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RESEARCH ARTICLE

In-situ condition monitoring of reinforced concrete structures

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ABSTRACT Performance of concrete structures is significantly influenced and governed by its durability and resistance to environmental or exposure conditions, apart from its physical strength. It can be monitored, evaluated and predicted through modeling of physical deterioration mechanisms, performance characteristics and parameters and condition monitoring of in situ concrete structures. One such study has been conducted using Non-destructive testing equipment in the city of Bhopal and around located in India. Some selected parameters influencing durability of reinforced concrete (RC) structures such as concrete cover, carbonation depth, chloride concentration, half cell potential and compressive strength have been measured, for establishing correlation among various parameters and age of structures. Effects of concrete cover and compressive strength over the variation of chloride content with time are also investigated.

KEYWORDS concrete, carbonation, chloride, corrosion, monitoring, models

1 Introduction

Early failure of civil structures was almost non-existent in past centuries. Structures were acknowledged for their durability, soundness and were expected to be permanent. Deterioration rate of RC structures increases with age, and rate of deterioration depends on exposure conditions and extent of careful detailing [1]. Deterioration of concrete structures occurs over its service life, depending on the environment and quality of design, construction, and maintenance [2]. A proposal announcement by National Science Foundation, USA as stated by Rens et al. [3] is: *"The infrastructure deteriorates with time, due to aging of the materials, excessive use, overloading, climatic conditions, lack of sufficient maintenance, and difficulties encountered in proper inspection methods. All of these factors contribute to the obsolescence of the structural system as a whole. As a result, repair, retrofit, rehabilitation, and replacement become necessary actions to be taken to insure the safety of the public"*. Deterioration of concrete structures is due to many physical mechanisms; however, it is mainly associated with the corrosion of rebars in RC structures. Corrosion due to chemical or electrochemical actions is most common form in RC deterioration [4], and is initiated mainly due to chloride ingress and carbonation [5]. During hydration of cement, a highly alkaline solution having pH value greater than 12.5 is formed in the concrete and due to this alkaline environment, a thin oxide passive film is formed over reinforcement steel which protects it from corrosion. The protective film is destroyed by penetration of chloride ions or when pH is reduced below value of 9 due to carbonation. Physical effect of corrosion of RC elements is visible as cross section loss of reinforcement, cracking and spalling of concrete cover etc thus, resulting in strength reduction.

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2 Scope and objective of present research

Premature failure of RC structures despite higher physical compressive strength of material is a significant problem.

Methods for realistic damage evaluation and modeling of deterioration during service life of structures are required. Several engineers and researchers such as Chai et al. [6] and Val et al. [7] have performed in situ tests on RC structures worldwide and proposed models for performance evaluation and service life prediction based on field survey data, however, variation in parameters influencing structural performance, durability and their rate of deterioration during service life of structures, are dependent on the climatic conditions of the region. Therefore, in situ condition monitoring of concrete structures has been conducted around city of Bhopal in India, to develop local performance model and have a comparative study with worldwide models available. Scope of present research is to evaluate variation in various durability or performance parameters such as carbonation depth, chloride concentration, half cell potential, compressive strength etc. with age in RC structure. Covermeter survey for finding concrete cover, rainbow indicator test for measuring carbonation depth of concrete, rapid chloride test for finding chloride concentration, half cell potential measurement by using Ag/AgCl reference electrode for evaluation of probability of corrosion and rebound hammer test for measuring compressive strength of the concrete have been conducted on in situ concrete structures.

From the results of field survey effects of concrete cover and compressive strength have been evaluated over the variation of chloride content with the increase in age of the structure.

3 Brief review of previous work in this research area

In last few decades several similar attempts have been made to evaluate condition of existing structures by performing field and laboratory tests for developing performance model for concrete structures, and for planning the schedule for repair and maintenance of structures.

Corrosion of steel bars embedded in RC structures has been recognized as major parameter for evaluating in situ condition and performance modeling by many researchers. Sangoju et al. [8] used a simple U-shaped specimen under flexural load with pre-cracks to study the corrosion behavior of steel rebars in chloride rich environment, and performed measurements such as chloride ion penetrability, sorptivity, half-cell potential, resistivity, total charge passed and gravimetric weight loss. Chai et al. [6] investigated corrosion of steel by performing accelerated corrosion test, through linear polarization method. Service life prediction model has been established using the experimental results. Val et al. [7] investigated corrosion induced crack initiation and propagation experimentally and numerically, and data obtained is modeled. Several other non destructive techniques have been used to inspect the structures, for monitoring condition of concrete structures. Pradhan and Bhattacharjee [9] reported results of an experimental study conducted on specimens made with different types of cement, steel and varying w/c ratio. Half cell potential measurements had been carried out periodically. Parthiban et al. [10] carried out potential surveys on the concrete structures, to determine the corrosion state of concrete. Polarization resistance has been measured by Soylev and Francois [11] to assess the rate of corrosion, and analyze steel concrete interface defects in order to define their potential to induce corrosion. Pal et al. [5] investigated the rate and amount of corrosion of steel in concrete, and corrosion has been examined by performing half cell potential, potentiodynamic test, accelerated electrolytic corrosion tests, accelerated carbonation test. Carino [12] presented study of three electrochemical NDT methods to investigate the status of corrosion in RC members such as half cell potential, concrete resistivity and polarization resistance.

Many researchers evaluated in situ condition of RC structures through methods based on propagation of stress waves. Ultrasonic Guided Waves have been used by Sharma and Mukherjee [13] for monitoring rebar corrosion in chloride and oxide environment and reported effect of rate of corrosion in the above two environments on Ultrasonic signals. An experimental investigation of the concrete using non linear Ultrasonic testing techniques has been presented by Shah and Hirose [14], Fast Fourier transformation (FFT) test is conducted to produce the frequency spectra, and data obtained are used to determine increase in damage. Nassr and El-Dakhakhni [15] presented a practical in situ nondestructive evaluation (NDE) technique for damage detection in FRP- strengthened concrete structures by detecting the local variation of material dielectric properties, using Coplanar Capacitance Sensors (CCSs), researchers also describes various NDE techniques e.g. Radiography, Ultrasonic testing, Infrared thermography. Ervin et al. [16] created an embedded Ultrasonic Sensing Network for assessment of reinforcement deterioration, and Guided Ultrasonic Waves has been used to monitor RC specimens undergoing accelerated corrosion. Stergiopoulou et al. [17] presented a procedure for non destructive testing of urban concrete infrastructures using UPV measurements, and applied to concrete garages. Effect of the age of concrete on the pulse velocity is investigated and a model is developed.

Chloride concentration and carbonation of concrete have been measured by many researchers for investigating in situ condition and evaluating deterioration of RC structures. Li et al. [18] performed chloride test to study effect of w/c ratios, and concrete stress on chloride ion penetration. Tesfamariam and Martin-Perez [19] proposed a model to estimate carbonation depth and consequently determine the probability of corrosion, the research also proposed a relationship between carbonation depth and age of the structure. Parameswaran et al. [20] proposed a deterioration model for assessing the remaining life of RC structures, through studies of the effect of exposure time over various parameters such as carbonation coefficient. Costa and Appleton [21] presented an experimental study to calibrate the parameters used in the penetration model, also determine the values of diffusion coefficient and surface chloride concentration for the various climatic conditions.

It has been recognized by several researchers that, measuring several parameters of a structure and combining results of these in situ tests provided more reliable results. NDT Inspection of steel bridges has been performed by Rens and Kim [22] using visual inspection, hammer sounding, Schmidt hammer, and UPV testing including tomographic imaging. Results had been used to determine and identify areas to be tested with local destructive tests such as compressive strength, chloride testing and Petrographic testing. An experimental investigation to detect the common flaws in concrete bridge decks by performing Infrared thermography, Impact Echo, and Ground Penetrating Radar (GPR) have been performed by Yehia et al. [23]. Durham et al. [24] examined the causes of longitudinal cracking deterioration by performing on site bridge inspections, determining live load positions, testing for concrete permeability, collecting local relative humidity data, and determining the in situ moisture content of the beams. Bola and Newtson [25] selected five sites for field evaluation of reinforcement corrosion and tested for permeability, chloride ion concentration, half cell potential, polarization resistance, and pH value. Corrosion activity is identified by half cell potential measurements, polarization resistance measurements, and visual inspection of bars. Amleh and Mirza [2] performed field tests on the decommissioned Montreal Dickson Bridge such as concrete cover test, half cell Potential, corrosion rate, electrical resistivity, chloride content at steel level (%), steel bar mass loss (%), absorption, pulse velocity, compressive strength, carbonation depth, petrographic examination and permeability test. Pascale et al. [26] carried out an experimental program involving both destructive and non destructive methods such as: pulse velocity, rebound hammer, pull-out, probe penetration, microcoring and combined methods, to define a relation between strength and parameters. The main properties identified by Dias and Jayanandana [27] for checking the durability are depth of carbonation, cover to reinforcement, chloride content, and sulfate content. Nondestructive techniques used are visual inspection, perusal of drawings, ultrasonic pulse velocity measurements, covermeter surveys, and core testing for the condition assessment of cement work, for obtaining material properties needed for evaluating strength, integrity, and for establishing durability.

From the above review it has been observed that concrete cover to reinforcement, carbonation depth, chloride content, probability of corrosion, and compressive strength and age of structures are the significant parameters responsible for the deterioration of RC structures, and have been evaluated by most of the researchers of monitoring condition of structures. Hence, these parameters have been selected in the present study for evaluating the condition of different RC structures in Bhopal City, such methods will be presented in the following section. Considering above parameters several service life models are developed by researchers, few of them are presented here in Table 1.

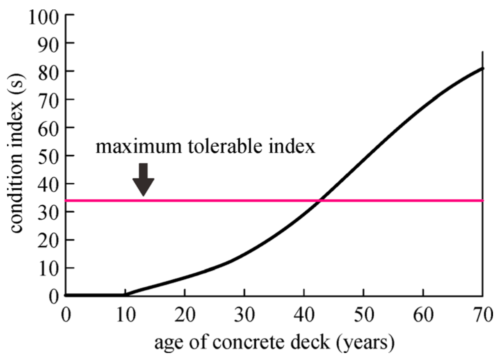
It has been observed from Table 1, that most of the researchers modeled parameters such as corrosion initiation, corrosion propagation, chloride ingress, and carbonation depth for evaluating performance degradation and estimating service life of RC structures. Considering combined effect of chemical and physical deterioration mechanisms on the performance of RC structures, produces more realistic model. Fick's laws of diffusion have been utilized by many researchers to model the service life of structures chloride assuming diffusion coefficient as function of the content of chloride and dependent on time and depth. This is a good approach, as now several researchers realized that diffusion coefficient is not a constant, it depends on the quality of concrete and exposure conditions. Change in environmental conditions significantly influence the performance and deterioration of RC structures, hence, models developed by considering the variation in environment conditions provide more realistic results.

4 Methodology and principles for testing

In the present research, field surveys of deteriorated concrete structures have been done. Numerous deteriorated structures of different age groups have been surveyed and around hundred RC structures of the city of Bhopal are identified and selected for in situ condition survey. Structures are selected from different age group ranging from newly constructed to as old as 60 years and on the basis of compressive strength of concrete. These structures have been numbered in order of their age as shown in Fig. 1. Field survey of selected structures have been performed and performance indicators/ parameters measured are concrete cover in mm, carbonation depth in mm, chloride content at rebar level as percentage of weight of concrete, Half cell potential in mV, Compressive strength of concrete in Mega-Pascal (MPa) along with survey of age of structures in years. Results measured by in situ performance testing of various identified structures have been tabulated in Table 2. The same is presented in graphical form in Figs. 1–7.

The clear concrete cover to reinforcement has been measured and recorded with the help of cover-meter, it is an electromagnetic battery operated device based on the principle that presence of steel rod within the concrete affects the field of an electromagnet, and this is accepted by BS 1881: Part 204. Measured concrete cover of surveyed

Table 1 Some service life models developed by other researchers

reference	parameter/ mechanism modeled	model	significant findings	comments
Sun et al. (2010) [28]	service Life	$t_{\mathrm{Lt}} = t_1(X_{\mathrm{cr}}\delta\sqrt{t_1 D_1})^{2/1-\beta}$ where $\delta = X_{\mathrm{cr}}/\sqrt{D_{\mathrm{Lt}} t_{\mathrm{Lt}}}$ and $\beta = \ln(D_2/D_1)/\ln(t_1/t_2)$ t_{Lt} = duration of service life in years, t_1 and t_2 are exposure ages in years for first and second inspection, X_{cr} = concrete cover depth (mm), D_1 and D_2 are chloride diffusion coefficient at t_1 and t_2, D_{Lt} = chloride diffusion coefficient at t_{Lt}, and β = age parameter and δ = reduction parameter.	A service life model has been proposed for RC structures exposed to chloride environment. Presented time and depth dependent chloride diffusion coefficient. This model is comparable with well known LightCon model. However, predicted service life is longer than the life calculated by LightCon model.	Proposed model is based on Fick's second law of diffusion, considering diffusion coefficient as function of the content of chloride and dependent on time and depth. This is a good approach, as now several researchers realized that diffusion coefficient is not a constant, it depends on the quality of concrete and exposure conditions. Increasing inspection period and considering environmental factors produces more realistic and accurate results.
Masada et al. (2007) [29]	concrete condition rating	$Y = a_0 + a_1 \cdot x_1 + a_2 \cdot x_2 + \cdots + a_n \cdot x_n$ $Y = a_0(x_1)^{a1}(x_2)^{a2}...(x_n)^{an}$ Where Y = concrete condition rating; $x_1, x_2, \ldots, x_n$ = age of structure in years, wall thickness, sulfate concentration etc.; $a_1, a_2, \ldots, a_n$ = parameters determined during analysis.	Applied this new inspection procedure for concrete culverts at 25 sites in Ohio, and inspection data has been examined to detect common problem in existing concrete culverts. A risk assessment method has been also presented to compute overall structural health rating and to recommend a course of action.	Most of the significant parameters influencing the service life have been considered in this model to evaluate the condition of concrete. Both linear and non linear models had been proposed as rate of deterioration may be constant or variable.
Huang et al. (2004) [30]	performance curve and estimated service life of a treatment or maintenance	 $ESL = \{[(t^*-t_o)^2 + K(t_m-t_o)^2]^{0.5} - (t^*-t_o)\}/K^*(-5.37*K + 6.88)$ for $K \neq 0$ $ESL = 0.5(t_m-t_o)^2/(t^*-t_o)*6.88$ for $K = 0$ ESL = estimated service life (years), t^* = time when treatment performed, t_m = time to reach maximum tolerable condition index, t_o = time at the first sign of corrosion, and K (mm / √year) is a factor depends on the rate of corrosion. t^*, tm and to are in years	Developed a project level decision support tool for making maintenance scenarios for concrete bridge decks deteriorated as a result of chloride induced corrosion.	A performance curve i.e., relation between condition and age of structure has been proposed based on spalled percentage, delaminated areas, and chloride content at rebar depth. Delamination and spalling are obtained by visual inspection based on experience; these types of evaluation may vary depending upon the surveyor and predictions made by the surveyor. Only chloride attack among several chemical attacks has been considered. If other attacks such as carbonation, sulfate, alkali silica reaction etc. were considered then accuracy will increase significantly.

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reference	parameter/ mechanism modeled	model	significant findings	comments
Marques and Costa (2010) [31]	corrosion initiation period	$t_1 = [(Rc65.c^2)/1.4 \times 10^{-3} k_0 k_1 k_2 (t_0)^{2n}]^{1/(1-2n)}$ $Rc65 = (a/D)$ $t1$ = initiation period (year), c = concrete cover (mm), D = diffusion coefficient of carbon-dioxide (mm / √year), a = amount of carbon- dioxide that origins the carbonation of the concrete, $Rc65$ = carbonation resistance, t_0 = reference period 1 year, n = accounts for wet and dry cycle influence, K_0 = accounts for testing methods and condition, K_1 = accounts for the presence of relative humidity, K_2 = accounts for cure.	Conducted an experimental study to evaluate performance properties of different concrete compositions. These test results have been considered in the mathematical models of the performance-based specifications. Service life has been evaluated using factor of safety and probabilistic approaches, of each composition. Evaluated service life has been compared to the target periods defined in the prescriptive specification. It has been observed from results that the convergence between the two methodologies still needs to be improved.	This model considered several factors such as carbonation, diffusion rate, wet and dry cycle, testing conditions, humidity and effect of cure. But, it is better to evaluate initiation period considering both carbonation and chloride attack.
	corrosion propagation period	$t_p = k \cdot \phi_o \cdot (1/1.15\alpha I_{corr})$ where $k = \left(74.5 + 7.3(c/Ø_o) - 17.4 f_{cd}\right)(0.2/Ø_o)$ I_{corr} = corrosion current density, x = steel reduction radius in mm, $Ø_o$ = initial diameter of the reinforcing steel in mm, $\alpha = 2$, and f_{cd} = concrete splitting tensile strength.		Model is based on the faradays law and Portuguese performance based specification, also considered corrosion current density dependent on different corrosion level and exposure conditions. Reduction in steel area reduces the load carrying capacity and indicates the deterioration level of RC.
Parameswaran et al. (2008) [20]	corrosion initiation period	$t_i = (c/K_c)^2$ c = concrete cover in mm, K_c = carbonation in mm / √year rate factor depends on exposure condition and air entrained coefficient.	This study has been conducted to observe the deterioration of concrete bridges due to carbonation. Remaining life assessed has been found to be essential for Bridge Management System.	These models have been developed to evaluate initiation and propagation periods by considering exposure conditions, concrete quality, cover, w/c ratio and other factors. Also considered effects of the factors, affecting service life of structures such as addition of admixtures, grade of concrete, concrete cover, air entrainment, and diameter of steel bars.
	corrosion propagation period	$t_p = 80(c/d_r)$ where c = concrete cover in mm, d_r = rate of corrosion		

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reference	parameter/ mechanism modeled	model	significant findings	comments
Li et al. (2011) [18]	chloride diffusion coefficient (D)	$D = D_o \cdot K_s \cdot \theta(x) \cdot t^{-m} = x^2 \times 10^{-6}/\{4t[\mathrm{erf}^{-1}\left(1 - C(x,t)/C_s\right)]^2\}$ where D_o = diffusion coefficient in unstressed concrete m^2/s, K_s = influence coefficient of state of stress, $\theta(x)$ = depth modification factor, m = an empirical coefficient, x = depth in mm, t = time in years, $C(x,t)$ = chloride content at depth x and time t, C_s = surface chloride content in % wt. of concrete	Observed that steel corrosion due to chloride penetration has been one of the most common problem related to durability of concrete structures. Usually studies were performed on unstressed concrete structure. However, in this study tests have been performed on specimens stressed and exposed to salt solution to study the effect of stress on the resistance to chloride ion penetration and diffusion of chlorides in concrete.	Evaluated diffusion coefficient is of mortar in concrete, and diffusion coefficient of concrete can be evaluated using this. Also presented effect of w/c ratio and concrete stress on penetration of chloride ion. For the concrete in tension penetration of chloride is rapid when compared with unstressed or compressed concrete, and smaller the w/c ratio smaller the 'D' and chloride content. Temperature has been considered as constant; however, if the variation of temperature and its effects on penetration of chloride ion is evaluated then proposed relation is more realistic.
Bastidas-Arteaga et al. (2008) [32]	effective diameter of bar	$d_{bar}(t) = d_o[1 - W(t)/W_o]$ where $d_{bar}(t)$ = diameter of the bar at time t, d_o = initial diameter of the bar in mm, $W(t)$ = amount of corrosion products at time t, and W_o = is the initial weight of bar.	Developed a probability based model based on effects of bio-deterioration in degradation of RC structures, to assess the life time of RC structures. This Model includes corrosive environment and cyclic loading. The developed model is applied for the analysis of bridge girders located in chloride contaminated environments, and it has been explained with a numerical example by computing the probability of failure of a reinforced concrete pile. This analysis indicated that the failure probability of RC structures depends on the corrosion rates, surface chloride concentration and the frequency of traffic.	Degradation of RC structures can be evaluated by measuring loss in diameter of steel bars. Loss in effective diameter of rebars due to corrosion reduces the load carrying capacity of structures resulting in failure of RC. In this research author has coupled bio-deterioration, chloride ingress and cracking for determining the condition of RC structures, through the loss in effective diameter of rebars.

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reference	parameter/ mechanism modeled	model	significant findings	comments
Cheung et al. (2009) [33]	corrosion initiation time (t)	$t=(1/k)\cdot(h_{\mathrm{mean}})^a\cdot(C_{\mathrm{s}})^b\cdot d^c$ where h_{mean} = annual mean relative humidity, C_{s} = source chloride concentration, d = effective cover depth, k, a, b and c = adjustment factor for the w/c ratio and weighing factors.	Developed a 2-D finite element based coupled model to evaluate the chloride penetration process in changing environmental conditions to predict the initiation time of corrosion. Observed that corrosion initiation period is governed by environmental conditions to which concrete is exposed and physical properties of the structure which includes heat transfer, moisture transfer, chloride diffusion etc.	Changes in environmental conditions significantly influence the corrosion initiation process. Proposed model calculate initiation period considering only chloride attack, but carbonation depth and other chemical attacks also have significant influence on the performance of structures.
Cao and Sirivivatnanon (2001) [34]	time (t) required by chloride (C_x) to reach at depth (x)	$t=(x^2/2k_1k_2k_3D_{\mathrm{a}}).[\mathrm{erf}^{-1}(1-C_x/\zeta\theta C_{\mathrm{s}})]$ where D_{a} = apparent diffusion coefficient, k_1,k_2 and k_3 are the exposure time, temperature, and stress correction factor respectively; C_{s} = surface chloride content, ζ = microclimatic load factor, and θ = crack width factor.	Presented a simple model to predict the service life of RC structures based on the solution derived from Fick's 2nd law of diffusion with modifications. Acceptable steel corrosion rate is suggested for use in the prediction of service life.	Usually chloride ingress models are valid for uniform materials, absolute concrete cover and unified environment. The proposed model accounts for most of the factors affecting the service life such as exposure time, temperature and stress variations, microclimatic conditions etc.
Liang et al. (2009) [35]	degree of deterioration depassivation time (t_{p})	$D_{\mathrm{d}}=1-(x/10)$ where x is the integrity of RC structure its value ranges from zero to ten. $t_{\mathrm{p}}=(1/4D_{\mathrm{c}})\cdot[L/(1-\sqrt{C^*}/C_{\mathrm{o}})]^2$ where L = concrete cove, D_{c} = chloride ion diffusion coefficient, C* = threshold value of chloride content, C_{o} = surface chloride content.	Proposed a mathematical model based on Fick's 2nd law of diffusion to evaluate the service life of RC bridges. Also considered three stages of corrosion initiation time (t_{c}), depassivation time (t_{p}) and propagation time (tcorr). Hence, total service life of existing RC bridge is $t=t_{\mathrm{c}}+t_{\mathrm{p}}+t_{\mathrm{corr}}$.	Most of the researchers divided service life in three phases such as initiation, depassivation and propagation. And proposed a model to calculate depassivation time. Model has been proposed for chloride environment, so it may not be valid for other conditions. More research is required to develop a model for all the environmental conditions.
Klinesmith et al. (2007) [36]	corrosion loss (y)	$Y=At^B(\mathrm{TOW}/C)^D(1+\mathrm{SO_2}/E)^{\mathrm{F}}(1+\mathrm{Cl/G})^He^{J(T+T_{\mathrm{o}})}$ Where Y = corrosion loss; t = exposure time; TOW = time of wetness; SO_2 = sulfur dioxide; Cl = chloride deposition rate; t = air temperature; and A, B, C, D, E, F, G, H, and T_{o} = empirical coefficients.	Evaluated the effect of environmental conditions over the corrosion. Formulated a model considering different environmental variables such as wetness time, sulfur dioxide, Salinity and temperature. Observed that developed models are reliable for use in several conditions.	To evaluate corrosion loss accurately effect of environmental factors such as sulfur dioxide and wetness time, chloride deposition rate and air temperature has been considered.

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reference	parameter/ mechanism modeled	model	significant findings	comments
Stewart and Val (2003) [37]	crack propagation (T_{ser})	$T_{ser} = [A \times (W_C/C)^{-B}]/i_{corr}$ where W_C = water cement ratio; C = concrete cover in mm; i_{corr} = corrosion rate; A and B are empirical constants	Presented models for reliability and life-cycle cost analyses of reinforced concrete bridges damaged by corrosion. A stochastic deterioration process for corrosion initiation and propagation and then crack initiation and propagation has been used to examine the effect of cracking, spalling and loss of reinforcement area on structural strength and reliability. Expected costs of failure for serviceability and ultimate strength limit states have been calculated and compared for different repair strategies and inspection intervals.	This model assumed constant corrosion rate, but it is better to consider time variant corrosion rate.
Sobhani and Ramezanianpour (2008) [38]	corrosion Initiation period (T_i)	$T_i = (c^2/4D_c).[\mathrm{erf}^{-1}(C_s - C_{cr}/C_s)]$ where c is cover depth in mm, D_c is diffusion coefficient m^2/s, C_s is surface chloride content and C_{cr} is critical chloride concentration (% wt. of concrete)	Developed an algorithm to evaluate the fuzzy membership functions from available information. Proposed an integrated system to convert the probablistic information into the corresponding fuzzy sets. Also detected that under harmful enviromental conditions, concrete prepared and placed properly can also get corroded.	Considered environmental conditions such as relative humidity, degree of drying and wetting, and average temperature. This model provides good results in estimating service life and predicting life cycle of structures.
	corrosion induced cracking period (T_{cr})	$T_{cr} = (W_{crit})^2/2k_p$ where W_{crit} is amount of corrosion products and k_p is the rate of rust production.		
Caner et al. (2008) [39]	remaining life of bridges	$B_1 = (G_c - 3)/M_s$ where B_1 = remaining bridge life in years; G_c = current condition rating based on inspection; and M_s = slope for deterioration of element	28 bridges of different age and conditions are inspected to develop a methodology for evaluating the remaining service life of a bridge and also, proposed a relationship between the current condition rating and age of the brides.	Proposed a methodology to evaluate the remaining service life of a bridge based on current condition. This model is based on the results of a short-term field tests, but it has been recognized that models developed using results of long-term regular inspections are better in accuracy.
Li et al. (2005) [40]	serviceability failure probability of corrosion affected concrete structures	Limit state function 'G' can be defined as $G(L,S,t) = L(t) - S(t)$ where S(t) denotes the response of structure at time t, such as stresses and deformation; and L(t) denotes a critical limit for structural response, which may change with time but in most practical use it is a constant prescribed in the design codes. With the limit state function, the probability of serviceability failure ps, can be determined by: $P_s(t) = P[G(L,S,T)\langle = 0] = P_s(t)\rangle L(t)$	A performance based methodology for assessing the serviceability of corrosion affected concrete structures has been presented. Time-dependent reliability methods have been applied to evaluate the probability of serviceability failure.	Major advantage of this model is that the structural response has been directly related to the design criteria used by structural engineers and asset managers.

Table 2 Measured data obtained by in situ testing

S. No. of surveyed structure	concrete cover (mm)	carbonation depth (mm)	chloride content (% wt. of concrete)	half cell potential (mV)	compressive strength (MPa)	age (years)
1	32	3	0.0050	–10.33	25	1
2	45	5	0.0060	–34.10	22	3
3	48	7	0.0062	–45.10	18	4
4	37	12	0.0065	–121.10	16	8
5	57	9	0.0068	–64.40	21	8
6	56	11	0.0080	–64.88	18	9
7	57	10	0.0080	–74.40	21	10
8	54	14	0.0080	–64.27	18	10
9	51	10	0.0100	–121.20	19	10
10	53	10	0.0100	–58.15	17	10
11	42	10	0.0950	–91.20	19	10
12	55	12	0.0100	–88.15	19	10
13	56	14	0.0130	–100.70	19	12
14	38	16	0.0150	–115.08	20	12
15	52	16	0.0180	–135.35	18	13
16	42	15	0.1100	–143.20	30	14
17	45	19	0.0800	–155.96	18	14
18	58	12	0.0150	–50.70	19	15
19	52	20	0.0200	–145.08	20	15
20	44	20	0.0500	–165.35	18	15
21	42	12	0.1100	–173.20	30	15
22	40	20	0.1200	–154.72	29	15
23	39	20	0.1100	–166.20	16	16
24	41	22	0.1300	–182.10	15	16
25	42	23	0.1300	–207.60	14	17
26	37	25	0.2200	–329.70	16	17
27	43	24	0.1600	–219.90	18	19
28	45	20	0.0800	–185.96	18	20
29	47	20	0.1200	–154.72	29	20
30	38	25	0.1500	–254.20	30	20
31	44	28	0.1700	–270.72	31	22
32	46	21	0.0900	–195.92	18	22
33	45	22	0.1300	–154.72	29	23
34	43	28	0.1900	–331.52	28	24
35	39	28	0.1900	–354.20	30	24
36	45	24	0.0900	–246.20	16	25
37	47	25	0.0800	–232.10	15	25
38	47	35	0.0900	–507.60	14	25
39	32	30	0.3000	–629.70	16	25
40	39	30	0.1900	–277.05	14	25
41	38	30	0.2100	–296.20	14	25
42	37	30	0.2200	–381.52	28	25
43	45	27	0.1200	–296.20	16	26
44	37	31	0.2500	–468.10	14	28

(*Continued*)

S. No. of surveyed structure	concrete cover (mm)	carbonation depth (mm)	chloride content (% wt. of concrete)	half cell potential (mV)	compressive strength (MPa)	age (years)
45	42	32	0.2300	–303.80	13	28
46	48	30	0.1100	–329.90	18	28
47	41	29	0.1800	–302.10	15	28
48	37	31	0.2500	–468.10	14	28
49	39	25	0.1500	–227.60	18	30
50	47	30	0.1200	–274.20	30	30
51	53	40	0.1300	–170.72	31	30
52	37	40	0.3500	–331.52	28	30
53	42	34	0.2500	–351.76	16	30
54	40	35	0.2800	–471.88	12	30
55	48	25	0.1500	–227.60	18	30
56	43	34	0.2400	–457.90	14	31
57	41	33	0.2800	–559.70	16	31
58	49	41	0.1400	–190.72	31	31
59	42	35	0.2700	–390.72	31	32
60	37	33	0.2900	–397.05	14	32
61	42	30	0.2000	–275.05	14	35
62	46	30	0.2200	–286.20	14	35
63	48	35	0.1900	–374.20	30	35
64	44	33	0.2600	–341.52	28	35
65	44	33	0.2600	–407.60	14	37
66	46	36	0.2800	–383.80	13	38
67	44	34	0.2800	–391.76	16	38
68	43	35	0.3100	–439.70	16	39
69	41	40	0.3100	–406.20	14	39
70	42	30	0.2300	–268.10	14	40
71	45	30	0.2900	–411.88	12	40
72	44	32	0.2800	–368.10	14	42
73	42	40	0.2900	–382.10	15	44
74	46	30	0.2600	–375.05	14	44
75	45	35	0.2500	–503.80	13	45
76	46	31	0.2700	–296.20	14	45
77	43	34	0.2900	–403.80	13	45
78	45	37	0.3000	–356.20	16	46
79	43	36	0.3000	–381.33	13	48
80	44	38	0.3200	–392.39	13	48
81	45	38	0.3000	–371.76	16	50
82	43	38	0.3000	–371.76	16	50
83	41	35	0.3400	–371.88	12	50
84	46	40	0.3500	–447.60	12	52
85	49	40	0.3400	–437.60	12	52
86	49	39	0.3100	–381.33	13	55
87	45	38	0.3200	–390.19	13	55
88	45	42	0.3700	–481.33	13	55

(*Continued*)

S. No. of surveyed structure	concrete cover (mm)	carbonation depth (mm)	chloride content (% wt. of concrete)	half cell potential (mV)	compressive strength (MPa)	age (years)
89	47	38	0.3500	–390.19	13	56
90	47	40	0.3000	–271.88	12	58
91	48	40	0.3000	–281.33	13	58
92	48	35	0.3000	–290.19	13	58
93	46	25	0.3200	–347.60	12	58
94	45	42	0.3400	–447.60	12	58
95	44	30	0.3800	–433.44	14	60
96	48	32	0.3600	–443.44	14	60
97	45	40	0.3600	–483.44	14	62
98	55	40	0.3600	–434.56	15	62

Table 3 Presents criteria according to ASTM C876 for Ag/AgCl

S. No.	half cell potential (mV)	% chance of corrosion
1	> – 119	10
2	– 119 to – 269	50
3	< – 269	90

structures is shown in Fig. 2 and had been found to be between 30 to 60 mm, which is in accordance with Indian field practices and standards.

Rainbow Indicator test has been used to determine the carbonation depth in concrete. In this test a freshly broken piece of concrete or a newly cut core is sprayed with the rainbow indicator, and allowed to dry, the approximate pH of the paste is indicated by different colors, pH less than 9 indicates carbonation. Average of three readings on a structure is considered for more reliable results, carbonation depth for concrete structures measured using rainbow indicator spray is shown in Fig. 3, and this indicates that carbonation depth in concrete structure increases with age of structure. Difference between concrete cover and carbonation depth of the surveyed structures have been presented in Fig. 4, which is an important parameter, if carbonation depth is close to or more than concrete cover than corrosion of rebars initiated and accelerated. It has been observed from data presented in Fig. 4 that difference between concrete cover and carbonation depth reduces with increase in age of the structure and thus facilitates initiation of corrosion.

Rapid Chloride Test (RCT) has been used to determine chloride content from dust samples taken from rebar depth level. Use of RCT is accepted by ASTM C114. By RCT soluble amount of chlorides in percentage of concrete weight is measured from concrete powder drilled out of in situ structures. Generally accepted threshold value of

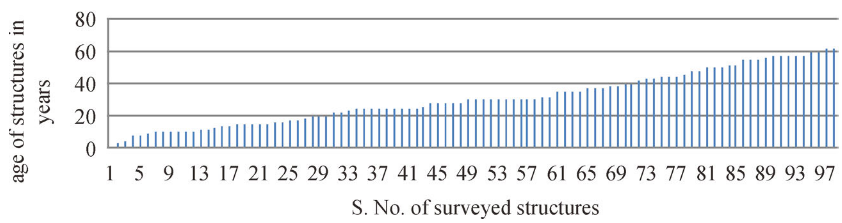

Fig. 1 Age of surveyed structures (years)

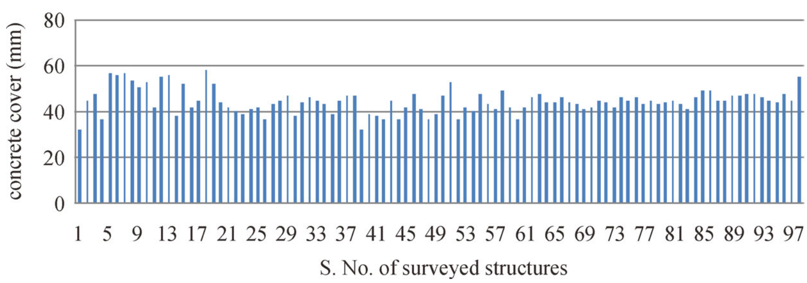

Fig. 2 Concrete cover of surveyed structures (mm)

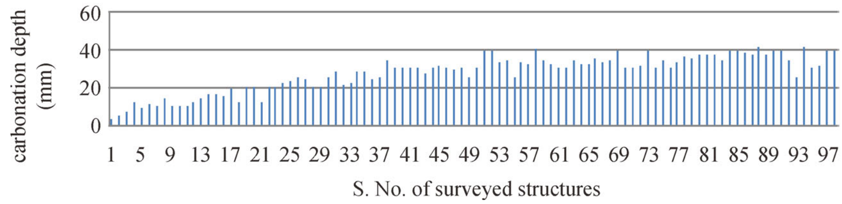

Fig. 3 Carbonation depth of surveyed structures (mm)

chloride content in RC structures is 0.2% by the weight of the concrete. So, if the chloride content at rebar depth is more than threshold value it initiates the corrosion of steel bar. Three samples from different location on each structure have been collected and tested using RCT and average of three values is considered. Results presented in Fig. 5 indicate that chloride content at rebar depth rises with increase in age of structures and in consequence increases the probability of corrosion. It has also been observed from the value, that chloride content at rebar depth reaches its threshold value after around 37 years of age, thereby, initiating the corrosion of rebars. However, this depends over several factors such as concrete cover and compressive strength. Effect of these parameters over the time required for chloride content at rebar depth to reach threshold value has been discussed later in this manuscript.

Half cell potential measurement has been widely used method for evaluating the corrosion state of embedded steel bars in RC structures. In this method potential of steel bars relative to a reference half cell placed on concrete cover is measured for evaluating probability of corrosion. Readings are taken by forming a grid on structure and average of these values have been considered and shown. Ag/AgCl half cell has been used to evaluate percentage of corrosion based on criteria listed in Table 3 and in accordance to ASTM C876. Results obtained are shown in Fig. 6, which indicate that percentage of corrosion increases with the increase in age of structure.

Rebound hammer test in conformation to IS: 13311 (Part 2) – 1992 has been used to measure compressive strength of the concrete structures in the present research. Average of rebound values obtained from at-least three locations and on each location average of nine values is considered for obtaining the compressive strength of a structure. Evaluated compressive strength of all the structures is presented in Fig. 7.

5 Performance modeling of structures with respect to parameters and age

The inference drawn from the results of in situ field experimentation is that deterioration of structures caused by corrosion of rebar is increased with the age of structure. Surveyed age of various identified structures has been

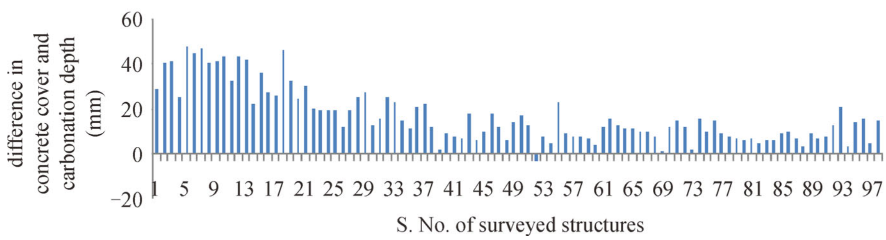

Fig. 4 Difference in cover and carbonation depth (Dccd)

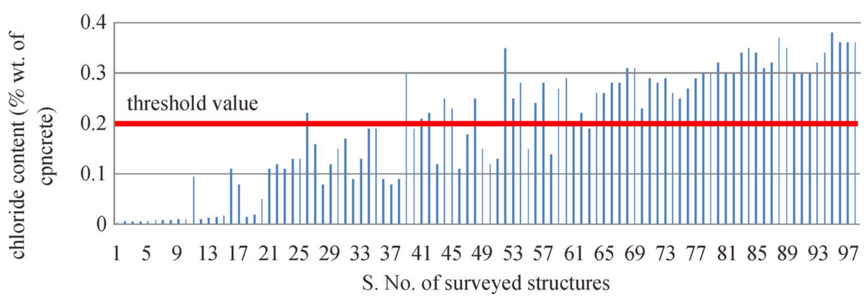

Fig. 5 Measured chloride content of surveyed structures at rebars level (% wt. of concrete)

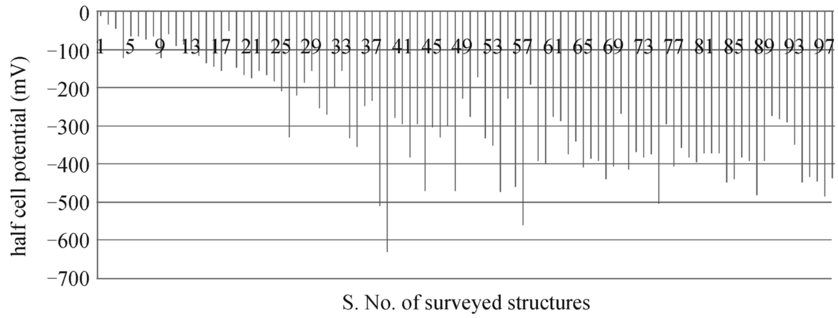

Fig. 6 Measured half cell potential values of surveyed structures (mV)

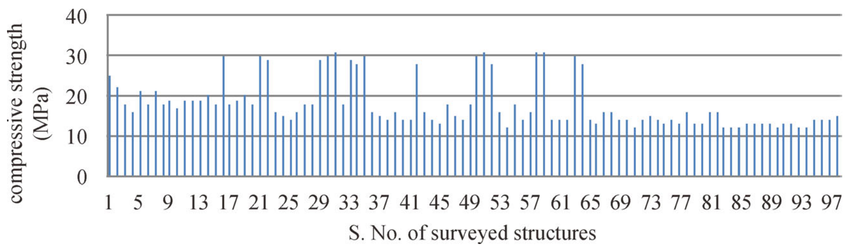

Fig. 7 Measured compressive strength of surveyed structures (MPa)

indicated in Fig. 7. Experimental data obtained from in situ survey and tests are modeled using curve fitting tools. Figure 8 shows the variation of carbonation depth with respect to age of structure and Fig. 9 shows the variation of chloride content at the rebar level with age of surveyed structures. Variation of half cell potential with age of the structure is also shown in Fig. 10. Carbonation depth, chloride content at rebar level increase and half cell potential decreases with the increase in age of structure. Equations showing variation of durability influencing parameters with age are indicated on Figs. 8–10. Increase in values of carbonation depth and chloride content with age and decrease in half cell potential with age indicates the increased in the probability of corrosion initiation and thus increases the deterioration level of concrete structures.

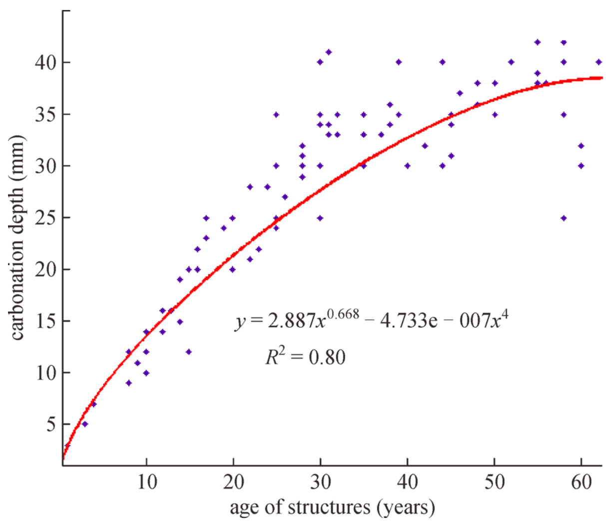

Fig. 8 Variation of carbonation depth with age in surveyed structures

6 Comparison and validation of field data

Corrosion initiation of reinforcing bars is primarily due to two major physical processes, that is, ingress of chloride ion and carbonation of concrete. Variation of above two parameters with age of structures or time of exposure has been studied by many researchers for modeling the service life of concrete structures. Variation of carbonation depth and chloride content with respect to age of structure obtained by in situ field survey and monitoring in present research has been presented by Eqs. (3) and (5) respectively and these equations have been verified and validated by comparing with similar relations proposed by other researchers and represented by Eqs. (1), (2) and (4).

6.1 Carbonation depth

Model proposed in present research for variation of carbonation depth with age or exposure time is compared with two models available in literature. Tesfamariam and Martin-Perez [19] proposed and modeled a relation between carbonation depth (x) in mm and exposure time (t) in years as $x = Kt^{(1/m)}$, where K = carbonation coefficient in mm/√age and m = constant, value of K depends on the various influencing conditions such as climate, region,

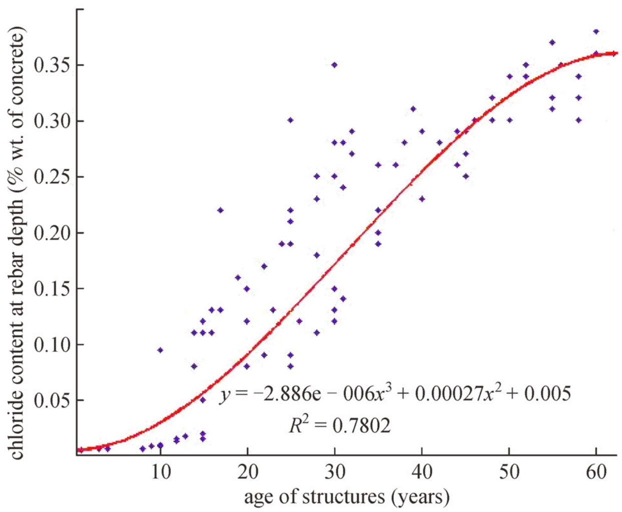

Fig. 9 Variation of chloride content with the age in surveyed structures

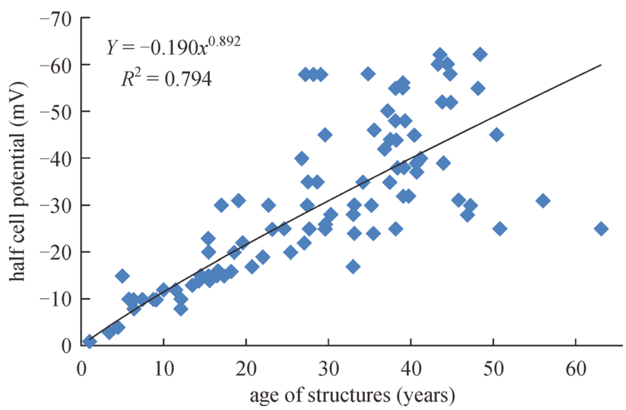

Fig. 10 Variation of half cell potential with age in surveyed structures

exposure etc. From table presented in present research for determining value of K, best suited value of K for present case for urban area and medium quality concrete is "5"and $m = 2$ so relation obtained is

$$x = 5t^{(1/2)}. \tag{1}$$

Parameswaran et al. [20] proposed a relation $x = k_c t^{(1/2)}$ to obtain carbonation depth of concrete structures, where x is carbonation depth in mm and t is the exposure time, from the values measured in present research, best suited value of K_c (mm/√age) for average compressive strength of 20 MPa, also considering environmental condition and cement type is "4.3", therefore, proposed relation is

$$x = 4.3t^{(1/2)}, \tag{2}$$

and the relation for evaluating carbonation depth (x) in mm with respect to age (t) in years of the structure, obtained in present research, shown in Eq. (3) is

$$x = 2.887{*}t^{0.668} - 4.733{*}10^{-7{*}t^4}. \tag{3}$$

It is the best fitted curve equation satisfying the in situ data. First only $2.887{*}t^{0.668}$ has been considered, but for curve to cover most of the data, an additional term is required. Therefore, when $4.733{*}10^{-7}{*}t^4$ term is added to first term, obtained curve is more suitable for present data.

Comparison of carbonation models represented by Eqs. (1), (2) and(3) has been presented in Fig. 11, and it has been observed that variation of carbonation depth with age indicated by all the three models has similar pattern of variation with age of structures. All three equations provide almost similar results for the structures of age less than 30 years, and variation between results of all three equations is low for the structures of age ranging between 30 and 60 years. However, the difference between values obtained from equations representing previous and present research increases with age for the structures of age more than 60 years. Therefore, it is inferred that Eq. (3) representing results of present research is validated only for structures of age less than 60 years.

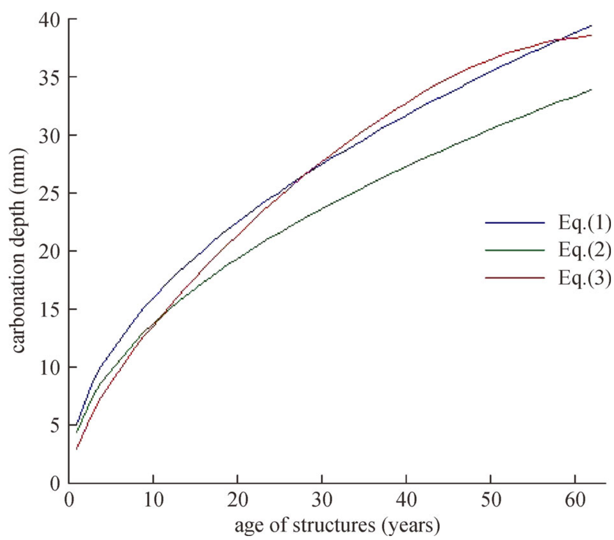

Fig. 11 comparison of present model for variation in carbonation depth with previous models

6.2 Chloride content

Model for variations of chloride content at rebar level with age proposed in present research has been compared with model proposed by other researchers. Variation of chloride content with respect to age and depth based on Fick's 2nd law diffusion has been modeled by Costa and Appleton [21] and a relation between chloride content (C) in percentage weight of concrete, exposure time (t) in years and depth of penetration (x) in mm is proposed. Best suited relationship for present conditions in accordance to it, is

$$C(x,t) = 0.24t^{0.47}\left[1 - \mathrm{erf}\left(\frac{x}{19.84t^{0.243}}\right)\right]. \quad (4)$$

And the model proposed in present research to obtain chloride content (C) in percentage weight of concrete at rebar depth (mm) and exposure time (t) in years is

$$C = -2.829*10^{-6}t^3 + 0.00027t^2 + 0.005. \quad (5)$$

Data presented in Fig. 9, is showing a trend similar to sigmoid curve, however, fitted curve and proposed equation, Eq. (5), satisfies the data better than any other options. Comparison of models represented by Eqs. (4) and (5) is obtained by performing curve fitting of experimental values and values of chloride content obtained by model proposed by Costa and Appleton [21]. It is presented in Fig. 12 and it has been observed that chloride content at rebar depth calculated by above equations is having similar trends of variation with age of structures.

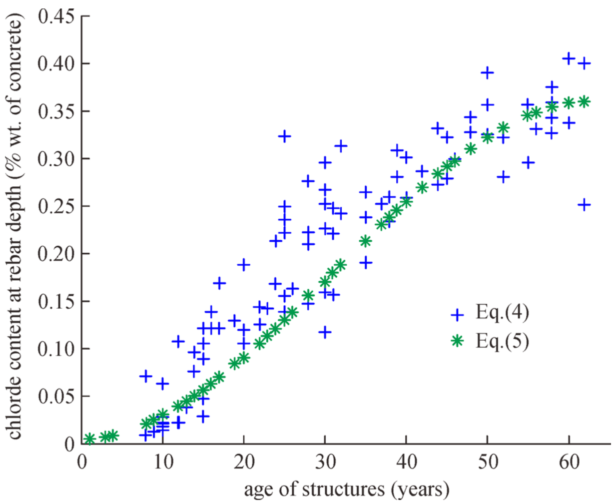

Fig. 12 Comparison of present model for variation in chloride content at rebar level with available model.

7 Effect of concrete cover and compressive strength on chloride content

The chloride content at rebar depth significantly influenced by parameters such as concrete cover and compressive strength. As concrete cover acts as first line of defense against ingress of harmful ions. Hence, by providing adequate concrete cover, chloride content at rebar depth can be maintained below threshold limit for a longer age and this reduces the probability of corrosion. Compressive strength also affects the time required by chloride content at rebar depth to attain the threshold limit. As compressive strength represents the quality of concrete, so in structures with low compressive strength, the chloride content at rebar depth reaches its threshold value earlier.

To validate above statements structures are classified in different groups based on concrete cover and compressive strength and are examined in next sections.

Table 4 Classification of structures based on concrete cover

group	concrete cover (mm)	No. of structures
Cc1	⩽40	16
Cc2	>40 and⩽45	35
Cc3	>45 and⩽50	34
Cc4	>50	13

Table 5 Classification of structures based on compressive strength

group	compressive strength (MPa)	No. of structures
Cs1	0 to 15	44
Cs2	16 to 25	38
Cs3	more than 25	16

7.1 Effect of concrete cover on relation between chloride content and age of structure

Structures are classified according to measured concrete cover in four groups from Cc1 to Cc4 as presented in Table 4. Variation of chloride content for structures of all the four groups with age are plotted in Fig. 13 to 16. It has been observed from these figures that in the structures with low concrete cover, chloride content at rebar depth reaches its threshold value earlier than those with high concrete cover. In Fig. 13, presenting structures with low concrete cover, for most of the structures chloride content attains threshold value before 30 years of age. Then, from Fig. 14 and 15, it has been found that with the increase in concrete cover of the structures, in most of the structures threshold value of concrete cover occurs after the age of 30 years for Cc2 structures and after the age of 45 years for Cc3 structures. Now, from Fig. 16, with structures of group Cc4 with high concrete cover, it has been observed that, in most of the structures chloride content is below the threshold value and it reaches its threshold value after the age of 60 years. Therefore, it has been concluded that time to attain threshold value of chloride content at rebar depth is significantly influenced by the provided concrete cover.

7.2 Effect of compressive strength on relation between chloride content and age of structure

For evaluating the effect of compressive strength over the relation between chloride content and age of structure, structures are classified according to measured compressive strength in three groups as presented in Table 5. Variation of chloride content at rebar depth with age of the structure, for the three groups Cs1 to Cs3 are plotted in Figs. 17 – 19. From these figures it has been found that in the structures with low compressive strength chloride

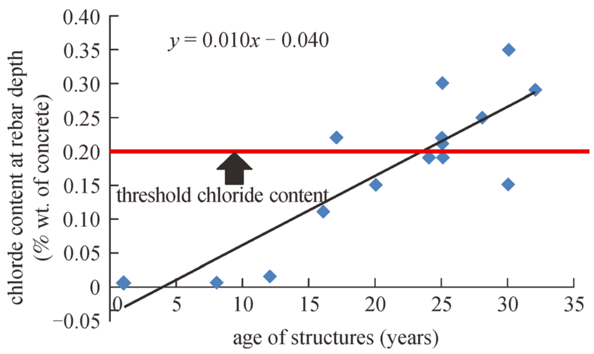

Fig. 13 Variation of chloride content with age of structure for Cc1 group

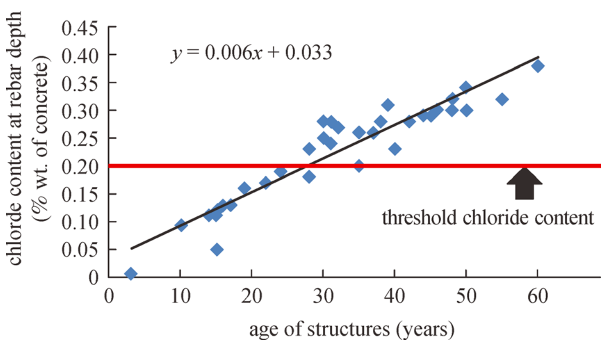

Fig. 14 Variation of chloride content with age of structure for Cc2 group

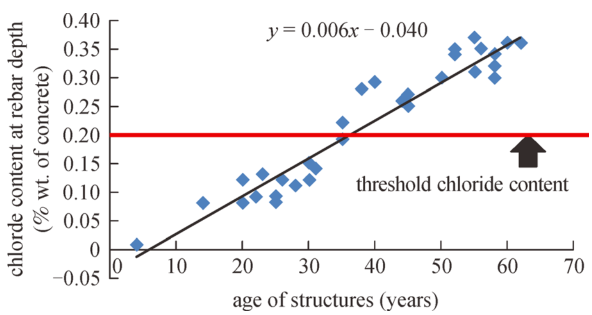

Fig. 15 Variation of chloride content with age of structure for Cc3 group

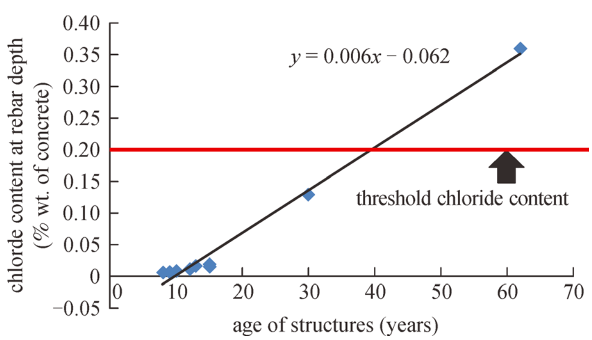

Fig. 16 Variation of chloride content with age of structure for Cc4 group

content at rebar depth earlier than the structures with high compressive strength. In Fig. 17, presenting the structures with low compressive strength, in most of the structures value of chloride content is more than threshold value after the age of 30 years. Figure 18, with structures having moderate compressive strength, showed that, most of the structures are having chloride content below the threshold value up to the age of 30 years. From Fig. 19 it has been observed that, many structures are having chloride content lower that threshold value. Therefore, it has been concluded that compressive strength of a structure significantly influenced the time required by chloride content to reach its threshold value.

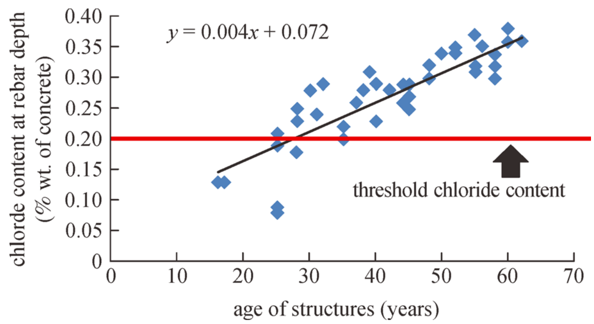

Fig. 17 Variation of chloride content with age of structure for Cs1 group

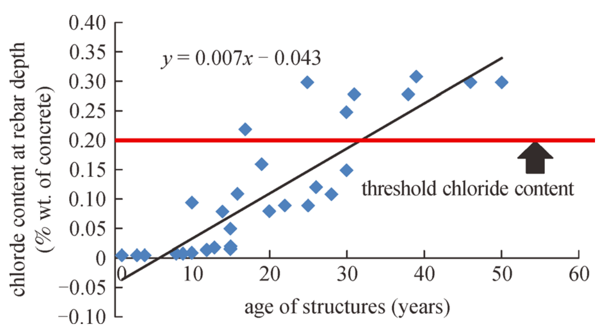

Fig. 18 Variation of chloride content with age of structure for Cs2 group

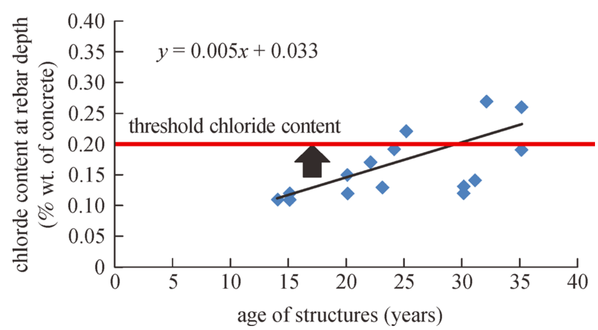

Fig. 19 Variation of chloride content with age of structure for Cs3 group

8 Conclusions

The present research demonstrates an example of in situ performance monitoring and condition assessment of RC structures through field and laboratory testing. Results indicated that variation in carbonation depth, chloride content and half-cell potential are significantly affected with age of RC structures and represents precisely present performance and in situ condition of RC structures during its service life. Carbonation depth and chloride content of concrete near rebar increases with age of the structures and half cell potential decreases with the increase in age of structures, increasing the deterioration level of RC structures.

Variation of carbonation depth, chloride content and half cell potential with the age of the structures has been modeled using curve fitting tools. Relationships are obtained for evaluating carbonation depth and Chloride content with respect to age and are validated showing good correlation by models presented by other researchers.

It has been concluded from Figs. 13–19 that, chloride content at rebar depth reaches its threshold value earlier in the structures with low concrete cover and compressive strength.

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References

1. Ahmed I, Ahmed M Z. Premature deterioration of concrete structures — case study. Journal of Performance of Constructed Facilities, 1996, 10(4): 164–170
2. Amleh L, Mirza M S. Corrosion response of a decommissioned deteriorated bridge decks. J Per Constr Fac, 2004, 18(4): 185
3. Rens K L, Wipf T J, Klaiber F W. Review of nondestructive evaluation techniques of civil infrastructure. J Per Constr Fac, 1997, 11(4): 152–160
4. Song H, Kwon S, Byun K, Park C. Predicting carbonation in early-aged cracked concrete. Cement and Concrete Research, 2006, 36(5): 379–389
5. Pal S C, Mukherjee A, Pathak S R. Corrosion behavior of reinforcement in slag concrete. ACI Materials Journal, 2002, 99 (6): 1–7
6. Chai W, Li W, Ba H. Experimental study on predicting service life of concrete in the marine environment. The Open Civil Eng J, 2011, 5:93–99
7. Val D V, Chernin L, Stewart M G. Experimental and numerical investigation of corrosion-induced cover cracking in reinforced concrete structures. Journal of Structural Engineering, 2009, 135(4): 376–385
8. Sangoju B, Gettu R, Bharatkumar B H, Neelamegam M. Chloride induced corrosion of steel in cracked OPC and PPC concretes: Experimental study. Journal of Materials in Civil Engineering, 2011, 23(7): 1057–1066
9. Pradhan B, Bhattacharjee B. Half cell potential as an indicator of chloride- induced rebar corrosion initiation in RC. Journal of Materials in Civil Engineering, 2009, 21(10): 543–552
10. Parthiban T, Ravi R, Parthiban G T. Potential monitoring system for corrosion of steel in concrete. Advances in Engineering Software, 2006, 37(6): 375–381
11. Soylev T A, Fracois R. Corrosion of reinforcement in relation to presence of defects at the interface between steel and concrete. Journal of Materials in Civil Engineering, 2005, 17(4): 447–455
12. Carino N J. Nondestructive techniques to investigate corrosion status in concrete structures. J Per Constr Fac, 1999, 13(3): 96–106
13. Sharma S, Mukherje A. Monitoring corrosion in oxide and chloride environments using ultrasonic guided waves. Journal of Materials in Civil Engineering, 2011, 23(2): 207–211
14. Shah A A, Hirose S. Non linear ultrasonic investigation of concrete damaged under uniaxial compression step loading. Journal of Materials in Civil Engineering, 2010, 22(5): 476–483
15. Nassr A A, El-Dakhakhni W W. Damage detection of FRP-strengthened concrete structures using capacitance measurements. Journal of Composites for Construction, 2009, 13(6): 486–497
16. Ervin B L, Kuchama D A, Bernhard J T, Reis H. Monitoring corrosion of rebar embedded in mortar using high frequency guided ultrasonic waves. Journal of Engineering Mechanics, 2009, 135(1): 9–18
17. Stergiopoulou C, Aggour M S, McCuen R H. Non destructive testing and evaluation of concrete parking garages. J Infra Sys, 2008, 14(4): 319–326
18. Li G P, Hu F J, Wu Y X. Chloride ion penetration in stressed concrete. Journal of Materials in Civil Engineering, 2011, 23(8): 1145–1153
19. Tesfamariam S, Martin-Perez B. Bayesian belief network to assess carbonation-induced corrosion in reinforced concrete. Journal of Materials in Civil Engineering, 2008, 20(11): 707–717
20. Parameswaran L, Kumar R, Sahu G K. Effect of carbonation on concrete bridge service life. J Bid Eng, 2008, 13(1): 75–82
21. Costa A, Appleton J. Chloride penetration in marine environment-part II: prediction of long term chloride penetration. Scien Rep RILEM354–359, 1998
22. Rens K L, Kim T. Inspection of Quebec street bridge in Denver, Colardo: destructive and nondestru testing. J Per Constr Fac, 2007, 21(3): 215–224
23. Yehia S, Abudayyeh O, Nabulsi S, Abdelqader I. Detection of common defects in concrete bridge decks using non desctructive evaluation techniques. Journal of Bridge Engineering, 2007, 12(2): 215–225
24. Durham S A, Heymsfield E, Tencleve K D. Cracking and reinforcement corrosion in short-span precast concrete bridges. J Per Constr Fac, 2007, 21(5): 390–397
25. Bola M M B, Newtson C M. Field evaluation of marine structures containing calcium nitrite. J Per Constr Fac, 2005, 19(1): 28–35
26. Pascale G, Leo A D, Bonora V. Nondestructive assessment of the actual compressive strength of high strength concrete. Journal of Materials in Civil Engineering, 2003, 15(5): 452–459
27. Dias W P S, Jayanandana A D C. Condition assessment of a

deteriorated cement works. J Per Constr Fac, 2003, 17(4): 188–195
28. Sun Y, Chang T, Liang M. Service life prediction for concrete structures by time-depth dependent chloride diffusion coefficient. Journal of Materials in Civil Engineering, 2010, 22(11): 1187–1190
29. Masada T, Sargand S M, Tarawneh B, Mitchell G F, Gruver D. Inspection and risk assessment of concrete culverts under Ohio's bridge. Journal of Performance of Constructed Facilities, 2007, 21 (3): 225–233
30. Huang Y, Adams T M, Pincheira J A. Analysis of life cycle maintenance strategies for concrete bridge decks. Journal of Bridge Engineering, 2004, 9(3): 250–258
31. Marques P F, Costa A. Service life of RC structures: carbonation induced corrosion. perspective vs. performance-based methodologies. Construction & Building Materials, 2010, 24(3): 258–265
32. Bastidas-Arteaga E, Sánchez-Silva M, Chateauneuf A, Silva M R. Coupled reliability model of biodeterioration, chloride ingress and cracking for reinforced concrete structures. Structural Safety, 2008, 30(2): 110–129
33. Cheung M M S, Zhao J, Chan Y B. Service life prediction of RC bridge structures exposed to chloride environments. Journal of Bridge Engineering, 2009, 14(3): 164–178
34. Cao H T, Sirivivatnanon V. Service life modelling of crack-freed and cracked reinforced concrete members subjected to working load. CIB world building congress, April 2001, Wellington, New Zealand, 2001, 1–11
35. Liang M, Huang R, Feng S, Yeh C. Service life prediction of pier for the existing reinforced concrete bridges in chloride-laden environment. Journal of Marine Science and Technology, 2009, 17(4): 312–319
36. Klinesmith D E, McCuen R H, Albrecht P. Effect of environmental conditions on corrosion rates. Journal of Materials in Civil Engineering, 2007, 19(2): 121–129
37. Stewart M G, Val D V. Multiple limit states and expected failure costs for deteriorating reinforced concrete bridge. Journal of Bridge Engineering, 2003, 8(6): 405–415
38. Sobhani J, Ramezaninpour A A. Modeling the corrosion of reinforced concrete structures based on fuzzy systems. In: Proceedings of the 3rd International Conference of Concrete Development. 27–29 April, Tehran, Iran, 2009, 729–741
39. Caner A, Yanmaz A M, Yakut A, Avsar O, Yilmaz T. Service life assessment of existing highway bridges with no planned regular inspections. J Per Constr Fac, 2008, 22(2): 108–114
40. Li C Q, Lawanwisut W, Zheng J J. Time-dependent reliability method to assess the serviceability of corrosion affected concrete structures. Journal of Structural Engineering, 2005, 131(11): 1674–1680