Parametric Study of Experimental Reference Method for Service Life Assessment of RC Structures Exposed To Carbonation

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***Abstract*— Concrete is the most versatile and robust construction material available and has obtained a dominating position in construction. Today many reinforced concrete (RC) structures deteriorate owing to corrosion of reinforcement, just after a few years of completion reducing their service life. So it is essential to have the causes of deterioration highlighted, aiming at rectifying errors in design methods, construction procedures, material compositions as well as systematic planning of maintenance and repair procedures, to ensure more reliable structures in the future. Corrosion of steel reinforcement is because to two reasons; carbonation of concrete and/or chloride ingress in concrete. Carbonation reduces the concrete quality, results in additional shrinkage in the carbonated region, reduces the concrete`s ability to protect reinforcement from corrosion and develops in poor to medium quality concrete exposed to normal conditions within several months to several years of construction depending on conditions. The paper details a parametric study of service life assessment of RC structures based on service life model EXPERIMENTAL-REFERENCE for different exposure conditions based on European standard EN1992-1-1 "Eurocode2 (2004)"**

***Index Terms*— Reinforced Concrete, Carbonation induced Corrosion, Service Life, Experimental-Reference method**

I. INTRODUCTION

The corrosion of steel reinforcement is one of the main causes of deterioration of RC structures (Bertolini et al. 2004). It is the most harmful and serious problem that is prevailing widely in many RC structures not only in India but in many parts of the world, with the increasing demand of cement concrete as the choice of material for the construction of large number of structures. With the advancements in material science, construction technology and forms of structures, more durable structures are expected to be constructed from the engineers with service life of more than 50 years. But due to corrosion it has been observed that many of the structures complete just 15 - 25 years of service life and continue beyond that in a distressed state until a sudden collapse. For this reason durability and service life aspects of RC structures are gaining focus today.

Corrosion which is the major concern of the damage of the RC structures is due to mainly two reasons: Chloride induced corrosion and Carbonation induced corrosion. Carbonation has been one of the major problems in concrete corrosion because it deteriorates the structure internally and before we know it, it already corrodes the reinforcement steel if not monitored properly and regularly, leading to reduction in service life of the structure.

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II. Experimental Reference Method

The "Exp-Ref" method for service life prediction for carbonation-induced corrosion of steel, similar as for chlorides, consists of three main elements:

1. Air-permeability (and concrete moisture check) and cover meters measured at site, (hence "exp").
2. Correlation between the measured coefficient of air-permeability and carbonation rate.
3. Definition of a reference condition (hence "Ref") with a definite service life attributed.

We know that:

$$SL=T_i+T_p$$

SL= service life (y)
T_i= initiation period (y)
T_p= corrosion propagation period (y)

For carbonation, T_p has to be taken into account properly in the assessment of service life and assuming that surface concentration of carbonation and curing factor are constant for the same exposure class, and decay factor, after so many years of hydration, is also the same for the reference condition. Based on these factors, Torrent R. and Luco L. F. (2014) gave the following expression to calculate time of initiation of corrosion, which when added to time of propagation, gives the value of service life.

$$T_1 = \frac{c^2}{c_{ref^2}} \cdot \frac{\ln^2(174.kT_{ref})}{\ln^2(174.kT)} \cdot T_{1ref}$$

Where
kT = air permeability.
c = cover depth (in mm)
c_{ref} = reference cover depth
kT_{ref} = reference and standard air permeability

After many years of development, experts from most European countries have agreed on a common classification of exposures covering all the conditions likely to be found in Europe (see Table 2.1) EN1992-1-1."Eurocode2 (2004)" and all the parameters are given according to exposure class.

TABLE 2.1
EXPOSURE CLASSES FOR CARBONATION-INDUCED CORROSION ENVIRONMENTS (SOURCE: EN1992-1-1)

Class of Designatio	**Description of Environment**	**Examples**
XC1	a-Dry b-Permanently wet	Inside buildings with low air humidity Permanently submerged in water
XC2	Wet, rarely dry	Many foundations

XC3	Moderate humidity	Inside buildings with moderate or high air humidity
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

Secondly and more important, they agreed that concretes with a w/c ratio below a certain w/c max limit and a cover depth above a certain limit, if well processed according to, are expected to reach a service life of 50 years under a defined Exposure Class. These limits are shown in the first two rows of Table 2.2.

TABLE 2.2
REQUIREMENTS FOR 50 YEARS SERVICE LIFE (SOURCE: EN1992-1-1)

	Exposure Classes				
Characteristic	**XC1a**	**XC1b**	**XC2**	**XC3**	**XC4**
w/c max	0.65		0.60	0.55	0.50
c_{min}(mm)	15		25		30
w/c ref	0.63		0.58	0.53	0.48
$kT_{ref}(10^{-16}m^2)$	1.41		0.79	0.45	0.25
c_{ref}(mm)	25		35		40
T_p(y)	45	10	10	25	2
$T_{i,ref}$(y)	5	40	40	25	48
β(y/mm²)	0.24	1.94	0.79	0.39	0.43

The service life SL can be computed from Eq. (3.1) and it provides estimate of the service life of a concrete structure SL (years), exposed to a given carbonation induced corrosion class, as a function of the measured cover depth c (mm) and the coefficient of air permeability kT (10^{-16} m²), both measured on site. Here, for this study, we have taken fixed values of kT from the range given as per reference exposure conditions mentioned in EN 1892-1-1. The values of clear cover have been varied to observe the variation of service life for each exposure class.

I. Limitations:

Exp- Reference model provides the service life of structure exposed to given exposures condition which must be chosen by the user and no factors or coefficients are to be chosen freely by the user.

II. Service Life Parameter: Air Permeability (kt):

The air permeability kT is very sensitive to the "Covercrete" microstructure, covering some 6 orders of magnitude (0.001x 10^{-16} to 100 x 10^{-16} m^2). The values of kT can be used to design/predict service life of structures on the basis of the real quality of the "Covercrete" (Torrent R. and Ebensperger L. 2012)

TABLE 2.3
SHOWS THE CLASSIFICATION OF CONCRETE PERMEABILITY (AGES FROM 28 TO 180 DAYS) AS FUNCTION OF kT.

Class	**kT (10^{-16} m^2)**	**Permeability**
PK1	< 0.01	Very Low
PK2	0.01 – 0.10	Low
PK3	0.10 – 1.0	Moderate
PK4	1.0 –10	High
PK5	> 10	Very High

TABLE 2.4:
SPECIFIED VALUES OF KT AS FUNCTION OF EXPOSURE (NOTE: THE SPECIFIED VALUE KT IS A CHARACTERISTIC UPPER VALUE)

Exposure Class	**Description**	**kT (10^{-16} m^2)**
XC1 to XC3	Mild Carbonation	Not required
XC4	Severe Carbonation	2.0
XD1, XD2a	Mild Chlorides	2.0
XD2b, XD3	Severe Chlorides	0.5

III. CALCULATION OF SERVICE LIFE (t_{sl}) BY "EXPERIMENT-REFERENCE" MODEL:

Case 1 (for exposure class XC1)
Design service life (initiation period) in years (t_i)
Concrete cover (c_{min}) = (15mm to 50mm with 5mm variation)
Reference concrete cover (c_{ref}) = (25mm to 60mm with 5mm variation)
Air permeability (kT) = .001 x 10^{-16} m^2
Reference air permeability (kT_{ref}) = 1.41 x 10^{-16} m^2
Standard/Reference Temperature (T_{iref}) = 40 °C
Propagation period in years (T_p) = 10 years

TABLE-3.1
SERVICE LIFE CALCULATION (IN YEARS) FOR CASE I FOR KT = .001 X 10^{-16} M^2 ACCORDING TO XC1 FOR CASE I:

T	**$T=T_i+T_p$**	**$T=T_i+T_p$**	**$T=T_i+T_p$**	**$T=T_i+T_p$**	**$T=T_i+T_p$**	**$T=T_i+T_p$**	**$T=T_i+T_p$**	**$T=T_i+T_p$**
T_p(yrs)	10	10	10	10	10	10	10	10
T_i (yrs)	142.28	176.03	202.07	222.78	239.59	253.48	265.13	275.04
x_c	15	20	25	30	35	40	45	50
T (yrs)	152.28	186.03	212.07	232.78	249.59	263.48	275.13	285.04

Case 2
Design service life (Initiation period) in years (T_i)
Concrete cover (c_{min}) = (25mm to 50mm with 5mm variation)
Reference concrete cover (c_{ref}) = (35mm to 60mm with 5mm variation)

Air permeability (kT) = .1 x 10^{-16} m^2
Reference air permeability (kT_{ref}) = .79 x 10^{-16} m^2
Standard/Reference Temperature (T_{iref}) = 40 °C
Propagation period in years (T_p) = 10

TABLE- 3.2
SERVICE LIFE CALCULATION (IN YEARS) FOR CASE II ACCORDING TO EXPOSURE CLASS XC2 WHERE KT IS .01 X 10^{-16} M^2 TO .1 X 10^{-16} M^2:

X_c (mm)	25	30	35	40	45	50
T_i	60.62	66.84	71.88	76.05	79.54	82.51
T_p	10	10	10	10	10	10
T	70.62	76.84	81.88	86.05	89.54	92.51

Case 3
Design service life (Initiation period) in years (T_i)
Concrete cover (c_{min}) = (25mm to 50mm with 5mm variation)
Reference concrete cover (c_{ref}) = (35mm to 50mm with 5mm variation)
Air permeability (kT) = 1 x 10^{-16} m^2
Reference air permeability (kT_{ref}) = .45 x 10^{-16} m^2
Standard/Reference Temperature (T_{iref}) = 25 °C
Propagation period in years (T_p) = 25

TABLE- 3.3:
SERVICE LIFE CALCULATION (IN YEARS) FOR CASE III ACCORDING TO EXPOSURE CLASS XC3 WHERE KT = 1 X 10^{-16} M^2:

T	$T=T_i+T_p$	$T=T_i+T_p$	$T=T_i+T_p$	$T=T_i+T_p$	$T=T_i+T_p$	$T=T_i+T_p$
X_c (mm)	25	30	35	40	45	50
T_i (yrs)	9.11	10.04	10.80	11.43	11.95	12.40
T_p (yrs)	25	25	25	25	25	25
T(yrs)	34.11	35.04	35.80	36.43	36.95	37.4

CASE 4
Design service life (Initiation period) in years (T_i)
Concrete cover (c_{min}) = (30mm to 50mm with 5mm variation)
Reference concrete cover (c_{ref}) = (40mm to 60mm with 5mm variation))
Air permeability (kT) = 2 x 10^{-16} m^2
Reference air permeability (kT_{ref}) = .25 x 10^{-16} m^2
Standard/Reference Temperature (T_{iref}) = 48 °C
Propagation period in years (T_p) = 2

TABLE- 3.4:
SERVICE LIFE CALCULATION (IN YEARS) FOR CASE IV FOR EXPOSURE CLASS XC4 FOR KT = 2 X 10^{-16} M^2:

	CASE XXI	CASE XXII	CASE XXIII	CASE XXIV	CASE XXV
X_c(mm)	30	35	40	45	50
T_i (yrs)	11.23	12.06	12.76	13.35	13.85
T_p(yrs)	2	2	2	2	2
T (yrs)	13.23	14.06	14.76	15.35	15.85

IV. RESULTS AND DISCUSSIONS

The Experimental-Reference model is based on the approach that we can directly take data from the field. However to reduce the effort of designers, in taking field measurements for calculation of service life, the European code EN 1992-1-1 gives the values of the parameters of this approach according to the exposure classes. This helps the users to directly calculate the service life based on the actual exposure condition of their structure.

In the present study, we have chosen all the data from the code EN 1992-1-1 for the various exposure classes which are given according to the European conditions and if we want to calculate the service life then first we have to choose the conditions according to the exposure class then find service life. Also wherever the exposure classes mentioned in the codes of other countries for example Indian Standard code IS 456-2000 differ from those mentioned in EN 1992-1-1, there will be a variation in the service lives of the structures observed in such areas from the service life values calculated using Experimental-Reference method and EN 1992-1-1.

The service lives have been calculated for the various exposure classes for clear cover values varying from minimum 15 mm to 50 mm with 5 mm difference in each two consecutive cases. the minimum value of cover is taken as per the minimum cover mentioned in Table 2.2 for each exposure class. The values for service lives are calculated by taking the value of air permeability according to exposure classes from EN 1992-1-1 (Shown by graph below).

Variation of service life (in years) with concrete cover (15 mm to 50 mm) according to their exposure class XC1, XC2, XC3 and XC4 for series 1,2,3 and 4:

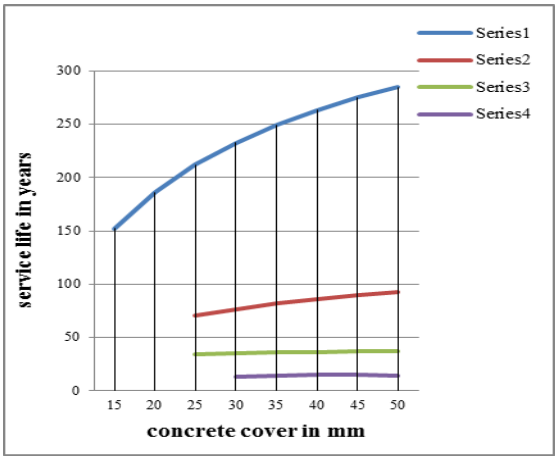

Figure 1: Graph between Concrete cover (15mm to 50mm) and service life at kT= 0.001, .1, 1 and 2 for exposure class XC1, XC2, XC3 and XC4.

1. Figure 1 shows that the service life increases with the increase in clear concrete cover from 152.27 years for cover = 15 mm to 285.04 years for cover = 50 mm for series 1. The exposure class 1 (XC1) is described for extremely dry and wet

conditions having rare to no chances of corrosion. Hence the parameters mentioned in the code are such that the service life values obtained are so high. These high values of service life show that for such exposure condition, carbonation is not affecting the service life.

2. Practically the service life values of structures in the areas having exposure class 1 will be less than those obtained above. This is because there are other factors also apart from carbonation which affect the service life and the formula for calculation of service life in this study takes into account only carbonation. So for exposure class 1, where there is rare to no effect of carbonation, service life values are so high.

3. When series 1 values are compared to service life values of series 2, we find that there is major reduction in service life in series 2. This is because as the value of air permeability increases, the service life will reduce. With the increase in concrete cover by 5 mm, the increase in service life reduces. Like in first increase of 5 mm cover, the increase in service life is 33.75 years, then with every successive 5 mm concrete cover increase, the increase in service life reduces (26.04, 20.91, 16.80, 13.89, 11.35 and 9.91 years) for series 1.

4. Series 2 shows variations of service life for the second exposure class which is wet or rarely dry condition. In this exposure class, carbonation will occur but its rate will be much less than that for higher exposure classes. So in this exposure class, the values of service life are lesser than those obtained for exposure class 1 but they will be greater than those further obtained for exposure classes 3 and 4. Also, the increase in service life has reduced as compared to first exposure class where climate is extremely dry or wet in which carbonation is not possible so service life is large there. The increase in service is 30.99% for series 2 for increase in cover from 25 mm to 50 mm.

5. With the increase in concrete cover by 5 mm, the increase in service reduces for series 2; like in first increase of 5 mm cover, the increase in service life is 6.22 years. Similarly with every 5 mm concrete cover increase, the increase in service life is 5.04, 4.17, 3.49, and 2.97 years respectively for series 2.

6. Series 3 shows variations of service life for the third exposure class which is moderate humidity, in which corrosion is more due to carbonation. So in this exposure class, the values of service life are less and the increase in service life with increase in clear cover, is extremely less as compared to XC1 and XC2. The increase in service life is 6.73% for kT= 1. When cover is increased from 25 mm to 50 mm, the service life increases from 34.11 to 37.4 years. This is the most widely observed exposure class for concrete structures hence we see that after 34 years, with no other governing factor apart from carbonation, the structure will need its first repair. With the increase in concrete cover, the increase in service reduces. For first increase of 5 mm cover, the increase in service life is 0.93 years, similarly with every 5 mm concrete cover increase, the increase in service life is 0.76, 0.63, 0.52 and 0.45 years respectively.

7. Series 4 shows variations of service life for the fourth exposure class XC4 which is cyclic wet and dry condition, in which corrosion is more due to more carbonation. This is the most severe or extreme exposure class, so in this exposure class, the values of service life and the increase in service life are extremely reduced as compared to all other exposure classes. The total increase in service life is 19.80 % in series 4, for XC4, when the cover is increased from 30 mm to 50 mm.

V. CONCLUSIONS

1. Service life depends on concrete cover, exposure condition, water cement ratio, air permeability mainly. Calculation of service life of structure using EN-1192-1-1 does not allow the user to choose the factors or coefficients to be taken for analysis.

2. The service life increases with the increase in concrete cover from 152.27 years for cover = 15 mm to 285.04 years for cover = 50 mm for XC1. There is 87.19% increase in service life when cover increases from 15mm to 50mm for XC1.

3. The extreme high values of service life for XC1 show that for such exposure condition, there will be no effect of carbonation on service life.

4. Practically the service life values of structures in the areas having XC1 will be less than those obtained above due to other factors apart from carbonation which affect the service life.

5. In XC2, carbonation will occur but its rate will be much less than that for higher exposure classes. So, the values of service life are lesser than those obtained for exposure class 1 but they are greater than those further obtained for exposure classes 3 and 4.

6. For XC3, when cover is increased from 25 mm to 50 mm, the service life increases from 34.11 to 37.4 years. This is the most widely observed exposure class for concrete structures hence we see that after 34 years, with no other governing factor apart from carbonation, the structure will need its first repair.

7. XC4 is the extreme exposure class, so here the values of service life and the increase in service life are extremely reduced as compared to all other exposure classes. When cover is increased from 30 mm to 50 mm, the service life increases from 16.45 to 19.82 years.

8. This study provides a basis for life time maintenance plan for newly constructed reinforced concrete structures so that they may be repaired on time and their service lives may be enhanced.

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