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INFLUENCE OF PORTLAND POZZOLANA CEMENT ON THE SERVICE LIFE OF REINFORCED CONCRETE UNDER CHLORIDE ATTACK

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ABSTRACT

This paper discusses the influence of blended cement on the service life of reinforced concrete (RC) structural components subjected to chloride-rich environments. The service life is assumed as the sum of the corrosion initiation and propagation periods. A comprehensive experimental programme was performed to obtain the chloride diffusion coefficient and corrosion current density that are used in the estimation of the corrosion initiation and propagation periods. The estimated service lives of ordinary portland cement (OPC) and portland pozzolana cement (PPC) concretes having thermo-mechanically treated steel reinforcement, when exposed to chloride environments, are presented. The results suggest that, under certain circumstances, the service life of an RC structure can double when PPC is used instead of OPC.

Keywords: Concrete, chloride induced corrosion, diffusion, service life.

INTRODUCTION

The highly alkaline environment within the fresh and uncontaminated concrete protects the embedded reinforcing bars (rebars) from corrosion. Such protection is obtained due to the presence of a dense ferrous (Fe^{2+}) or ferric (Fe^{3+}) oxide layer (known as passive film) that prevents further oxidization of the rebar (Broomfield, 2006). In chloride rich environments, the chlorides from outside environment can diffuse, through the cover concrete, towards the steel reinforcement. The corrosion of the rebar initiates when the chloride concentration at or near the rebar surface reaches a minimum concentration, known as the critical chloride threshold concentration (C_{tc}). The value of C_{tc} is an important parameter necessary for estimating the service life. This parameter exhibits significant variation and can depend on various factors (Richardson, 2002). The chloride-induced corrosion is catalytic in nature and is very difficult to stop, once initiated. The volume of the corrosion products or rust produced can be approximately 6 to 8 times more than the volume of the original steel corroded. This volumetric expansion can create significant tensile stresses in the cover concrete, resulting in cracking and spalling of the cover concrete. Typically, a particular amount (say, 10%) of cracking/spalling or structural capacity loss will define the end of service life, unless adequate repair work is performed.

The prediction of service life is necessary to ensure long term safety and sustainability of RC structures subjected to chloride-induced corrosion. As shown in Figure 1, the overall service life of an RC structure exposed to chloride environments can be taken as the sum of the durations of corrosion initiation, corrosion propagation, and repair phases. It should be noted that the duration of the initiation phase is typically much longer than that of the propagation or repair phases.

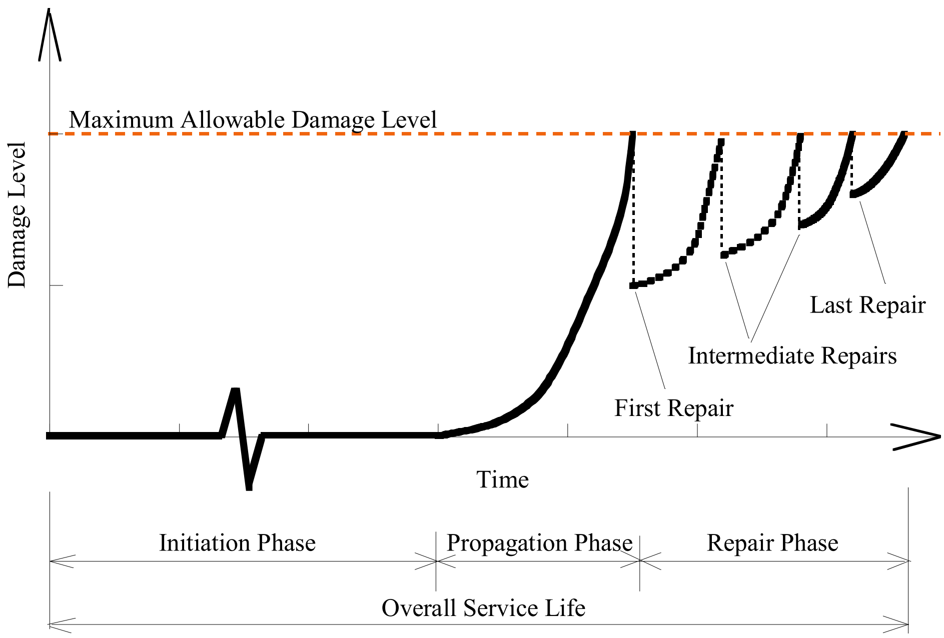

Figure 1. Different stages of deterioration in an RC structure (Pillai, 2003)

Many investigators have considered corrosion deterioration of RC in two stages: (i) initiation stage and (ii) propagation (Tuutti, 1982; Amey et al., 1998). In the initiation stage, the main process is the ingress of chloride ions towards the rebar. In this stage, the corrosion rate of the rebar is negligible, as long as the chloride content is below C_{tc} and the passivity of the reinforcement is maintained. The duration of the initiation stage could vary widely, depending on the aggressiveness of the temperature, humidity and chloride conditions of the environment, the quality of the cover concrete and the C_{tc} of the embedded steel. The propagation stage is defined as the time between the initiation of corrosion of the rebar and the cracking and spalling of the cover concrete. It has been reported that the rate of corrosion is uniform or constant (i.e., stable) at the earlier stages of the propagation stage, and can increase and vary (or become unstable) at later stages. This increase and variation in later stages is because the rate of ingress of moisture, chlorides and oxygen and/or the rate of removal of the existing dense and thick layer of corrosion products (which provides some protection against further corrosion) can increase when the cover concrete starts cracking. The corrosion process/progress at this later stage could differ from those occurring before the cover concrete is cracked. Consequently, the deterioration stages of RC structures due to rebar corrosion can be classified into three, namely (Austroads, 2000): corrosion initiation, stable corrosion propagation and unstable/unpredictable corrosion propagation.

Many researchers have proposed different methodologies for predicting the service life when exposed to chloride ions (Ahmad et al., 1997; Anoop et al., 2002; ACI 365.1R, 2010; Life-365, 2010). However, in most literature, the service life is approximated to be only the length of the corrosion initiation phase (Tuutti, 1982; Bentur et al., 1998; Life-365, 2010). Such an approach may be too conservative in most cases because of (1) the excess reinforcement provided due to safety considerations and (2) the insignificant damage or cross-sectional loss of the reinforcement at the end of the corrosion initiation phase (Austroads, 2000). In this paper, the service life has been estimated as a sum of the corrosion initiation time (t_i) and stable corrosion propagation time (t_{sp}), as defined in Austroads (2000).

EXPERIMENTAL PROGRAMME

Commercially available ordinary portland cement (OPC) and fly ash based portland pozzolana cement (PPC), and potable water were used in the mixes, along with river sand, and graded crushed granite (with maximum grain sizes of 20 mm and 12 mm in the ratio of 1.5:1). The ACI 211 (2010) guidelines were followed in the concrete mix design and a water to cement ratio (w/c) equal to 0.57 was used. The material quantities per cubic meter of the cement, fine and coarse aggregates were 300, 870 and 1056 kg, respectively. Specimens such as cubes of 150×150×150 mm for compressive strength test, cylinders of 100 mm diameter and 200 mm height for rapid chloride penetration test (RCPT) and chloride diffusion coefficient test were cast. The 28-day average compressive strength and charge passed in the RCPT (as per ASTM C 1202) for OPC and PPC concretes were 33.2 MPa and 2600 Coulombs; and 30.7 MPa and 861 Coulombs, respectively. A specially designed U-shaped RC specimen (Figure 2) with a TMT rebar of 12 mm diameter placed with 20 mm clear cover at bottom were subjected to accelerated chloride attack for studying the corrosion of the rebar in OPC and PPC concretes (see Bhaskar et al., 2011, for test details).

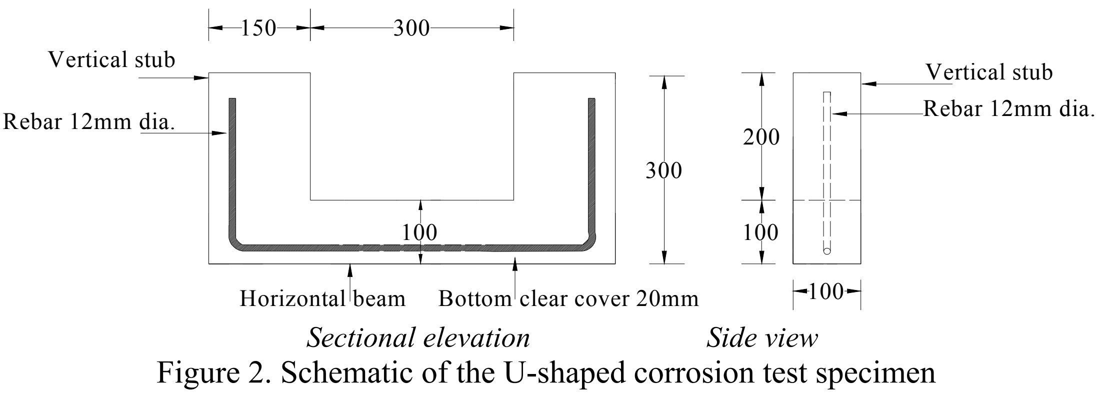

Figure 2. Schematic of the U-shaped corrosion test specimen

Evaluation of chloride diffusion coefficient (D_c)

The chloride diffusivity is a parameter that reflects the resistance of the concrete to chloride penetration. In order to evaluate the apparent diffusion coefficient in the present study, tests have been carried out as per the Nordtest Method (NT Build 355, 1997). In this method, two reservoirs separated by the concrete cylinder specimen are filled with 0.25 N sodium chloride (NaCl) solution and 0.25 N sodium hydroxide (NaOH) solution, and a constant voltage of 12 V DC is applied across the specimen. The chloride ions migrate from the NaCl solution reservoir, through the concrete specimen, to the NaOH solution reservoir. The chloride flux through the specimen is determined by using the increase in chloride concentration with time in the NaOH solution after steady state is achieved. For this, 50 ml of NaOH solution is taken from the reservoir at different intervals and tested for Cl^- concentration using standard volumetric titration method. A curve is drawn between chloride concentration, c (in mmol/cm^3) and time, t (in days). For a constant voltage, the chloride concentration in the NaOH solution increases gradually and linearly with time. The slope, dc/dt, over the linear portion is determined and D_c value has been calculated as per the methodology proposed by Gjørv (1994), and Zhang and Gjørv (1994).The test is stopped when constant chloride concentration is observed over a period of time, i.e., $dc/dt = 0$ (Prabakar et al., 2010). The chloride diffusion coefficient, D_c. for OPC and PPC concretes have been found to be 7.67×10^{-13} and 3.92×10^{-13}m^2/sec at 6 months, respectively. The lower value of D_c for PPC concrete can be attributed to the pozzolanic reaction between fly ash and $Ca(OH)_2$ to form secondary calcium hydrates, causing pore size refinement (Saraswathy and Song, 2007).

SERVICE LIFE OF STRUCTURES

The successful estimation of the initiation, stable propagation and unstable propagation periods is the basis for service life prediction. If all these periods are known within reasonable doubt, then the service life could be estimated. It is seen that different researchers have different opinions of what should be defined as the service life (Austroads, 2000; ACI 365.1R, 2010; Life-365, 2010). In the present study, it is assumed that the service life (t_s) is the sum of the corrosion initiation period (t_i) and stable propagation period (t_{sp}) and expressed as follows (Austroads, 2000):

$$t_s = t_i + t_{sp} \tag{1}$$

Initiation period (t_i)

Based on Fick's 2nd law of diffusion, many researchers have used the following closed-form solution for predicting t_i when the concrete is exposed to chloride environments (ACI 365.1R, 2010; Life-365, 2010):

$$C(x,t) = C_0\left[1 - erf\left(\frac{x}{2\sqrt{(D_c t_i)}}\right)\right] \tag{2}$$

where $C(x,t)$ is chloride concentration at depth x (or C_{tc} in this case) after time t_i; C_0 is the chloride concentration at the concrete surface; D_c is the apparent chloride diffusion coefficient ; erf is the Gaussian error function, and x is the clear depth of rebar from concrete surface or clear cover thickness.

Once the values of C_{tc}, C_0 and D_c are available, the time for $C(x,t)$ at the depth of the rebar to reach C_{tc} gives t_i. In reality, the values C_{tc}, C_0 and D_c are random variables. The value of C_{tc} depends upon various factors that include the microstructure and metallurgical parameters of the rebar, the complex microstructure of the surrounding concrete, the pH of the concrete pore solution, binding capacity of cement, the local environmental characteristics, and the test procedures used to evaluate this parameter (Alonso et al., 2000; Pillai and Trejo, 2005; Angst et al., 2009). A higher threshold would lead to a longer predicted life and vice-versa, provided the other conditions are the same. Therefore, the threshold value should be carefully selected. In the present study, the C_{tc} value is assumed as 0.4%, by weight of cement, which is the most commonly used value for the estimation of t_i by various researchers (Austroads, 2000; Broomfield, 2006; ACI 365.1R, 2010; Life-365, 2010).

In general, the value of C_0 increases with the time of exposure of the structure. However, the data from the field indicate that C_0 tends to reach a 'maximum' value, which generally depends on the concrete porosity and aggressiveness of chloride environment. In the present study, the surface chloride concentration is assumed to be 1% by weight of cement (similar to the typical values in the marine tidal zone, as in Life-365, 2010). Also, it should be noted that the threshold chloride concentration assumed is same for both OPC and PPC concretes, which may not be true (Richardson, 2002).

Stable propagation period (t_{sp})

Among the literature on service life prediction of concrete structures, the literature on corrosion propagation period is relatively less than that on the corrosion initiation period. In the present study, t_{sp} has been computed using the model proposed by Rodriguez et al. (1996). In this model, the loss in rebar diameter, at any time t (in years), can be estimated as:

$$\theta(t) = \theta(0) - p(t) \tag{3}$$

$$p(t) = 0.0116\ \alpha i_{corr}(t_s - t_i) \tag{4}$$

where $\theta(0)$ is the initial diameter of the rebar (in mm); $p(t)$is the loss of section (in mm) in time t; $t_{sp} = t_s - t_i$, i_{corr} is the average value of corrosion current density (in μA/cm^2); 0.0116 is a factor which converts μA/cm^2 to mm/year; t_s is the total time elapsed (in years), t_i is the time for initiation of corrosion (years), and α is a pitting factor (for including the effect of highly localized pitting normally associated with chloride-induced corrosion; for uniform corrosion, α = 2 and for pitting corrosion, α = 5 to 10), as in González et al. (1995).

ESTIMATION OF SERVICE LIFE

Initiation period

For computing the corrosion initiation period, t_i, Eq. (2) can be written as:

$$t_i = \frac{x^2}{4D_c\left[erf^{-1}\left(1 - \frac{C_{tc}}{C_0}\right)\right]^2} \tag{5}$$

Using Eq. (5) and available values on diffusion coefficient, D_c, the corrosion initiation periods, t_i, have been evaluated for a cover thickness of 20 mm, C_{tc} = 0.4% and C_0 = 1%, by weight of cement, and are presented in Table 1. For OPC and PPC concretes, the D_c values were assumed to be 7.67×10^{-13} and 3.92×10^{-13}, respectively. Based on these parametric assumptions, the corrosion initiation periods, t_i, for OPC and PPC concretes were estimated to be 2.1 and 4.2 years, respectively. It can be concluded that by using PPC instead of OPC, the corrosion initiation time can be approximately doubled.

Stable propagation period

For the computation of t_{sp}, the corrosion rate or corrosion intensity level (i_{corr}) and damage level are needed. As mentioned previously, the U-shaped specimens of OPC and PPC were subjected to accelerated chloride induced corrosion for the same duration (at 3.5% NaCl solution; 10 V anodic potential for 22 days). At the end of specified duration, specimens were autopsied and the rebars were removed and cleaned as per ASTM G1 to determine the extent of corrosion. The gravimetric weight loss (i.e., amount of corrosion) of the rebar was estimated as the loss in weight over the middle 300mm length of the rebar. Based on the gravimetric weight loss, the equivalent corrosion rate or current density, i_{corr}, for OPC and PPC concretes were estimated to be 768 and 289 μA/cm^2, respectively (Bhaskar, 2012). It can be seen that the value for PPC concrete is much lower than that of OPC concrete due to the increased resistivity and lower porosity obtained by the incorporation of fly ash (Scott and Alexander, 2007; Bhaskar et al., 2011). Because these values have been obtained under accelerated conditions, they are likely to be much higher than what could occur in the field. As reported by Andrade et al. (1990) and Austin et al. (2004), the i_{corr} values obtained under field conditions for extreme chloride induced corrosion conditions are generally in the range of 100 to 200 μA/cm^2, for normal grades of concrete (as in case of the OPC concrete of the present study). Andrade et al. (1990) and González et al. (1995) further reported that values of 1–3 μA/cm^2 are frequent in active corrosion and that values of the order of 10 μA/cm^2 or higher are seldom observed in the field.

For OPC concrete, the i_{corr} values obtained experimentally by Bhaskar (2013) and the typical range of values reported by Andrade et al. (1990) are significantly different. Therefore, it is necessary to map the laboratory i_{corr} value to the more realistic field value in order to estimate the service life using Eq. (5). Hence, in the present study, for OPC concrete, it is assumed that the i_{corr} value is between 1 and 10 μA/cm^2 (a more realistic field value) instead of i_{corr} values observed in laboratory (i.e., 768 μA/cm^2). The field value for PPC concrete is obtained from the ratio of laboratory i_{corr} values of PPC and OPC concrete as (Morinaga et al., 1994):

$$\left(\frac{i_{corr,OPC}}{i_{corr,PPC}}\right)_{Lab} = \left(\frac{i_{corr,OPC}}{i_{corr,PPC}}\right)_{Field} \tag{6a}$$

$$\left(i_{corr,PPC}\right)_{Field} = \left(\frac{i_{corr,PPC}}{i_{corr,OPC}}\right)_{Lab} \times \left(i_{corr,OPC}\right)_{Field} \tag{6b}$$

Now, another important parameter that is needed to estimate the stable propagation period (t_{sp}) is the definition of the level or levels of deterioration that may affect the serviceability or the load-carrying capacity of the structure. The levels of deterioration classified in the Bulletin No. 162 (CEB, 1983) and Andrade et al. (1990) were considered in fixing the damage levels. The estimations in the present study are made for damage level C or for the upper limit of the loss in steel section of 10% (i.e., it is assumed that the end of stable propagation period (t_{sp}) is reached when the steel section decreases by 10%).

Now, the last step in the estimation of t_{sp} consists of calculating the time taken to reach the assumed deterioration level, i.e., 10% loss in steel section from the initiation period. Therefore,

$$t_{sp} = \frac{\theta(0) - \theta(t)}{0.0116\,\alpha i_{corr}} \tag{7}$$

where,

t_{sp}	=	stable propagation period (in years)
$\theta(0)$	=	initial diameter of the rebar (in mm)
$\theta(t)$	=	net diameter of the rebar (in mm), after an assumed 10% section loss
i_{corr}	=	average value of corrosion current density ($\mu A/cm^2$)
α	=	pitting factor (for uniform corrosion, $\alpha = 2$; pitting corrosion, $\alpha = 5$ to 10)

Knowing the values of t_i and t_{sp}, the total service life (t_s), can be estimated, using Eq. (1). Table 1 and Figure 3 present t_i, t_{sp} and t_s for OPC and PPC concretes, when the field i_{corr}-value of OPC concrete is assumed as 1, 5 and 10$\mu A/cm^2$. From these, it can be said that the service life of RC structures subjected to chloride induced corrosion depends largely on the chloride diffusion and aggressiveness of the exposure conditions. When the i_{corr} is 1 $\mu A/cm^2$, the service life (t_s) of PPC concrete is approximately 2.5 times more than that of OPC concrete. When the i_{corr} is 10 $\mu A/cm^2$, the service life (t_s) of PPC concrete is approximately 2 times more than that of OPC concrete. Life-365 (2010) takes t_{sp} as 6 years for most commonly used uncoated steels, which coincides with the value obtained here for OPC concrete with an i_{corr} of 1 $\mu A/cm^2$.

Table 1. Service lives of concretes for different field i_{corr}-values assumed for OPC concrete

Type of concrete	*Corrosion initiation period (t_i), years*	*Stable propagation period (t_{sp}), years*	*Service life (t_s), years*
i_{corr}-valueof OPC concrete = 1 $\mu A/cm^2$			
OPC	2.1	6.0	8.1
PPC	4.2	16.3	20.5
i_{corr}-valueof OPC concrete = 5 $\mu A/cm^2$			
OPC	2.1	1.2	3.3
PPC	4.2	3.2	7.4
i_{corr}-valueof OPC concrete = 10 $\mu A/cm^2$			
OPC	2.1	0.6	2.7
PPC	4.2	1.6	5.8

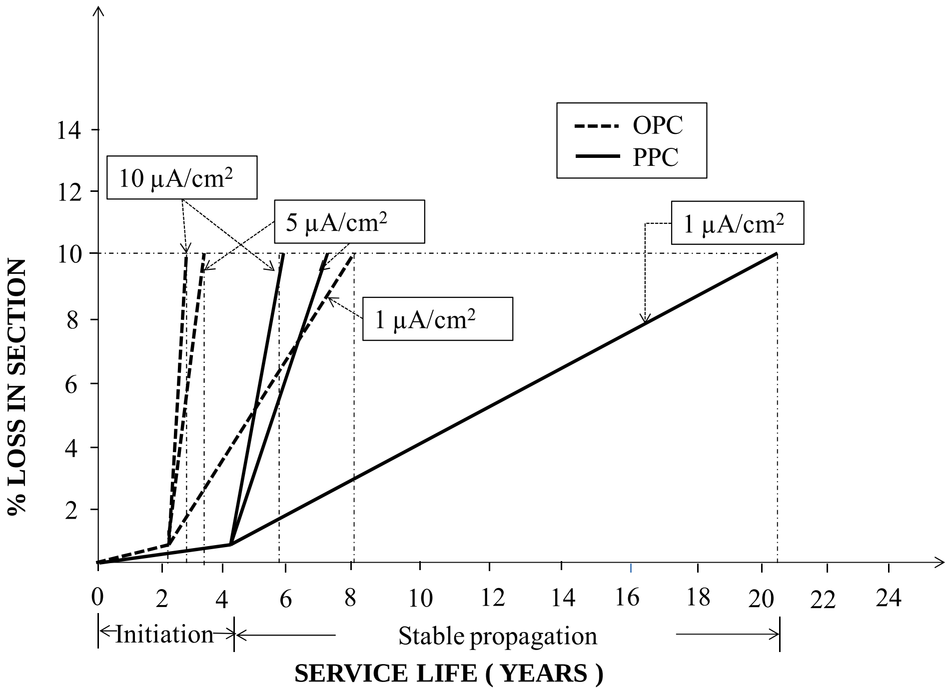

Figure 3. Service life of OPC and PPC concretes for different conditions

The service life estimations reveal that PPC concrete will have better corrosion resistance than OPC concrete due to the delayed corrosion initiation period and decreased corrosion rate during the propagation period. This can be attributed to the higher resistivity and pore refinement due to secondary hydration in the fly ash based PPC concrete. It can be observed that when corrosion rate is low, the durations of initiation and propagation periods are significant in estimating the overall service life; whereas when corrosion rate is high, the duration of initiation period is significant and the duration of propagation period is insignificant in estimating the overall service life.

As reported by Mehta (2002), the results obtained in this study also indicate that the use of PPC will prolong the useful life of a structure, and thereby contribute significantly to sustainable construction. In addition, the use of PPC will lead to the reduction of cement clinker usage, and consequently to minimising the consumption of limestone and other natural resources and to lowering the emission of CO_2.

CONCLUSIONS

The overall service life (t_s) can be assumed as the sum of corrosion initiation period (t_i) and stable propagation period (t_{sp}). Based on this and under the conditions considered in this study, the following conclusions have been drawn:

- The t_i and t_{sp} values can be estimated based on the experimentally evaluated D_c and the computed i_{corr}-values, respectively. When the i_{corr}-values are low to medium, both t_i and t_{sp} contributes significantly to the overall service life. However, at higher i_{corr} (i.e., at severe chloride exposures), only t_i contributes significantly to the overall service life.
- The service life of PPC based concrete is found to be nearly twice that of corresponding OPC based concrete.

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