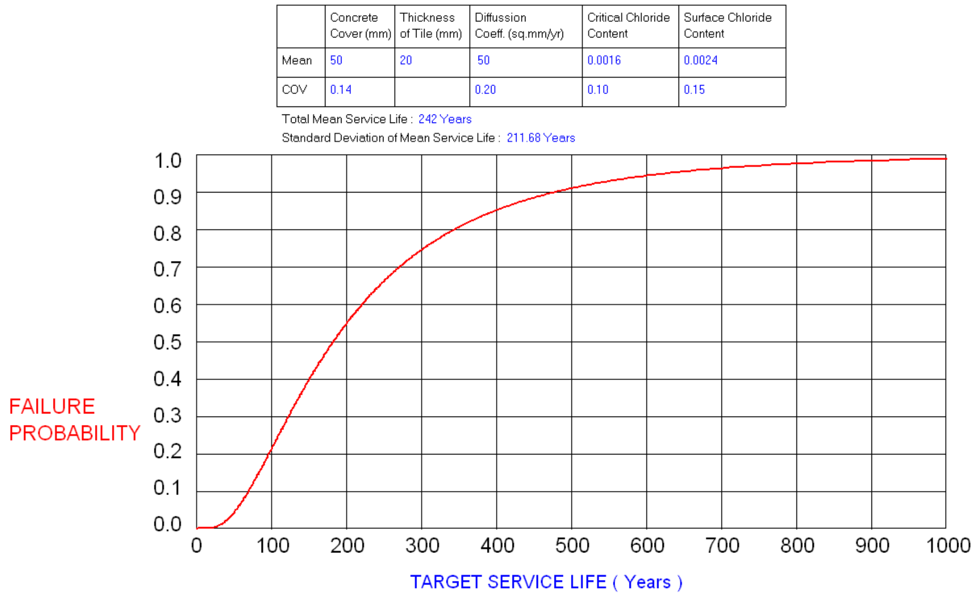
	Climate Factor	Concrete Cover (mm)	Maintenance Period (yr)	WC Ratio	Length of Tile (mm)	Breadth of Tile (mm)	Thickness of Tile (mm)	Durability of Stone (yr)	Thickness of Joint (mm)	Imperfaction in Joint	Bar Dia (mm)	Corrosion Rate (mm/yr)	Cement Type
Mean	0.7	30	50	0.50	600	300	20	100	10	0.20	16	0.04	1.00
COV	0.20	0.14		0.05				0.20		0.20		0.50	0.15

Total Mean Service Life 393 Years (Due to cover : 318 Years, Due to Reinforcement : 3 Years, Due to Stone Cover 72 Years)
Standard Deviation of Mean Service Life : 244.29 Years

Fig. 3: Service life prediction of Reinforced Concrete Trenches due to carbonation

SERVICE LIFE PREDICTION DUE TO CHLORIDE ION ATTACK

A typical failure probability curve for predicting the service life of RCTs due to chloride ion attack is presented in Fig. 4. The study shows that service life due to chloride ion content depends mainly on concrete quality (diffusion coefficient), thickness of concrete cover, and surface chloride concentration. Threshold limit of chloride content has been taken as 0.0016 from the literature [4]. The surface chloride content considered for this analysis is assumed surface chloride content. Actual service life of these modules is much higher with respect to chloride ion present in the sub-soil and water.



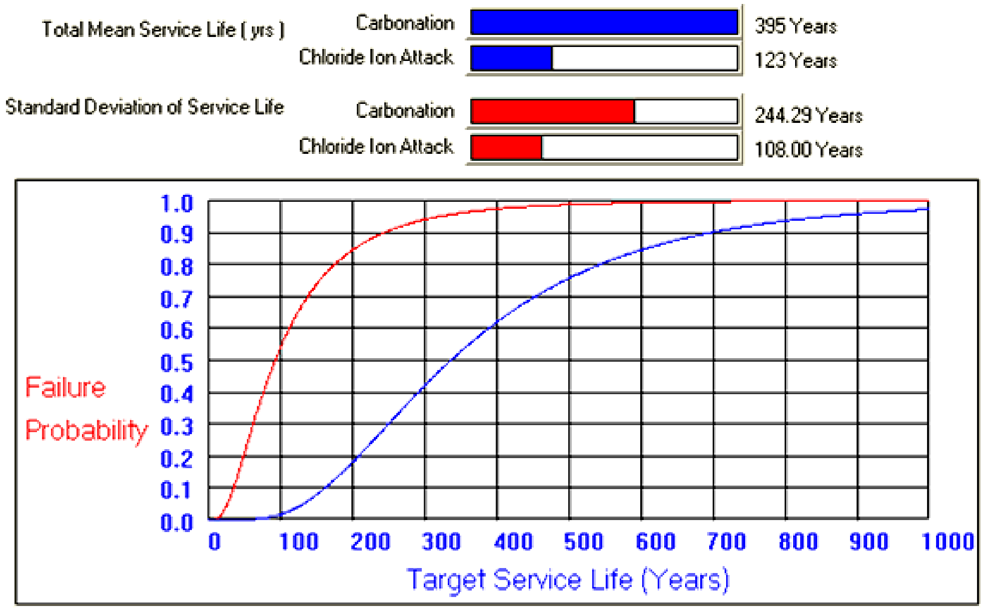
	Concrete Cover (mm)	Thickness of Tile (mm)	Diffussion Coeff. (sq.mm/yr)	Critical Chloride Content	Surface Chloride Content
Mean	50	20	50	0.0016	0.0024
COV	0.14		0.20	0.10	0.15

Total Mean Service Life : 242 Years

Standard Deviation of Mean Service Life : 211.68 Years

Fig. 4: Service life prediction of Reinforced Concrete Trenches due to chloride ion attack

Comparison of service life results due to carbonation and chloride ion attack is presented in Fig. 5 as failure probability curve. The study show that mean service life due to Carbonation is generally higher compared to Chloride ion attack.



Total Mean Service Life (yrs)
Carbonation 395 Years
Chloride Ion Attack 123 Years

Standard Deviation of Service Life
Carbonation 244.29 Years
Chloride Ion Attack 108.00 Years

Fig. 5: Comparison of results for carbonation and chloride ion attack

EFFECT OF VARIOUS PARAMETERS ON SERVICE LIFE OF REINFORCED CONCRETE TRENCHES

To study the effect of various parameters on the service life of structures, the numerical value of the parameters under study was changed, keeping all other parameters constant. Subsequently, another parameter was changed, keeping all other constant. Effect of different parameters on service life was studied. In the present paper, effect of concrete cover thickness in service life due to chloride ion attack and effect of joint thickness on service life due to carbonation is presented.

Effect of Concrete Cover

Concrete cover provides physical barrier to reinforcement against deleterious chemical agents by providing highly alkaline passive layer around reinforcement. In due course of time due to continuous presence of deleterious chemical agents present in the soil and groundwater this passivity may get destroyed which may lead to initiation of corrosion. The failure probability curves have been drawn for varying concrete cover thickness keeping all other parameters same and is presented in Fig. 6. The study reveals that the service life contribution due to concrete cover alone increases approximately as the square of the concrete cover thickness.

Coeff. of Diffusion (mm^2/year)	Critical Cl Content	Surface Chloride Content
100	0.0016	0.0024

Concrete Cover (mm)	30	40	50	60	70	80
Mean Service Life (in Years) Std. Dvn. of Service Life (in Years)	22 20	40 35	62 55	89 79	121 108	158 141

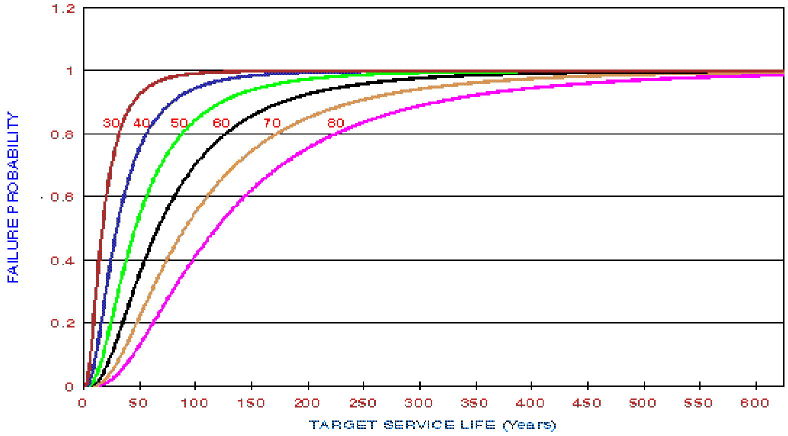


Fig. 6: Effect of concrete cover on service life of RC Trenches (due to Chloride attack)

Effect of Joint Thickness on Service Life Due to Carbonation

Water proofing layer has been provided all around in the operating RCTs. This layer consists of stone tiles of 600x600x20 mm and 300x300x20mm size. These tiles are fixed to the external surface of the RCTs. The size of mortar joints between two tiles varies marginally. Study has been performed to understand the impact of varying joint thickness on service life and the result is depicted in Fig. 7.

Climate Factor	Concrete Cover	Maintenance Period	Water Cement Ratio	Stone Tile Size	Joint Size
0.7	20 mm	50 years	0.5	300 x 300 mm	5-20 mm

Size of Mortar Joint between Tiles (mm):	+ 5	- 10	- 15	+ 20
Mean Service Life (years):	343	236	199	181
Standard Deviation Service Life (years):	126	105	99	96

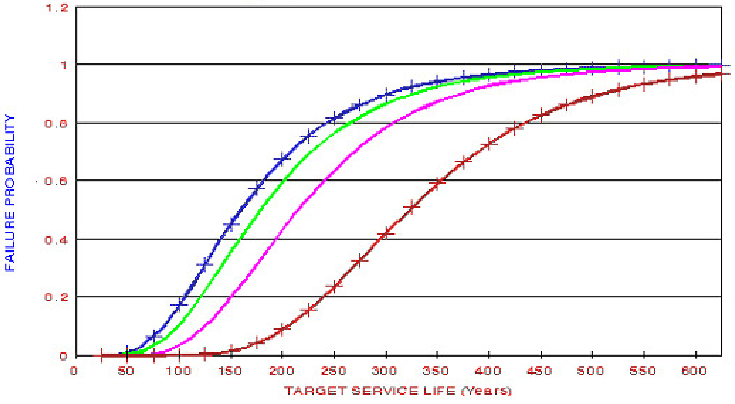


Fig. 7: Effect of joint thickness on service life due to carbonation

The result show that for moderate climate, 50 years maintenance period, 20 mm concrete cover, size of tiles 300x300 mm and increase in joint thickness from 5mm to 20mm will decrease the service life from 343 years to 181 years. This reveals that lesser the joint width better is the RCTs surface and results in increased service life.

CONCLUSION

Software has been developed to predict the service life of reinforced concrete trenches using the available mathematical models for carbonation and chloride ion attack on the concrete structure. The computer programme is based on the theory of reliability. Probabilities of failure for different target lives have been calculated for different values of safety index. Effects of different parameters on the service life of the RCTs have been studied in detail.

From parametric study, it was found that water-cement ratio, concrete cover thickness and width of joint between tiles are the major parameter having significant influence on service life. Maintenance period of the RCTs has the least influence. Service life due to carbonation suggest that lesser imperfection in the surface of RCTs either due to larger size of stone tiles or smaller width of joints results in increased service life. Service life due to chloride ion attack model suggests that surface chloride content has the maximum influence on the service life of the structures. Chloride diffusion coefficient and concrete cover also affects the service life significantly. Service life contribution due to concrete cover alone increases approximately as the square of concrete cover thickness.

The service life were predicted for operating NSDFs at Trombay, Tarapur and Kota using the site specific parameters, suggests that the structures will have a service life of at least 236 years, if they are maintained properly at regular interval.

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