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Service Life Prediction of Concretes Incorporated with Fly Ash and Alccofine with respect to Chloride Ion Penetration

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Abstract

Chloride-induced corrosion poses a significant threat to the degradation of reinforced concrete structures, especially in extreme environments such as marine and industrial exposure conditions, where the damage can be particularly severe. This study provides an experimental investigation utilizing three distinct water-binder ratios (0.3, 0.4, and 0.5) applied to three types of concrete mixtures: conventional concrete, concrete blended with 40% fly ash, and concrete blended with 40% fly ash and 2% alccofine as a replacement by weight of total cementitious materials. The primary objective is to assess the impact of these variations on critical performance indicators, including chloride ion penetration at various depths, surface chloride ion concentration, chloride diffusion coefficient, and compressive strength. By comparing specified properties across different concrete compositions, the study seeks to clarify the importance of these supplementary materials in mitigating chloride-induced corrosion. Particularly noteworthy is the evaluation of chloride ion penetration at various depths and the determination of surface chloride ion concentration and diffusion coefficient, contributing to an understanding of the performance of these concrete mixtures. The concrete incorporating fly ash and alccofine shows a good result in improving compressive strength and the resistance of chloride ion diffusivity for the water-to-binder ratio of 0.3.

Keywords: *Chloride-induced corrosion, chloride diffusion coefficient, Fly ash, Alccofine, Service life prediction*

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INTRODUCTION

The service life of reinforced concrete structures in ocean and industrial areas is primarily determined by the rate of degradation caused by reinforcement corrosion. The presence of corrosion products such as oxides and hydroxides in the pores of concrete near the rebar will build up the hoop stresses around the steel reinforcement, ultimately inducing cracks or spalling in the concrete. This, in turn, infiltrates the moisture, oxygen, and chlorides needed to embed the reinforcement. Chloride ion intrusion is a significant cause of the deterioration of critical infrastructure. Once the chloride concentration within the concrete exceeds a specific threshold value determined by various material and environmental factors, corrosion of the reinforced steel begins. This degradation poses a threat to structural integrity by reducing the cross-sectional area of the reinforcing steel and compromising the bond between the steel and concrete interface [1]–[6].

The cement matrix in concrete creates a highly alkaline environment. It protects the reinforcing bars chemically by forming a protective passive layer, or oxide film, on the surface of the reinforcing bars [7]. The concrete cover serves as a physical barrier, preventing dangerous chemical compounds like chloride ions from entering the concrete [1]. However, when a sufficient amount of chloride reaches the reinforced bars the passivating layer can experience a localized breakdown, leading to an initiation of the corrosion process [2], [8]. The chloride ions will infiltrate into the hardened concrete through capillary suction or diffusion, whereas capillary suction will transport the chloride ions faster than the diffusion process [9].

Chlorides in concrete can be chemically and physically bonded to cement hydrates and surfaces (bound chlorides) or as free ions in pore solution (free chlorides). It is considered that the initiation of corrosion takes place only due to free chlorides that are dissolved in the pore solution, as these free chlorides will penetrate through the concrete cover. Thus, the bound chlorides are harmless to concrete [2], [9], [10]. The chloride ion diffusion coefficient determines the rate of chloride infiltration into the concrete, which changes with exposure time [4]. In general, to measure the chloride diffusion coefficient in concrete, there are two ways of penetration tests: the diffusion cell test, known as the steady-state diffusion test, and the salt ponding test, known as the non-steady state test [5].

Concrete durability can be increased by using appropriate concrete cover and high-quality concrete. Thus, to achieve good durability for concrete structures, the pore filling of the concrete plays an important role. The increase in the concrete cover's resistance often has beneficial results, as it lengthens the time for initiation of corrosion because it improves the barrier by preventing various aggressive species from moving towards the reinforcement. For this pore filling, the blending of supplementary cementitious materials (SCMs) with cement plays a key role in filling the pores of the concrete, as the fineness of the SCMs is much finer than the cement fineness. The addition of SCMs has shown an increase in concrete durability, a decrease in chloride ion penetration, and an improvement in the pore size distribution. Adding these SCMs to the concrete is a wider advantage as some of the materials are cheaper than Portland cement, which shows the potential benefit to the environment [5].

SCMs like fly ash and Alccofine offer significant advantages when incorporated into concrete. Blending of fly ash and alccofine to the cement in concrete will react with calcium hydroxide pozzolonically and produce additional calcium-silicate hydrates (C-S-H) gel, which provides a refined pore structure and reduces the permeability of concrete [11], [12]. Fly ash is an industrial by-product obtained from thermal power plants, where only a portion of it is being used in the concrete, either as a partial replacement or by blending it with Portland cement. Normally, fly ash is replaced at very low levels of 15-20% in Portland cement, however, many authors have suggested that a replacement of fly ash between 40-60% shows greater resistance to chemical attacks such as alkali-silica reaction, chloride ion penetration, and sulfate attack and reduces the permeability of the concrete, and provides good strength to the concrete [13]. Alccofine is a new generation, a micro fine substance with a significantly smaller size of particles than conventional hydraulic materials like fly ash and cement, which is obtained as a byproduct of the iron ore industry [12].

The cement mixture utilized, the water-to-binder (w/b) ratio, the duration of curing, exposure length, and other physical properties all have an impact on chloride penetration to the concrete [4]. Using fly ash and alccofine, a compact interfacial zone forms between the aggregates and the matrix. Concrete incorporating fly ash and alccofine shows greater resistance to harmful chloride ions penetration [3]. The replacement of fly ash in concrete doesn't play any role within 28 days because of its slow pozzolanic reaction, so 28 days will not be the realistic reference time for the prediction of the service life of concrete blended with fly ash. 28 days will be the reference time for the prediction of the service life of Portland concrete as Portland cement concrete matures at the age of 28 days [11].

This study seeks to assess the beneficial effect of cement blended with fly ash and alccofine on the diffusivity of chloride ions and the development of compressive strength in the resulting concrete to varying water-to-binder ratios. The accelerated chloride diffusion test method, specifically the salt ponding test, is used for this study.

MATERIALS AND TEST METHODS

Materials:

The materials used in the present study were as follows: ordinary Portland cement (OPC 53 grade) (specific gravity: 3.12), fly ash (specific gravity: 2.12), and alccofine (specific gravity: 2.03) were used as a cementitious material, and natural river sand (N-Sand) (specific gravity: 2.76), manufactured sand (M-Sand) (specific gravity: 2.56) have been used as a fine and coarse aggregate of two distinct sizes:20mm beneath (specific gravity: 2.86), 10mm down was used. A poly carboxylate-based super plasticizer named Hi-Forza 369 was used. Table 1 presents the chemical composition of OPC 53 grade, fly ash, and alccofine.

Table 1: *The Chemical compositions of OPC, Fly ash, and Alccofine (%)*

Type	**CaO%**	**SiO_2%**	**Al_2O_3%**
OPC	62.3	22.6	4.2
Fly ash	1.4	60.5	30.8
Alccofine	30	30	20

Mix Proportioning:

For this experimental work, several number of trials have been carried out to get good workability and a uniform mix throughout the work, based on the trial and error method the water content is fixed at 160 Kg/m3 for all nine mixes. The fly ash is replaced at 40% by the weight of total cementitious material for the mix series of B and C in all the three water-to-binder ratios and alccofine is replaced at 2% by the weight of total cementitious material for the mix series of C in all the three water-to-binder ratios. Table 2 represents the mix proportioning values per 1m3 of concrete.

Table 2: *Mix proportioning per 1m^3 of concrete*

Mix Designation	**W/B Ratio**	**Water Content (Kg)**	**Cement Content (Kg)**	**Fly Ash (Kg)**	**Alccofine (Kg)**	**SP (Kg)**	**Fine Aggregate**		**Coarse Aggregate**	
							M-Sand (Kg)	**N-Sand (Kg)**	**20mm (Kg)**	**10mm (Kg)**
A1	0.3	160	533	0	0	3.5	208.63	387.46	694.26	462.84
B1		160	320	213	0	3.5	208.63	387.46	694.26	462.84
C1		160	309	213	10.67	3.5	208.63	387.46	694.26	462.84
A2	0.4	160	400	0	0	2.6	224.60	417.12	747.41	498.27
B2		160	240	160	0	2.6	224.60	417.12	747.41	498.27
C2		160	232	160	8.00	2.6	224.60	417.12	747.41	498.27
A3	0.5	160	320	0	0	2.1	234.18	434.91	779.30	519.53
B3		160	192	128	0	2.1	234.18	434.91	779.30	519.53
C3		160	186	128	6.40	2.1	234.18	434.91	779.30	519.53

Sample Preparation and Cast:

The cast iron moulds have been used for the preparation of samples of size 150 mm X150 mm X150 mm. A total of eleven cubes have been cast for each of the nine mixes for this work. Initially, all the cube moulds were cleaned and applied with grease inside the moulds. The drum mixer has been for mixing all the concrete, for all mixes. The drum mixer is cleaned initially to avoid absorption of water. The concrete materials were added to the mixer one on one based on their respective proportions and mixed thoroughly until a uniform mix was obtained. The concrete is filled into the moulds in two layers, each of the layers has been vibrated to remove entrapped air content in the concrete. The cube specimens were kept aside for 24 hours for conventional concrete and the concretes blended with fly ash and alccofine were kept aside for 48 hours as the rate of hydration is slow in fly ash concrete so, setting time for the fly ash is very high, these cube specimens were covered by wet jute bags for curing. The specimens were demoulded after their respective time and then the specimens were transferred to the curing tank.

TEST METHODS

The tests were carried out as per the Indian standard specifications for all specimens. For this experimental work, the tests conducted are compressive strength and chloride diffusion tests.

Compressive strength Test:

The cube specimens were tested at 28, 56, and 84 days as per the IS specification 516 [14]. From each of the mix, three cube specimens were tested and the average of those three specimens was considered as compressive strength for the respective number of days.

Chloride Ion Penetration Test:

Initially, the specimens were cured for 28 days in a normal curing tank then the specimens were exposed to a 3.5% NaCl solution. These cubes were tested at 6 weeks and 12 weeks by extracting the powder from the cubes by drilling. The powder was extracted at various depths. The IS specification 14959 (Part-2):2001 [15] was used for determining the total chloride ion concentration at various depths. For determining the surface chloride concentration the plot between chloride ion concentration (in the Y-axis) and their respective depths (in the X-axis) was considered. By best fitting the curve the surface chloride ion concentration was determined. By using Fick's second law equation the chloride ion diffusion coefficient was determined using equation 3.

Fick is the first person to put diffusion on a quantitative basis by considering heat conduction through a mathematical equation. Therefore, the mathematical theory regarding diffusion in isotropic substances is based on the assumption that the amount of transfer of a diffusing material over a unit area of an element depends on the concentration gradient measured normal to the section, i.e.

$$F=-D\ \partial C/\partial x \qquad (1)$$

Here F is the rate of transfer per unit area of section, C is the concentration of the diffusing substance and D is known as the diffusion coefficient. Fick’s second law of equation can be given as:

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

If we apply boundary conditions C(x, t=0) = C0, and C(x=0, t>0) =Cs then equation 2 becomes,

$$C(x,\ t) = Cs\ [1-\mathrm{erf}(x/(2\sqrt{Dt}))] \qquad (3)$$

Here Cs is the surface chloride content and erf is the error function [16].

Prediction Models:

Table 3 shows the existing models for predicting the service life of concretes with respect to chloride ion penetration.

Table 3: *Service life Prediction models*

Model	Governing Equations	Highlights of the model
FIB [17]	$C_{crit} = C(x=a,t) = C_0 + \left(C_{S,\Delta x} - C_0\right)\left[1 - erf\,\frac{a-\Delta x}{2\sqrt{D_{app,c}t}}\right]$ By using the below equation the chloride diffusion apparent coefficient can be determined for the concrete: $D_{app,c} = k_e D_{RCM,0}\, k_t\, A(t)$ $k_e = exp\left(b_e\left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right)$	The diffusion coefficient is time-dependent and surface chloride concentration is considered as constant.

	$A(t)=\left(\frac{t_0}{t}\right)^{a}$ C_{crit}=critical chloride content [wt.-%/c], $C(x,t)$=content of chlorides in the concrete at a depth x and time t, C_0=initial chloride content of the concrete, $C_{S,\Delta x}$=chloride content at a depth Δx and a certain point of time t, x=depth with respect to corresponding chloride ion concentration $C(x,t)$[mm], a=concrete cover [mm], Δx=depth of the convection zone [mm], $D_{app,C}$=apparent coefficient of chloride diffusion through concrete [mm^2/year], t=time [years], erf=error function, k_e=environmental transfer variable[-], b_e=regression variable [K], T_{ref}=standard test temperature [K], T_{real}=temperature of the structural element or the ambient air, $D_{RCM,0}$=chloride migration coefficient [mm^2/a], k_t=transfer parameter [-], $A(t)$=sub function considering the ‘ageing’ [-], t_0=reference point of time [years].	
DuraCrete [18][19]	$C(Z,t)=C_s\left[1-erf\frac{Z}{2\sqrt{k_eXk_tXk_cXD_0X\left(\frac{t_0}{t}\right)^{n}Xt}}\right]$ D_0=diffusion coefficient at a reference time t_0 t_0=reference time in days k_e=environmental variable correcting D_0 k_t=test variable correcting D_0 k_c=execution variable correcting D_0 n=age factor which depends on the time D_0 t=the exposure period Z=depth to corresponding chloride ion concentration C_s=Surface chloride ion concentration at the concrete surface The below equation shows the time for corrosion initiation at the reinforcement layer. So, Z in the above equation is replaced by d, which is the cover depth of concrete. $T_{cl}=\left(\frac{d^2}{4Xk_eXk_cXk_tXD_0X(t_0)^n}X\left(erf^{-1}\left(1-\frac{C_{CR}}{C_S}\right)\right)^{-2}\right)^{\frac{1}{1-n}}$ C_{CR}=critical threshold value	The diffusion coefficient is time-dependent and the surface chloride concentration is considered as constant.
Mangat et.al [20]	$C(x,t)=C_0\left[1-erf\left(\frac{x}{2\sqrt{D_ct}}\right)\right]$ The relationship between D_c and time can be given by an empirical relationship of the form: $D_c=D_it^{-m}$ $m=2.5\left(\frac{w}{c}\right)-0.6$	The diffusion coefficient D_c in the experimental data is time-dependent.

	To predict the long-term chloride concentration in the materials, the time dependence of the diffusion coefficient D_c needs to be incorporated in Fick's second law of diffusion. $C(x,t) = C_0\left[1 - erf\left(\frac{x}{2\sqrt{\frac{D_i}{(1-m)}t^{(1-m)}}}\right)\right]$ x=distance from the concrete surface (cm), t=time (sec), D_c=diffusion coefficient (cm^2/s), C_0=equilibrium chloride concentration on a concrete surface, D_i=effective diffusion coefficient at time t is equal to 1 second, m=empirical constant	
Chalee et.al [21]	$\frac{\partial C}{\partial t} = D_c \frac{\partial^2 C}{\partial x^2}$ The relationship between D_c and exposure time t can be approximated by an empirical relationship in the form of an inverse exponential function: $D_c = (t)^{-\beta}$ $\frac{\partial C}{\partial t} = t^{-\beta}\frac{\partial^2 C}{\partial x^2}$ The general solution can be written as: $C_{x,t} = C_0\left[1 - erf\left(\frac{x}{2\sqrt{\frac{t^{(1-\beta)}}{(1-\beta)}}}\right)\right]$ The $C_{x,t}$ can be determined by evaluating the β and C_0 values using the best fit of the chloride penetration profile curves. $\beta = \delta(F) + \emptyset$, $C_0 = \alpha In(t) + \gamma$ $C_{x,t}$=total chloride concentration (% by weight of binder), t=exposure time (years), x=distance from the concrete surface (mm) C_0=chloride concentration at the concrete surface, $\beta, \delta, \emptyset, \alpha, \gamma$=empirical coefficients F=fly ash replacement (%)	The diffusion coefficient D_c in the experimental data is time-dependent.
Harilal et.al [22]	$C(x,t) = C_s - (C_s - C_i)Xerf\left(\frac{x}{\sqrt{4XD_{cl}Xt}}\right)$ $C(x,t)$=chloride concentration measured at depth x C_s=surface chloride concentration C_i=initial chloride concentration $D_{cl}(t) = D_{cl}X\left(\frac{t_0}{t}\right)^m$, $m = 0.2 + 0.4\left(\frac{\%\ of\ fly\ ash}{50}\right)$ $D_{cl}(t)$=the apparent chloride diffusion coefficient at age t (days) D_{cl}=apparent chloride coefficient for concrete t_0= 28 days t= age of the specimen in days m=decay constant/maturity coefficient	The initial chloride concentration is considered as zero in this study. D_{cl} is considered a time-variant function. The value of m is considered as 0.6, as it is the maximum decay constant allowed.

Clinconc [23]	$C(x,t) = C_{ini} + (C_s - C_{ini})\left[1 - erf\left(\frac{x}{2\sqrt{D_{F2}t}}\right)\right]$ $C(x,t)$=chloride concentration at depth x after exposure period t, C_{ini}=initial chloride concentration in the concrete, C_s=chloride concentration at the exposure surface, D_{F2}= chloride diffusion coefficient	The initial chloride concentration in the experimental data is considered as zero.
Probabilistic [24]	$C(x,t) = (C_s - (C_s - C_i)\left[erf\frac{x}{2\sqrt{D_{app}(t).t}}\right]$, $D_{app}(t) = D_{app}(t_0)\left(\frac{t_0}{t}\right)^{\alpha}$ $C(x,t)$=content of chlorides in the concrete at a depth x (structure surface: x=0m) and at time t [wt. %/c], C_s=surface chloride ion concentration at the concrete surface [wt. %/c], C_i=initial chloride content [wt. %/c], x=depth with respect to corresponding chloride ion concentration $C(x,t)$ [mm], $D_{app}(t)$=apparent coefficient of chloride diffusion through concrete [mm^2/years] at time t, α= ageing factor giving the decrease over time of the apparent diffusion coefficient.	The initial chloride concentration for this investigation has been set as zero.
LIGHTCON [25], [26]	The chloride diffusion coefficient after 1 year of exposure from knowing the equ(w/c) can be expressed by the relation: $D_1 = 25000k_D\ X\ exp\left(-\sqrt{\frac{10}{eqv\left\{\frac{w}{c_D}\right\}}}\right)$ Where the equivalent w/c ratio with reference to diffusion is: $eqv\left\{\frac{w}{c_D}\right\} = \frac{W}{PC+FA+7X\ SF}$ Time dependency of the achieved chloride diffusion coefficient D_a can be expressed mathematically by the power function: $D_a(t) = D_1X\left(\frac{t}{t_1}\right)^{-\alpha} = D_1t^{-\alpha}$ $\alpha = k_\alpha X(1 - 1.5\ X\ eqv\left\{\frac{w}{c_D}\right\})$, $C_1 = k_b\ X\ eqv\left\{\frac{w}{c_b}\right\}$, $eqv\left\{\frac{w}{c_b}\right\} = \frac{W}{PC + 0.75\ X\ FA - 1.5\ X\ SF}$ W=water content PC=Portland cement FA=fly ash SF=silica fume t_1=1year t denotes the time (origin equal to the first chloride exposure of the concrete) D_1 Achieved chloride diffusion coefficient at 1 year after the first chloride exposure α is an exponent (age parameter)	The chloride diffusion coefficient D is time-dependent. The LIGHTCON model assumes that the chloride diffusion coefficient D is independent of the locality x and the chloride content though it may depend on time.
Andrade's [27]	The mathematical representation of the Andrade's model is: $y_{0.4\%} = k_{Cl}\ X\ t^b$	This model requires real degradation data

	Here, $y_{0.4\%}$ is the depth of the chloride ion penetration in concrete k_{Cl}=Chloride coefficient (cm^2/year) t=time in years The chloride coefficient k_{Cl} represents the first-year ingress of the critical chloride concentration C_{cr} into the concrete The penetration can be represented in a generic form by the below equation: $y_{0.4\%} = [f(f_{ck}, UR, T, Cl, K_1, K_2, Ad)]\ X\ t^b$ The general form of the model proposed is shown in the below equation: $y_{0.4\%} = \frac{K_0\ X\ UR^{b_1}\ X\ T^{b_2}\ X\ Cl^{b_3}}{K_1\ X\ f_{ck}^{b_4}\ X\ K_2\ X\ (1+Ad)^{b_5}}\ X\ t^{b_6}$ Where K_0 is the general constant $b_1 - b_6$ is the variable coefficients The final model can be represented by non-linear regression, $y_{0.4\%} = \frac{7.35\ X\ UR^{0.7}\ X\ T^{0.1}\ X\ Cl^{0.7}}{K_1\ X\ f_{ck}\ X\ K_2\ X\ (1+Ad)^{0.2}}\ X\ \sqrt{t}$ Where $y_{0.4\%}$ is the position of critical chloride concentration C_{cr} from the concrete surface (mm) UR= the relative humidity of the atmosphere (%) T =the environmental temperature (°C) Cl = the environmental chloride concentration (%) K_1 = the factor based on the cement used f_{ck}=compressive strength (28 days) (MPa) K_2 = the factor based on the admixture used Ad=the admixture content in concrete (%) t is the time (years)	or natural test data from concrete degradation due to chloride penetration. The maximum amount of chloride that can be allowed in a structural element at the reinforcement level is 0.4% by cement mass.

For this study, to predict the service life of concretes with respect to chloride ion penetration, the LIGHTCON, FIB, and Andrade models were used.

RESULTS AND DISCUSSIONS

Compressive Strength:

The compressive strength results are shown in Fig. 1. At 28 days the conventional concrete showed a good result which was 68.72 MPa concrete blended with 40% fly ash was 60.34 MPa and concrete blended with 40% fly ash and 2% alccofine was 61.57 MPa. The concrete blended with fly ash and alccofine at 40% and 2% showed good compressive strength development at 84 days which was 78.27 MPa, whereas the concrete blended with fly ash at 40% was 74.85 MPa and for the conventional concrete was 71.43 MPa. According to the results, the strength of the concretes incorporating fly ash and alccofine improves as the curing time increases. The concrete incorporating fly ash and alccofine has an excellent pore-filling action, which contributes to its comparatively high strength development. The use of finer materials increases the durability of the concrete. The use of a low water-to-binder ratio results in satisfactory strength growth.

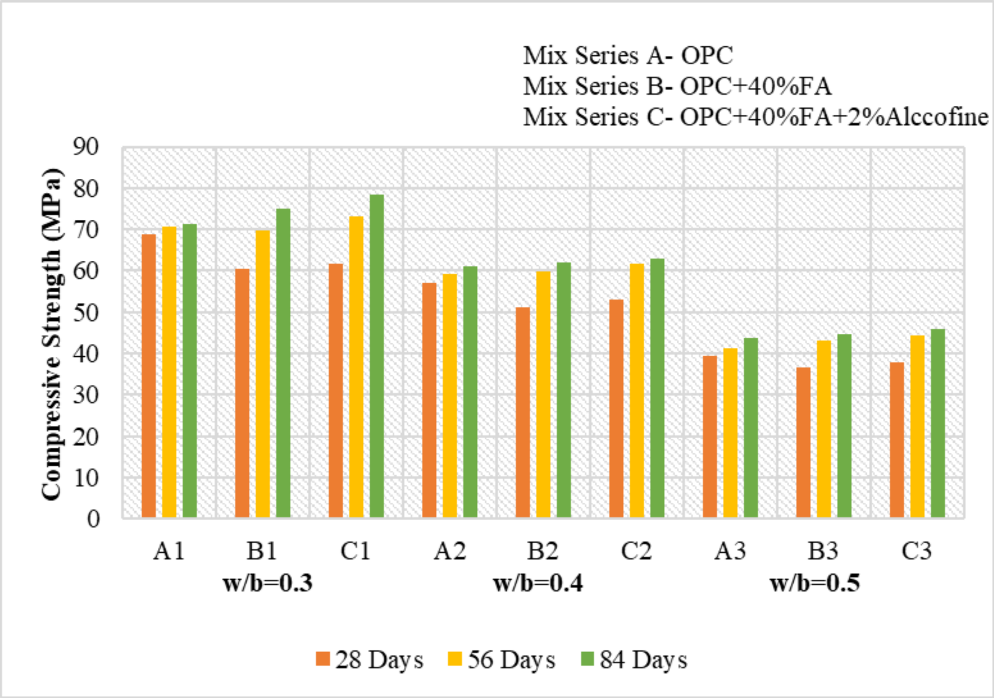
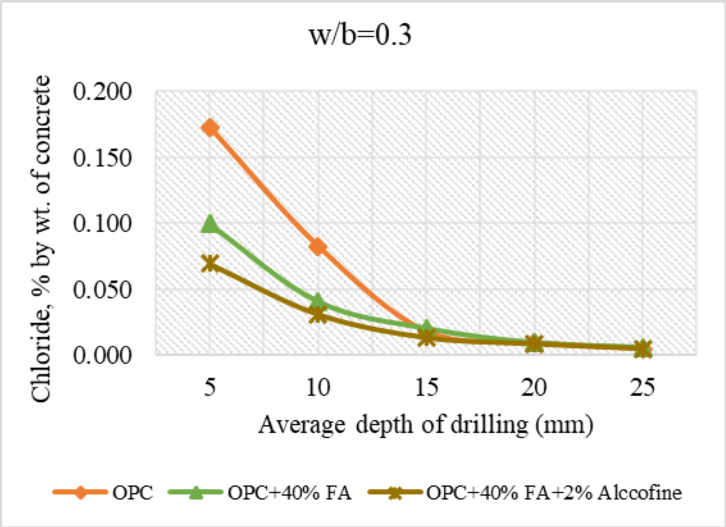
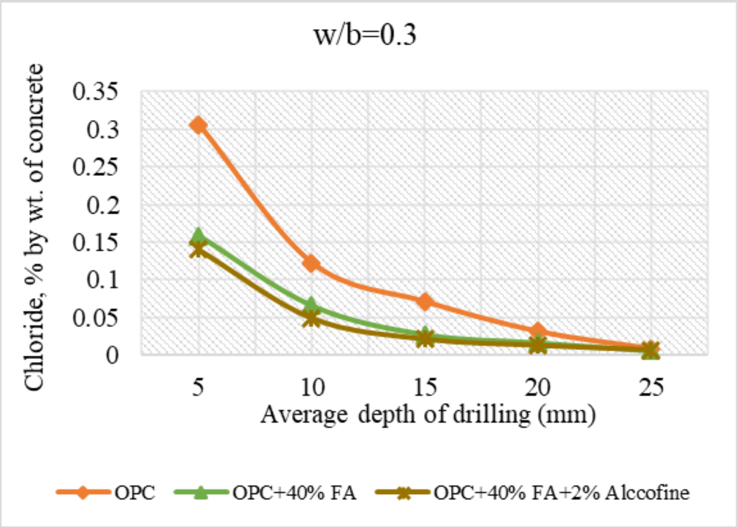


Fig. 1: *Compressive strength of concretes*

Chloride content at various depths:

After exposing the cube specimens to 3.5% NaCl solution for 6 weeks and 12 weeks the results are shown in Fig. 2. For the water-to-binder ratio of 0.3, the results show that the incorporation of fly and alccofine show good resistance to chloride ion penetration into the concrete at 6 weeks and 12 weeks. Thus the addition of fly ash and alccofine in the concrete shows a greater pore filling than the conventional concrete and concrete blended with fly ash and it also shows that the use of less water-to-binder ratio is much more effective in achieving good resistance to the chloride ion penetration. The dense texture of the concrete provides enhanced durability against chloride ion penetration.

Exposure Period: 6 Weeks	**Exposure Period: 12 Weeks**
	

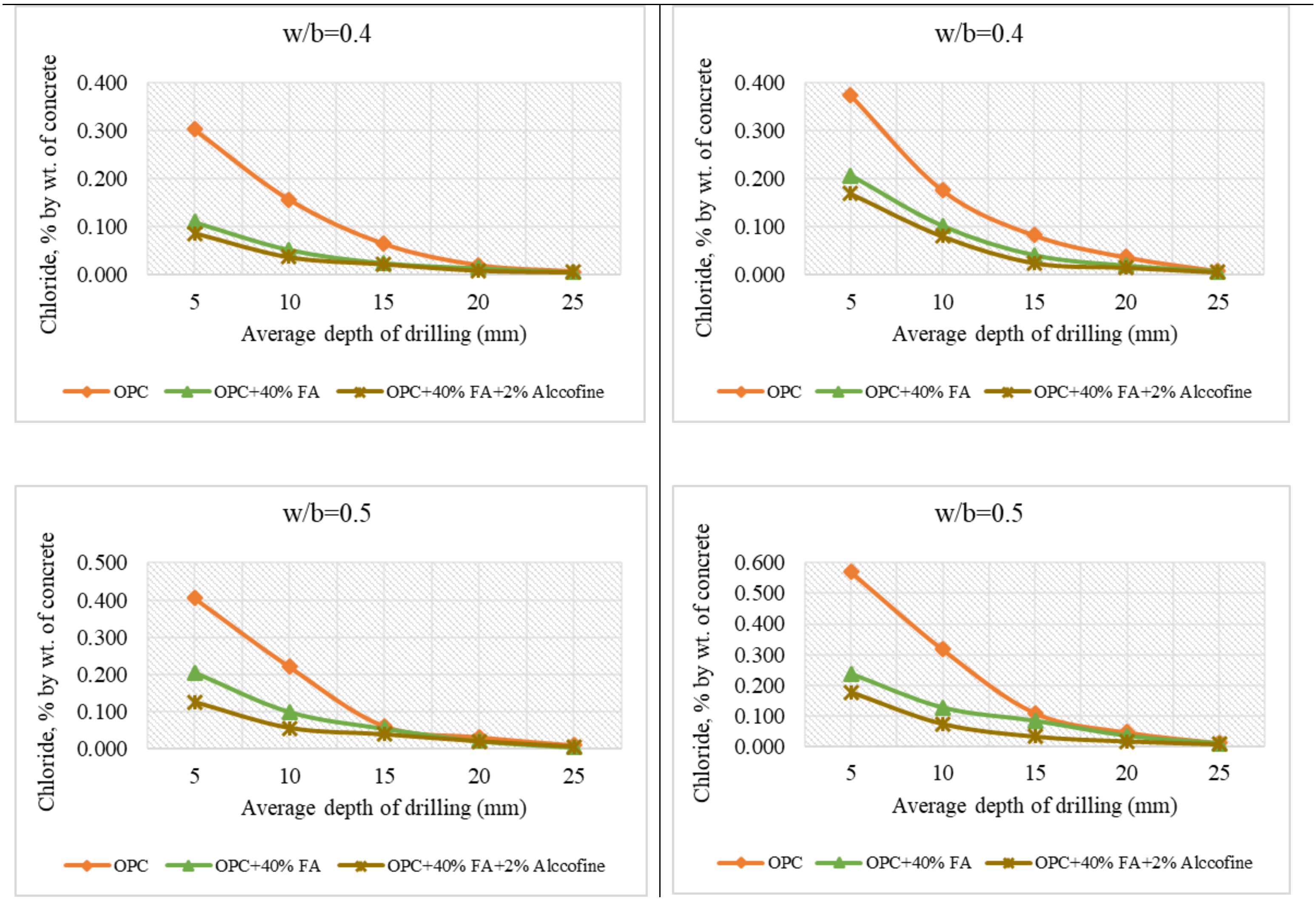


***Fig. 2:** Chloride content at various depths*

Surface Chloride Concentration: [%/weight of concrete]
The surface chloride ion concentration of concretes is given in Table 4. The cube specimens were exposed to 3.5% NaCl solution and tested on 6 weeks and 12 weeks of period. The results indicate that the concrete blended with fly ash and alccofine has a very low surface chloride concentration very low compared to the other concretes.

***Table 4:** Surface Chloride Concentration*

Mix Designation	6 Weeks	12 Weeks
A1	0.3240	0.6418
B1	0.2045	0.3322
C1	0.1400	0.3175
A2	0.5186	0.7130
B2	0.2122	0.3826
C2	0.1704	0.3257
A3	0.6898	0.9445
B3	0.3773	0.4085
C3	0.2542	0.3648

Chloride ion diffusion coefficients:

The chloride ion diffusion coefficients of concrete are given in Table 5 at an exposure period of 6 and 12 weeks. The diffusion coefficient values lie between 10-11m2/s to 10-12m2/s. The incorporation of fly ash and alccofine shows a beneficial effect on the rate of chloride ion diffusion.

Table 5: *Chloride ion diffusion coefficients*

Mix Designation	6 Weeks (m^2/s)	12 Weeks (m^2/s)
A1	8.85988X10^{-12}	3.39962X10^{-12}
B1	7.45721X10^{-12}	3.39287X10^{-12}
C1	7.02392X10^{-12}	2.90643X10^{-12}
A2	1.15382X10^{-11}	4.25954X10^{-12}
B2	8.38837X10^{-12}	4.62673X10^{-12}
C2	7.80399X10^{-12}	4.11994X10^{-12}
A3	1.16602X10^{-12}	6.39912X10^{-12}
B3	9.36087X10^{-12}	5.69521X10^{-12}
C3	7.43168X10^{-12}	3.51746X10^{-12}

Service life prediction of concretes:

For the present study, the threshold chloride concentration has been determined as 0.4.% by weight of cement and the concrete cover is taken as 75mm as per IS 456. The time taken to obtain the necessary chloride concentration at a cover depth of 75mm is considered the corrosion initiation period. Table 6 shows the input parameters and service life prediction. Table 7 shows the calculated service life for concretes using LIGHTCON, FIB, and Andrade's model.

Table 6: *Input Parameters and Service life prediction*

Input Parameters	Notation	Units	Values
LIGHTCON Model:			
Water content	W	Kg/m^3	160
Portland cement	PC	Kg/m^3	309.34
Fly ash	FA	Kg/m^3	213.34
Alccofine	Al	Kg/m^3	10.67
Time of first exposure to chloride year	t	Year	0.076
Calculated Parameters			
Diffusion coefficient after one year of exposure	D_1	mm^2/yr	49.80
Equivalent water/binder ratio	eqv{w/b}	-	0.25
Age parameter	α	-	0.36
Development of achieved chloride diffusion coefficient	D_a	mm^2/yr	127.89
Surface chloride content after one year of exposure	C_1	-	1.81
Chloride ingress in the first year	k_1	mm	14.54
Time to reach the critical chloride content		Years	180.051
FIB Model:			
Chloride content at a depth Δx and a certain point of time t	$C_{s,\Delta x}$	-	2.78
Concrete cover depth	a	m	0.075
Transfer parameter	k_t	-	1
Ageing exponent	a	-	0.6
Chloride migration coefficient	$D_{RCM,0}$	mm^2/s	4.2E-12
Regression variable (K)	b_e	K	4800
Standard test temperature (K)	T_{ref}	K	293
Temperature of the structural element or the ambient air (K)	T_{real}	K	305.37

Calculated Parameters			
Apparent coefficient of chloride diffusion	$D_{app,\,c}$	mm^2/s	5.51E-8
Subfunction considering the ageing	A(t)	-	0.00686
Time to reach the critical chloride content		Years	278.29
Andrade's model:			
Relative humidity	UR	%	77
Temperature	T	°C	33
Environmental chloride concentration	Cl	%	3.5
The factor that varies in function of the type of cement used	K_1	-	1.05
The factor that varies in function of the admixture type used	K_2	-	1
The amount of admixture in concrete	Ad	%	42
Compressive strength (28 days)	f_{ck}	N/mm^2	61.57
Calculated Parameters			
Time to reach the critical chloride content		Years	392.21

Table 7: *Calculated service life for concretes using prediction models*

Service life of concretes (in years)			
Mix Designation	**LIGHTCON model**	**FIB model**	**Andrade's Model**
A1	70.89	101.88	134.75
B1	88.49	199.04	369.58
C1	180.051	278.29	392.21
A2	58.29	82.56	92.74
B2	69.72	135.96	264.33
C2	149.23	198.92	289.74
A3	**	31.29	43.96
B3	48.57	103.72	135.97
C3	120.35	163.57	149.08

** indicate that the model is not fitted for that data

CONCLUSIONS

From this study, the following conclusions are drawn:

I. The incorporation of fly ash and alccofine into the concrete as a partial replacement shows a dense microstructure of the concrete, thus making the concrete resist more for the chloride attack.

II. The service life is higher for the concrete blended with fly ash and alccofine than that of plain concrete and concrete blended with fly ash.

III. Due to the dense microstructure of concrete blended with fly ash and alccofine the chloride ion diffusion coefficient and surface chloride concentration are much less when compared to that of concrete blended with fly ash and plain concrete.

IV. The compressive strength of concretes blended with fly ash and alccofine shows good results at a later age of concrete at a low water-to-binder ratio.

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