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Service Life Prediction of Concretes Incorporated with Ground Granulated Blast Furnace Slag and Icrete with respect to Chloride Ion Penetration

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Abstract

The reduced service life of concrete structures in coastal or de-icing salt conditions is commonly attributed to corrosion generated by chloride. Therefore, extensive research is being conducted to estimate the time taken for threshold chloride ions to reach the reinforcement and break the protective layer, initiating the corrosive process. This study conducted an experimental investigation on controlled concrete, concrete incorporating 50% GGBS, and concrete incorporating both 50% GGBS and 2% Icrete as the replacement of cementitious materials, with three different water-cement ratios (0.3, 0.4, and 0.5). The comparison was made based on their compressive strength, chloride ion concentration at different depths, chloride diffusion coefficient, and their service life. The results indicate that the concrete incorporating both GGBS and Icrete performed better than that of the controlled concrete and concrete incorporating GGBS only, in terms of higher compressive strength, reduced chloride ion penetration, reduced chloride ion diffusion coefficient, and higher service life.

Keywords: Service life prediction, GGBS, Icrete, chloride ion concentration, diffusion coefficient

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INTRODUCTION

The extended service life of concrete structures is a key concern for the sustainability and functionality of the infrastructure. Service life is defined as the time after installation—or, in the case of concrete, placement—during which all attributes surpass the minimally acceptable values when regularly maintained. Information regarding the current condition of the concrete, rates of deterioration, past and future loading, and the identification of end-of-life are needed to predict the service life of the present concrete structures [1]. The expected service life of any building or structural component depends on factors such as material properties, operational and maintenance procedures, and their exposed environmental conditions [2]. While most reinforced concrete (RC) structures meet the current 50-year service life expectations, the challenge now lies in extending durability of the RC structures to 100 years or more, especially for critical structures like nuclear containment facilities [3].

Concrete acts as the barrier to corrosion of the steel reinforcement physically, as well as chemically because of its high pH. Concrete, which is not influenced by outside factors, has a pH between 12.5 and 13.5. Rebar and water in concrete combine to generate a thin layer of rust that serves as a passive layer of protection. However, active corrosion of the steel bars results from the partial or total loss of passive layer, known as depassivation. As a result, concrete can crack and continue to deteriorate due to the expanding nature of the corrosive products of iron. The chloride ions, which are primarily found in deicing salts or seawater, are the major cause that can damage the passive film at the surface of the steel and start corrosion [4]. Chloride may ingress into the concrete by means of various transport mechanisms such as ionic diffusion, permeation, capillary sorption, wick action, and

dispersion [5] Among these, diffusion, driven by the chloride concentration gradient, is regarded as the primary transport pattern [6]. When the sufficient quantity of chlorides i.e., threshold quantity reaches reinforcing bars then it leads to localized breakdown of the passive layer resulting in the initiation of corrosion process. There are two states of chlorides present in the concrete: free chlorides, and bound chlorides. Free chlorides get dissolve in the pore solution and are only responsible for the initiation of corrosion. On the other hand bound chlorides are chemically and physically bound to the cement hydrates and their surfaces [5].

This corrosion induced by chloride ion penetration varies based on factors such as the thickness of the covercrete, concrete quality, and environmental conditions, leading to non-uniform (pitting) corrosion [7]. The mechanical behavior of the damaged RC structure due to corrosion is different than undamaged one. The key changes that occur are the reduction in the diameter of steel bars, the reduction in the bond between concrete and steel bars, and the cracking of the covercrete. As the volume of the rust product is greater than that of the steel bars, it exerts radial pressure on the concrete surrounding the steel bars, and as a result cracking and spalling of covercrete occurs [8]. Due to this reduction in the cross-sectional area of corroded steel rebars, there is a reduction in the load-bearing capability of the RC structures [7].

The cost of corrosion is as high as US \$2.5 trillion per year which is around 4% of the GDP of the world and 4.2% of the GDP of India [9].

The initiation period and propagation period are the two major periods that are typically estimated when calculating service life models. The initiation period is the amount of time needed for the chlorides to penetrate the concrete cover and build up at the surface of the rebar in a sufficient quantity (threshold amount) capable of breaking down the passive protective layer and starting corrosion. The propagation period starts with initiation of corrosion followed by cracking, spalling and collapse of the RC structure [10].

Supplementary cementitious materials (SCMs) like Ground Granulated Blast Furnace Slag (GGBS) and Icrete have advantages over OPC in terms of durability, sustainability, and economy, they are frequently used as replacements of cementitious materials. From a chloride-induced reinforcement corrosion perspective, the replacement of cementitious materials by SCMs is usually preferred mainly due to their improved resistance to chloride penetrability. GGBS is a non-metallic by-product of the iron manufacturing process. Similarly, Icrete is also an industrial by-product. It has been shown that densification of the concrete microstructure through partial replacement of cementitious materials with these SCMs significantly reduces the penetrability of chloride ions. During the process of hydration, they react with water and calcium hydroxide ($\text{Ca}(\text{OH})_2$) to produce Calcium Silicate Hydrate (C-S-H) which helps to refine pores and restricts the chloride diffusing pathways [11].

In this paper, the effects of SCMs (GGBS and Icrete) and the water-to-cement ratio on the development of compressive strength, chloride ion concentration (% by weight of concrete) at various depths, and chloride diffusivity of concretes are investigated. The chloride diffusivity is determined by immersion/ponding test on salt solution.

MATERIALS AND TEST METHODS

Materials:

Two different sizes of well-graded crushed aggregates (20-10mm and 10-4.75mm) and natural river sand as well as manufactured sand were used as coarse and fine aggregates respectively. Ordinary Portland Cement (OPC) conforming to IS 269:2015 [12] was used. GGBS conforming to IS 16714:2018 [13] and, Icrete were used as the replacement for OPC in this work. The physical and chemical properties of OPC, GGBS, and Icrete are presented in Table 1. A polycarboxylate (PC) based superplasticizer was used as a chemical admixture to reduce water content.

Preparation of Test Specimens:

For each mix proportion, eleven 150-mm cubes were cast. Fresh concrete was filled in the cube moulds in two layers and compacted using a table vibrator to remove entrapped air. The top surface was finished using the trowel. The samples were then stored for 24 hours for controlled concrete and for concretes incorporating GGBS and Icrete, the samples were stored for 48 hours. In both cases, the samples were covered with wet jute bags. The specimens were then placed in a water-curing tank immediately after demoulding. Table 2 shows the 9 concrete mix proportions with different water-to-cementitious materials ratios (w/cm) and replacement levels of OPC with GGBS and Icrete.

Table 1: Chemical and physical properties of the cementitious materials (in % by weight)

Properties	OPC - 53 grade	GGBS	Icrete
Chemical Properties			
CaO	66.67	37.63	33.6
SiO ₂	18.91	34.81	35.7
Al ₂ O ₃	4.51	17.92	21.8
Fe ₂ O ₃	4.94	0.66	1.4
MgO	2.53	7.80	6.3
SO ₃	2.52	0.20	0.13
Physical Properties			
Fineness, m ² /kg	320	386	1200
Specific gravity	3.14	2.9	2.85

Table 2: Mixing proportions in kg/m³ of concrete.

Mix	w/cm	% of GGBS	% of I-Crete	Water Content (Kg)	OPC (Kg)	GGBS (Kg)	I-Crete (Kg)	Fine aggregate (Kg)		Coarse aggregate (Kg)		Super plasticizer (Kg)
								M-Sand	N-Sand	20-10 mm	10-4.75 mm	
1	0.3	0	0	160	533.4	0	0	208.7	387.5	694.3	462.9	3.47
2		50	0	160	266.7	266.7	0	208.7	387.5	694.3	462.9	3.47
3		50	2	160	256.1	266.7	10.6	208.7	387.5	694.3	462.9	3.47
4	0.4	0	0	160	400	0	0	224.7	417.2	747.5	498.3	2.6
5		50	0	160	200	200	0	224.7	417.2	747.5	498.3	2.6
6		50	2	160	192	200	8	224.7	417.2	747.5	498.3	2.6
7	0.5	0	0	160	320	0	0	234.2	435	779.3	519.6	2.08
8		50	0	160	160	160	0	234.2	435	779.3	519.6	2.08
9		50	2	160	153.6	160	6.4	234.2	435	779.3	519.6	2.08

TEST METHODS

Compressive strength Test:

For each mix, three samples were tested for compressive strength at 28 days, 56 days, and 84 days. Each mix sample contained three specimens and the average of three is taken as the compressive strength value.

Chloride Ion Penetration Test:

After curing the sample for 28 days in a water curing tank, the specimens were exposed to 3.5% NaCl solution for 6 weeks and 12 weeks period. After ponding/immersion of the specimen in NaCl solution, the powder was extracted from the specimen at various depths. The total chloride concentration at

various depths (% by weight of concrete) was then determined by using IS 14959 (Part 2): 2001 [14]. The surface chloride concentration was determined by plotting and best fitting the curve obtained with chloride ions concentration (in the Y-axis) and respective depths (in the X-axis). Then chloride diffusion coefficient of the concrete was determined using Fick's second law (error function solution) using Equation 3.

Fick's first law states that the transport of chloride ions through the unit area per unit time (Flux F) is proportional to the chloride ions concentration gradient, i.e. $\partial C/\partial x$, and is given by,

$$F = -D \partial C / \partial x \quad 1$$

Here the negative sign indicates the diffusion of the chloride ions occurs in the opposite direction of a higher concentration of chloride. Here, D is the proportionality constant known as the diffusion coefficient.

Fick's second law, derived from Equation 1 is given by:

$$\partial C / \partial t = D (\partial^2 C) / (\partial^2 x) \quad 2$$

If we use the boundary conditions $C(x, t=0) = C_0$, $C(x=0, t>0) = C_s$ then the analytical solution for Equation 2 becomes,

$$C(x, t) = C_s [1 - \text{erf}(x / (2\sqrt{Dt}))] \quad 3$$

In Equation 3, $C(x, t)$ is the chloride content at depth x and time t , D is the diffusion coefficient, C_s is the surface chloride content, and erf is the error function [15]. This method of determining chloride content depends on constant chloride diffusion coefficients and the surface chloride content. However, researchers have found out that the diffusion coefficients and surface chloride content vary with time and given several prediction models mainly based on Fick's law [16]. In this paper, the service life of the concretes is calculated using error function solutions and some well-known prediction models and their obtained results are compared.

Prediction Methods and Models

Several service life predictions models based on our literature review are presented in Table 3. Andrade's model does not depend upon diffusion coefficient and surface chloride concentration. In Firouzi's and Sun's models, chloride diffusion coefficient and surface chloride concentration both vary with time. Whereas in FIB, DuraCrete, Mangat's, Bamforth, and Lehar's models, chloride diffusion coefficient varies with respect to time and surface chloride concentration is constant.

Table 3: List of service life prediction models from literature review

S. No.	Models and governing equations	Remarks
1	<p>Andrades's model [17] (in 2017)</p> <p>Mathematical representation of the model is:</p> $y_{0.4\%} = k_{cl} \times t^b$ <p>Where, k_{cl} = the chloride coefficient (cm^2/year) which represents the first-year ingress of critical chloride concentration, t = time in years, and b = coefficient to be determined.</p> <p>k_{cl} is the function of the following parameters:</p> $y_{0.4\%} = [f(f_{ck}, UR, T, Cl, K_1, K_2, Ad)] \times t^b$ $y_{0.4\%} = \frac{K_0 \times UR^{b_1} \times T^{b_2} \times Cl^{b_3}}{K_1 \times f_{ck}^{b_4} \times K_2 \times (1 + Ad)^{b_5}} \times t^{b_6}$ <p>Where, K_0 is general constant and b_1-b_6 is variable coefficients.</p> <p>After analyzing the collected data using non regression analysis the final model is given by:</p> $y_{0.4\%} = \frac{7.35 \times UR^{0.7} \times T^{0.1} \times Cl^{0.7}}{K_1 \times f_{ck} \times K_2 \times (1 + Ad)^{0.2}} \times \sqrt{t}$	Service life of structure is calculated without using diffusion coefficient and surface chloride concentration. It can be used for structure which is under construction.

	<p>Where, $y_{0.4\%}$= location of critical chloride concentration from the surface (mm) UR= relative humidity (%) T= environmental temperature (°C) Cl= environmental chloride concentration (%) K_1= factor based on type of cement f_{ck}= characteristic compressive strength (MPa) K_2= factor based on admixture type Ad= amount of admixture (% by weight of cement) t= exposure time (years)</p>	
2	<p>FIB model [18] (in 2006) FIB (International Federation for Structural Concrete, 1998) was formed by merging CEB (European Committee for Concrete, 1953) and FIP (International Federation for Prestressing, 1952). FIB model (fib bulletin 34:2006) is based on the limit state equation for depassivation of reinforcement and is fully probabilistic model. The model is represented by:</p> $C_{crit} = C(x = a, t) = C_0 + (C_{S,\Delta x}) - C_0 \left[1 - \operatorname{erf} \frac{a - \Delta x}{2\sqrt{D_{app,C} \cdot t}} \right]$ <p>Where, C_{crit}= critical chloride content (wt. %/c) $C(x = a, t)$= chloride content at depth x=a, and at time t C_0= initial chloride content of concretes (wt. %/c) $C_{S,\Delta x}$= chloride content at the depth Δx, after certain time x= depth of concretes with certain % of chlorides a= concrete cover (mm) Δx= convection zone depth (mm) t= time in years $D_{app,C}$= apparent chloride diffusion coefficient (mm²/s) $D_{app,C} = k_e D_{RCM,0} k_t A(t)$ k_e = environmental transfer variable and is given by; $k_e = \exp \left(b_e \left(\frac{1}{T_{ref}} - \frac{1}{T_{real}} \right) \right)$ b_e = regression variable (K) T_{ref} = standard reference temperature (K) T_{real} = temperature of surrounding $D_{RCM,0}$ = chloride migration coefficient k_t = transfer parameter $A(t) = \left(\frac{t_0}{t} \right)^a$ a= ageing exponent t_0 = reference time (years)</p>	<p>Diffusion coefficient varies with time and surface chloride concentration is constant.</p>
3	<p>DuraCrete model [19] (2019)</p> $\frac{C_{cr}}{\gamma C_{cr}} - A_{C_{s,cl}} \cdot \left(\frac{w}{b} \right) \cdot \gamma C_{s,cl} \left[1 - \operatorname{erf} \left(\frac{x - \Delta x}{2\sqrt{\gamma R_{cl} \cdot k_{e,cl} \cdot k_{c,cl} \cdot k_s \cdot k_t \cdot D_{RCM,0} \left(\frac{t_0}{t} \right)^{n_{cl}}}} \right) \right] = 0$ <p>C_{cr} = critical chloride concentration (eigen value) (% by wt. of binder) γC_{cr} = fractional coefficient (critical chloride ion concentration) $A_{C_{s,cl}}$ = regression coefficient</p>	<p>Diffusion coefficient varies with respect to time and surface chloride concentration is constant</p>

	<p> $\frac{w}{b}$ = water binder ratio $\gamma C_{s,cl}$ = fractional coefficient (surface chloride concentration) x = cover concrete depth (mm) Δx = construction deviation of cover concrete (mm) γR_{cl} = fractional coefficient (chloride ion diffusion) $k_{e,cl}$ = environmental influencing factor $k_{c,cl}$ = curing coefficient $D_{RCM,0}$ = chloride ion diffusion coefficient (mm²/year) n_{cl} = degradation coefficient for chloride diffusion t_0 = testing time for diffusion (years) t = design life span of structures (years) erf = error function q = activation energy (K) T = reference temperature (in Kelvin, 293K) T_0 = monthly average temperature (K) </p> $k_t = \frac{T}{T_0} \exp \left[q \left(\frac{1}{T_0} - \frac{1}{T} \right) \right]$ <p> $C_{s,cl}$ = surface chloride concentration (% by wt. of binder) $C_{s,cl} = A_{C_{s,cl}} \cdot \left(\frac{w}{b} \right) \cdot \gamma C_{s,cl}$ </p>	
4	<p>Mangat's model [20], [21] (1994, 1999)</p> $C(x, t) = C_0 \left[1 - erf \left(\frac{x}{2\sqrt{D_c t}} \right) \right]$ <p>Where, $C(x, t)$ is chloride concentration at depth x during time of exposure t, C_0 is surface chloride concentration, erf is error function, x is the depth of concrete, t is exposed time, and D_c is the diffusion coefficient.</p> $D_c = D_i t^{-m}$ $m = 2.5 \left(\frac{w}{c} \right) - 0.6$ $C(x, t) = C_0 \left[1 - erf \left(\frac{x}{2\sqrt{\frac{D_i t^{1-m}}{1-m}}} \right) \right]$ <p>With the values of m, C_0, x, and $C(x, t)$ first D_i is calculated and later by substituting the value of it service life t is calculated.</p>	Surface chloride concentration constant (i.e. 1.5% by wt. of binder and diffusion coefficient varies with time)
5	<p>Bamforth model [22] (1999)</p> $C(x, t) = C_s \left[1 - erf \left(\frac{x}{2\sqrt{D_a t}} \right) \right]$ <p>Where, $C(x, t)$ is chloride ion concentration at depth x during time of exposure t, C_s is surface chloride concentration, erf is error function, x is the depth of concrete, t is exposed time, and D_a is the apparent diffusion coefficient.</p> <p>Here, D_a is time dependent and decreases with time.</p> $D_t = D_{28} \left(\frac{t_{28}}{t} \right)^m$ <p>Where, D_t is diffusion coefficient at time t, D_{28} is diffusion coefficient at time t_{28} (28 days), and m is the constant (0.14 to 0.6).</p>	Surface chloride concentration constant and diffusion coefficient varies with time
6	<p>Firouzi's model [7] (2020)</p> $\frac{\partial C(x, t)}{\partial t} = D(t) \frac{\partial^2 C(x, t)}{\partial x^2}$	Surface chloride concentration and diffusion coefficient both

	<p>Where, $C(x,t)$ is the chloride ions concentration as the function of time t and position x $D(t)$ is the chloride diffusion coefficient (time dependent) Surface chloride concentration at time t is given by: $C_s(t) = C_0 + k\sqrt{t}$ $k=2.11$ constant C_0 = initial surface chloride concentration at the time of exposure $D_a(t) = \frac{D_{ref}}{1-m} \left[\left(1 + \frac{t_{ex}}{365 \times t} \right)^{1-m} - \left(\frac{t_{ex}}{365 \times t} \right)^{1-m} \right] \cdot \left(\frac{t_{ref}}{365 \times t} \right)^m$ $D_a(t)$ = apparent chloride diffusion coefficient (mm²/year) D_{ref} = diffusion coefficient at $t_{ref}=28$ days m= age factor (0.43-0.51) t= time in years $t_{ex} = 28$ days With the application of time dependent surface chloride concentrations and the diffusion coefficient the chloride concentration corresponding to depth of penetration x and time t is given by: $C(x,t) = C_0 \left[\operatorname{erfc} \left(\frac{x}{2\sqrt{D_a t}} \right) \right] + k\sqrt{t} \left[\exp \left(\frac{-x^2}{4D_a t} \right) - \left(\frac{x\sqrt{\pi}}{2\sqrt{D_a t}} \right) \operatorname{erfc} \left(\frac{x}{2\sqrt{D_a t}} \right) \right]$</p>	varies with respect to time
7	<p>Sun's model [23] (2010)</p> $\delta = \frac{x_{cr}}{\sqrt{D_{LT} t_{LT}}} = 2 \operatorname{erfc}^{-1} \left(\frac{\int_{C_{sm}}^{C_{cr}} D(C) dC - \int_{C_{sm}}^{C_i} D(C) dC}{\int_{C_{sm}}^{C_s} D(C) dC - \int_{C_{sm}}^{C_i} D(C) dC} \right)$ <p>x_{cr}=concrete cover depth; t_{LT}=length of service lifetime; D_{LT}=chloride diffusion coefficient at t_{LT} and x_{cr}; C_{cr}= critical chloride content to initiate corrosion; $D_2 = D_1 \left(\frac{t_1}{t_2} \right)^\beta$ D_2 = chloride diffusion coefficient at time t_2 and certain depth x from surface; D_1 = chloride diffusion coefficient at time t_1 and same depth x from surface; β = age parameter and is given by: $\beta = \frac{\ln(D_2/D_1)}{\ln(t_1/t_2)}$ Service life is defined as $C_r=C_{cr}$ at surface of reinforcement, then $x=x_{cr}$, and D_{LT} for $t=t_{LT}$ is given by: $D_{LT} = D_1 \left(\frac{t_1}{t_{LT}} \right)^\beta$ Now, $\delta = \frac{x_{cr}}{\sqrt{D_1 \left(\frac{t_1}{t_{LT}} \right)^\beta t_{LT}}}$ and the service life is given by: $t_{LT} = t_1 \left(\frac{x_{cr}}{\delta \sqrt{D_1 t_1}} \right)^{2/1-\beta}$</p>	Surface chloride concentration and diffusion coefficient both varies with time
8	<p>Lehner's model [24] (2022)</p>	Surface chloride

Diffusion coefficient (chloride profile)

$$C(x, t) = C_0 \left\{ 1 - \operatorname{erf} \left(\frac{x}{\sqrt{4D_c t}} \right) \right\}$$

Diffusion coefficient (electrical resistance method)

$$D = \frac{RT}{Z^2 F^2} \frac{t_i}{\gamma_i C_i \rho B R}$$

$$D_{c, nom, t} = D_{c, nom, 28} \left(\frac{t_{28}}{t} \right)^m$$

Where $C(x, t)$ = the chloride ions concentration (%cem) in depth x from the concrete surface (m) at time t (s)

C_0 = the surface concentration of chloride ions (%cem)

erf = the error function

D_c = the effective diffusion coefficient (m^2/s)

D = the diffusivity of the chloride ion (m^2/s)

R = the universal gas constant (J/K-mol)

T = the absolute temperature (K)

Z = the ionic valence (-)

F = the Faraday constant (C/mol)

t_i = the transfer number of the chloride ion (-)

γ_i = the activity coefficient of the chloride ion (-)

C_i = the concentration of ions in pore water (C/mol)

$\rho B R$ = the bulk (volume) electric resistivity (Ω -m)

$D_{c, nom, 28}$ = the nominal diffusion coefficient $\theta (m^2/s)$

concentration is constant with time and diffusion coefficient varies with time.

RESULTS AND DISCUSSIONS

Compressive Strength development:

Each sample was tested at 28 days, 56 days, and 84 days after water curing to determine their respective compressive strength. The compressive strength development for all the concrete mix is illustrated in Fig.1. At 28 days among all water to cementitious materials (w/cm) ratios, the controlled concrete (mix 1) with $w/cm = 0.3$ has the highest compressive strength of 68.67MPa and concrete incorporating 50% GGBS only with $w/cm = 0.5$ has lowest compressive strength of 37.94MPa. At 56 days concrete incorporating 50% GGBS only (mix 2) with $w/cm = 0.3$ shows the highest compressive strength of 73.56MPa among all w/cm ratios. At 84 days concrete incorporating both GGBS 50% and Icrete 2% (mix 3) with $w/cm = 0.3$ has the highest compressive strength of 79.86MPa. From the results it is reported that the 28 days compressive strength of concretes is higher for controlled mix whereas its strength development does not vary much for the 56 days and 84 days age as most of the hydration reaction takes place within 28 days for it. In the case of concretes incorporating SCMs like GGBS and I-Crete, the strength of concrete goes on increasing beyond 28 days and at 84 days with continuous curing the strength surpasses the strength of controlled concrete for all the w/cm ratios this is because of refinement of pores by formation of additional calcium silicate hydrate (CSH) by the pozzolanic reaction of GGBS with calcium hydroxide [25].

The results presented in Table 4 show that the rate of development of compressive strength of concretes incorporating GGBS and Icrete is more than that of controlled concrete at 56 days and 84 days regardless of w/cm ratios.

Table 4: Rate of development of compression strength as a ratio to the 28-day strength

Mix	28 days	56 days	84 days
1	1.00	1.05	1.06
2	1.00	1.15	1.20
3	1.00	1.09	1.22
4	1.00	1.06	1.08
5	1.00	1.18	1.19
6	1.00	1.13	1.23
7	1.00	1.04	1.08
8	1.00	1.14	1.18
9	1.00	1.18	1.21

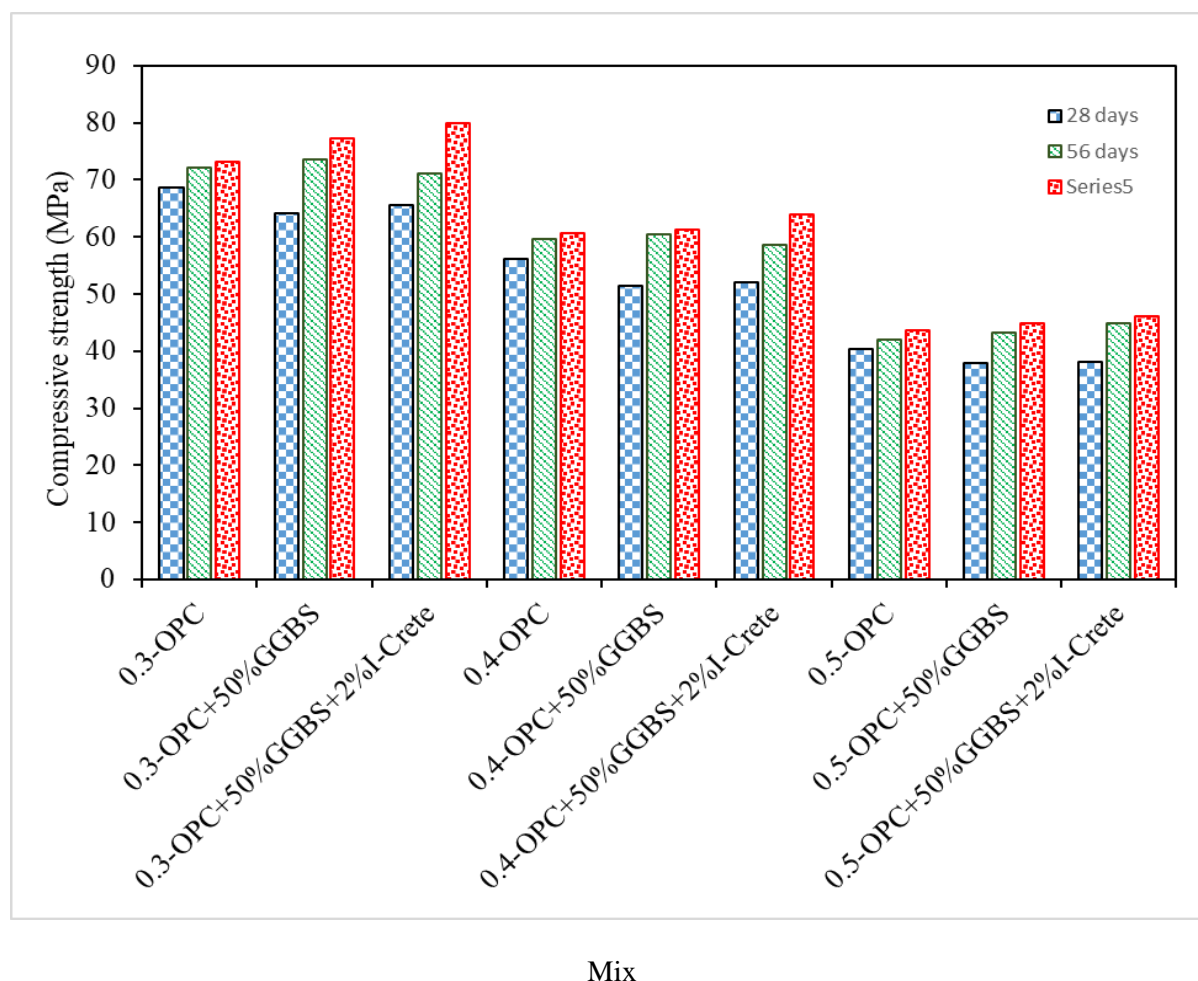


Fig.1: Compressive strength of concretes

Chloride content at various depths:

The chloride content at various depths (by wt. of concrete) with various w/cm ratios (0.3, 0.4, and 0.5) and exposure duration (6 and 12 weeks) is shown in Fig. 2. The chloride content for concretes incorporating both GGBS and Icrete is least among all the mixes regardless of w/cm ratio and exposed duration. The chloride content for controlled mix shows higher chloride content than other mixes regardless of w/cm ratio and exposed duration. The chloride concentration gets increased with increase in duration of exposure and w/cm ratio. The reduction in chloride content for concretes incorporating SCMs (GGBS and Icrete) is due to the blocking of path for diffusion of chloride by pore filling effect as they are finer than cement particles, and the secondary pozzolanic reaction which converts calcium hydroxide to CSH gel which contributes for the pores refinement [11].

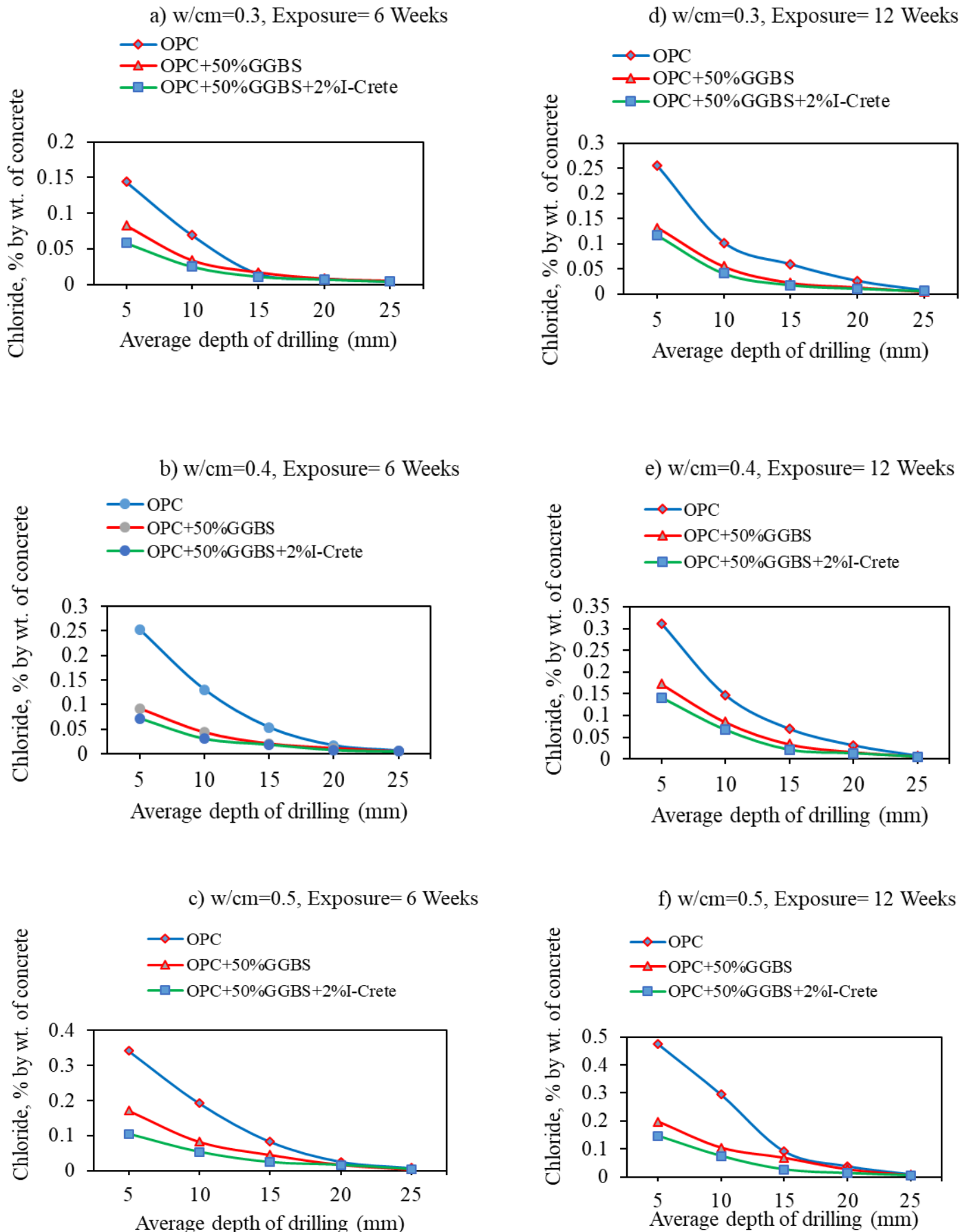


Fig.2: Chloride concentration at various depth, w/cm ratio, and exposure duration

Diffusion coefficient:

As shown in Table 5, the diffusion coefficient and surface chloride concentration for concretes incorporating both GGBS and Icrete (i.e. mix 3, 6, and 9) is less than other mixes at both 6 weeks and 12 weeks of exposure to the 3.5% salt solution. The least diffusion coefficient and surface chloride concentration is for mix 3 (concrete incorporating both GGBS and Icrete at w/cm = 0.3) at both 6 and 12 weeks of exposure due to pore refinement and densification of the concretes. Similarly, the highest diffusion coefficient and surface chloride concentration is for mix 7 (controlled concrete at w/cm = 0.5) at both 6 and 12 weeks of exposure.

Table 5: Diffusion coefficient and surface chloride concentration of the concrete

Diffusion coefficient (m ² /s)			Surface chloride concentration (% by weight of concrete)	
Mix	6 weeks	12 weeks	6 weeks	12 weeks
1	8.76×10 ⁻¹²	3.43×10 ⁻¹²	0.27	0.5348
2	7.05×10 ⁻¹²	3.40×10 ⁻¹²	0.1704	0.2768
3	6.89×10 ⁻¹²	2.91×10 ⁻¹²	0.119	0.2646
4	1.16×10 ⁻¹¹	8.80×10 ⁻¹²	0.4322	0.5942
5	8.39×10 ⁻¹²	4.67×10 ⁻¹²	0.1768	0.3188
6	7.80×10 ⁻¹²	4.14×10 ⁻¹²	0.142	0.2714
7	1.51×10 ⁻¹¹	9.99 ×10 ⁻¹²	0.538	0.7004
8	9.33×10 ⁻¹²	5.67×10 ⁻¹²	0.3144	0.3404
9	8.62 ×10 ⁻¹²	4.89 ×10 ⁻¹²	0.1982	0.2648

Service life predictions

In this paper the chloride content 0.4% by wt. of cement is taken as the critical chloride content and the cover of concrete is taken as 75mm. The time taken to accumulate the critical chloride content at the depth of 75mm (concrete cover) is taken as the initiation time for corrosion. Service life of all concrete mixes is determined based on the initiation time and is presented in Table 7 where three different models namely Andrade's, FIB, and DuraCrete models are used for determining the initiation time. The calculated service life of concretes incorporating both GGBS and Icrete (mix 3, 6, and 9) is comparatively higher than other concretes. Similarly, the service life of controlled concretes (mix 1, 4, and 7) is lower than that of the concretes incorporating GGBS (mix 2, 5, and 8) only and along with Icrete. (-) values shows the model is not applicable for that mix and value obtained is discarded. Input values and calculated service life of the concretes are presented in the Table 6 for Andrade's, FIB, and DuraCrete models below for the mix, i.e., the mix incorporating both GGBS and Icrete at 0.3 w/cm. The service life of concrete obtained from the FIB model is applicable for concretes incorporating SCMs and the obtained service life for that concrete is greater than those obtained from the Andrade's and DuraCrete model.

Table 1: Input Parameters and calculated Service life

Models	Input parameters			Calculated service life (years)
Andrade's model	Relative humidity (%)	UR	75	431.4
	Temperature (°C)	T	32	
	Environmental chloride conc (%)	Cl	3.5	
	Factor type of cement	K ₁	0.98	
	Compressive strength MPa (28 days)	f _{ck}	65.54	
	Factor admixture type	K ₂	1	
	Amount of admixture in conc. (%)	Ad	52	
FIB model	Cover depth (m)	x	0.075	520
	Surface chloride content (% by wt. of	C _{s,o}	2.78	

	cement)			
	Test method variable	k_t	1	
	Reference concrete age (days)	t_o	28	
	Concrete age (years)	t	2200	
	Age exponent (for GGBS concrete)	a	0.45	
	Chloride migration coefficient (mm^2/s)	$D_{\text{RCM},0}$	$1.0\text{E}-12$	
	Regression variable (K)	b_e	4800	
	Standard reference temperature (K)	T_{ref}	293	
	Temperature of surrounding (K)	T_{real}	305.37	
	apparent chloride diffusion coefficient (mm^2/s)	D_{app}	$1.91\text{E}-14$	
	Ageing function	$A(t)$	0.00986	
DuraCrete model	Surface chloride concentration (% by wt. of cm)	$C_{\text{S,cl}}$	1.8216	970
	Eigen value of critical chloride concentration (% by wt. of cm)	C_{cr}	2.3	
	Fractional coefficient of critical chloride concentration	γ_{Ccr}	1.03	
	Regression coefficient	$A_{\text{CS,cl}}$	5.06	
	Water binder ratio	w/b	0.3	
	Fractional coefficient of Cl concentration at the surface of concrete	$\gamma_{\text{CS,cl}}$	1.2	
	Cover thickness (mm)	x	75	
	Construction deviation for cover thickness (mm)	Δx	8	
	Fractional coefficient of Cl ion diffusion	γ_{Rcl}	1.5	
	Environmental influencing factor	$k_{\text{e,cl}}$	3.88	
	Curing coefficient of Cl	$K_{\text{e,cl}}$	0.79	
	Chloride ion diffusion coefficient (mm^2/year)	$D_{\text{RCM},0}$	91.646	
	Testing time for diffusion (year)	t_0	0.25	
	Degradation coefficient of Cl diffusion	n_{cl}	0.71	
	Design life span of structure (year)	t	9.27	
	Load factor	k_s	1	
	Temperature factor	k_t	1.249	
	in (Kelvin)	T	298	
	in (Kelvin)	T_0	293	
	in (Kelvin)	q	3600	

Table 2: Calculated service life of concretes using prediction models

Service life of concretes (in years)			
Mix ID	Andrade's model	FIB model	DuraCrete model
1	137.92	-	547
2	407.9	482	568
3	431.4	520	970
4	91.95	-	-
5	261.9	117	189
6	265.9	155	286
7	-	-	-
8	142.37	72	97.2
9	144.57	93	161

CONCLUSIONS

From the obtained test results and used service life prediction models, the following conclusions are drawn:

- i. The chloride ion concentration at various depths is the function of time. As time increases, the chloride ion concentration increases. The chloride ion concentrations are lower for concrete incorporating both GGBS and Icrete for various depths than controlled concrete and concrete incorporating GGBS only as the replacement.
- ii. Concrete's diffusion coefficient is time dependent. The diffusion coefficient decreases with increasing time. The diffusion coefficient for concretes incorporating both GGBS and Icrete is lower than that of controlled concrete and concrete incorporating GGBS only as the replacement.
- iii. The service life of concretes obtained from all three models indicates that the service life is higher for concretes incorporating both GGBS and Icrete than that of controlled concrete and concrete incorporating GGBS only as the replacement.
- iv. The compressive strength of concretes incorporated with GGBS and Icrete is more at the age of 90 days than the controlled concrete.

ACKNOWLEDGMENTS

The authors thank Koneru Lakshmaiah Educational Foundation and Amazecrete Pvt. Ltd. for their support and for supplying the necessary resources.

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