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SERVICE LIFE PREDICTION FOR CONCRETE COMPOSITE WITH CARBON FIBRES FOR MARINE ENVIRONMENT

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Abstract

As construction technologies are improved and as we go for advanced technologies in construction of infrastructure facilities the importance of concrete technology is also more demanding. The field of concrete technology has many new admixtures which improves the properties of concrete. Durability and performance of structures are the main focus now. In view of this, apart from just proportioning a concrete mix, researchers are now interested in testing the performance of the material in varied environmental conditions. Service life prediction is the evaluation of the performance of the structure over a period of time. The prediction involves knowledge of materials science, laboratory testing and data from structures that are in service. It is a complex area where interpretation of correct data has been used and it involves systematic approaches. Researchers have used numerous methodologies and mathematical formulae that are used for the service life prediction. Accelerated laboratory tests forms the basis for these kinds of predictions. This paper deals with proportioning of concrete composite that can be used in aggressive marine environment, subject to severe exposure and the service life prediction of *the material in such environment. Admixtures play a major role in making concrete durable. This paper discusses the properties of concrete composite that has been customized with silica fume, fly ash and copper slag for improving the strength of concrete. Carbon fibres have been added to resist the impact of sea waves and also to improve the flexural toughness of concrete. As there are various factors that have been considered in proportioning this particular concrete mix, experimental trials have been designed with reference to central composite design of Response Surface methodology using Design Expert software. The trials were cast using these design mixes and tests were conducted for strength properties and durability parameters. The experimental results have been analyzed for ANOVA to test the accuracy of results. Multiple optimizations have been done to get the best mix with maximum strength and minimum durability issues.*

Keywords

Strength, Durability, Composite, Tests, Fibres

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1. Introduction

Corrosion due to chloride ingress is the major reason for deterioration of concrete structures. Structures along the sea coast are prone to destruction mainly due to this type of distress. The cost to maintain these structures after corrosion has initiated, is very high. If unnoticed, it results in spalling of concrete and exposure of reinforcing steel, eventually leading to the collapse of the structure. Corrosion causes two types of damage- it reduces the bond between concrete and steel and in the final stage reduces the cross section of the reinforced bar. Literature review shows that the design life of these structures is never met and they are subjected to repair or rehabilitation much before the design life. In this process the role of concrete is to maintain a high alkaline medium protecting the steel by a passive layer of Fe_2O_3 on the steel. The cover concrete plays a major role in protecting the steel from corroding. But once the cover concrete becomes permeable the corrosion process is initiated by the following process. Depassivation of steel occurs when the alkaline medium of concrete surrounding the steel reduces (i.e pH of concrete is 9), which is due to the ingress of CO_2 termed as Carbonation induced corrosion (Rosenberg et al., 1989; Gulikers, 1996), or pitting corrosion due to dissolution of chloride ions in the pore solution of concrete. So it is clear that cover concrete should be impermeable and there are many ways of making the concrete impermeable like reducing the w/c ratio, adding supplementary cementitious materials and curing the concrete adequately will prevent the formation of surface cracks. Reliable service life models are very essential for Engineers to proportion the concrete mix to arrive at a durable concrete mix ratio so that the structure performs well during the intended design period (Cliffton, 1993). The corrosion process consists of two stages as explained by many researchers (Tuutti, 1982). The first stage is the initiation phase where the steel is in passive state and the chloride ions start diffusing through the cover concrete. The second stage is the propagation phase where the onset of corrosion has started and the steel has started to deteriorate by reduction in the cross sectional area. In the initiation phase the cover concrete, threshold value of chloride concentration and its diffusivity are the significant parameters that influences the corrosion process. But in the propagation stage rate of corrosion is the main parameter which determines the progress of corrosion. The rate of corrosion in turn depends on the oxygen diffusivity, resistivity of the concrete pore solution and other environmental factors like temperature and humidity (Tuutti, 1982; Lopez and Gonzalez, 1993). Most of the early service life predictions were based on only the initiation phase as it was believed that after the initiation of corrosion the maximum time for the concrete to crack will be around 5 to 10 years (Collins and Grace, 1997) whereas if propagation phase was considered it will be difficult to quantify the rate of corrosion as it depends upon many random factors like the nature of corrosion products formed, the amount of diffusion of chloride ions and acceleration of the corrosion rate. But Andrade and Alonso, (1996) predicted that propagation phase should be considered for service life prediction because it is the deterioration of steel and concrete that eventually decides the life of the structure. Many researchers like Shamsad (2003), Baroghel et al (20111), Wael et al (2016) and young et al (2017), have used varied approaches to determine the service life of concrete Hence it was concluded that while designing new structures the models considering the initiation phase can be considered and for existing structures service life can be predicted by considering the propagation phase. There are many approaches for service life prediction. This paper deals with material characterization and service life prediction of concrete composite with carbon fibres.

2. Methodology

2.1 Materials Used

The materials used in this work comprises of conventional concrete making materials like cement (Portland Pozzolana cement of 53 grade), sand, coarse aggregate and water. Copper slag which is waste from copper smelting Industry was used as sand replacement. Supplementary

Cementitious materials like fly ash and silica fume were used to improve the strength and durability of concrete. The water/cement ratio was maintained as 0.35 and superplasticiser (Glenium) was used as 1% by weight of cement. Chopped carbon fibres were also used to improve the flexural resistance.

2.2 Experimental Design

The concrete proportioning consists of different ingredients at different levels. The mix design for the concrete mix was done as per IS codes. The range of admixtures to be used in the experimental investigation was fixed based on preliminary trials. As there are numerous variables involved in the production process, the number of experimental trials with a wide range of admixtures will be more. In order to control the number of trials and to arrive at meaningful conclusions, design expert software was used, which will design the number of trials and the combination for each trial. Two fractional factorial design (Central composite design with response surface methodology) was adopted for this study. The trials designed by the software were used for casting concrete cubes of size 15 cm x 15 cm for testing compressive strength of concrete and beams of size 10 cm x 10 cm with a length of 50 cm was cast for testing the flexural strength of concrete. The specimens were subjected to a steam curing of 100˚C for 24 hours. Then the specimens were tested for compressive and flexural strength (Geetha and Selvakumar, 2017).

3. Results

3.1 Material Characterization

The first stage in the experimental programme was characterizing the concrete mix by optimizing the various ingredients used in the process. The experimental trials were designed using Design expert software which generates the combination of the trials from the factors that are entered in the software. Upper limit and lower limits of the factors considered are entered. The combination of the proposed constituent of materials are casted as cubes and cylinders as mentioned in the methodology section and tested for compressive strength and flexural strength at 28 days in the laboratory and the results are given in Table-1. The test results as obtained from table-1, are input in the software. The significance of the test results and the interaction effect of the factors are analysed using ANOVA analysis.

Table 1: *Trial runs and the experimental results of the response*

	Factor 1	Factor 2	Factor 3	Response 1	Response 2
Run	A:Fly ash (%)	B:Silica fume (%)	C:carbon fibres (%)	Compressive strength (MPa)	Flexural strength (MPa)
1	20	10	0	42.8	3.89
2	20	0	0.05	48.1	4.12
3	0	10	0.05	58.21	5.71
4	0	0	0	38.26	2.89
5	0	5	0.025	51.22	4.89
6	24	5	0.025	56.98	4.61
7	10	0	0.025	45.2	4.04
8	10	12	0.025	53.8	4.91
9	10	5	0	40.12	3.25
10	10	5	0.06	59.12	6.12
11	10	5	0.025	47.2	4.02
12	10	5	0.025	47.2	4.02
13	10	5	0.025	47.2	4.02
14	10	5	0.025	47.2	4.02
15	10	5	0.025	47.2	4.02

The results of the response surface graph are given in the graphs. Fig-1 shows that compressive strength increases as the fly ash and silica fume content increased. Similarly as the carbon fibres content increased the strength increased (Figure 2 and 3). The same trend was observed with respect to flexural strength also as given in graphs 4 to 6).

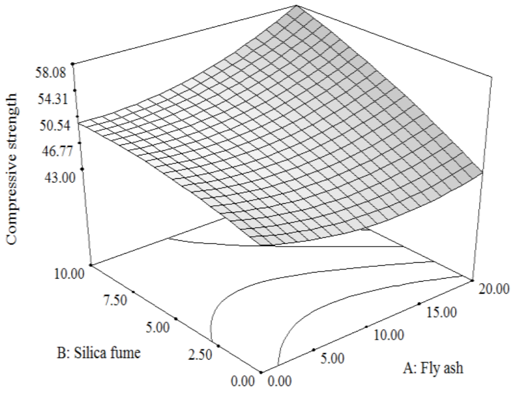

Figure1: *Response surface graph with fly ash and silica fume*

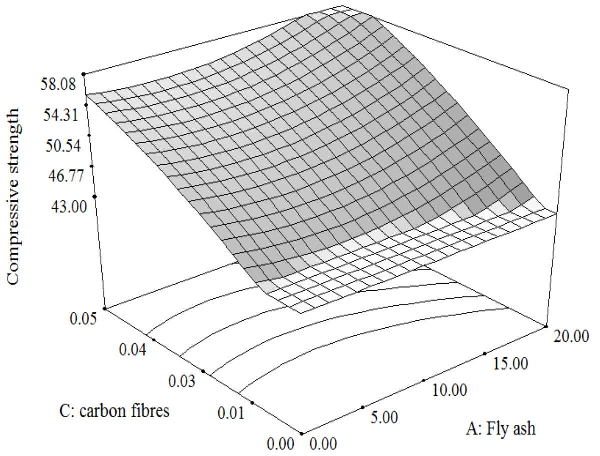

Figure 2: *Response surface graph with fly ash and carbon fibres*

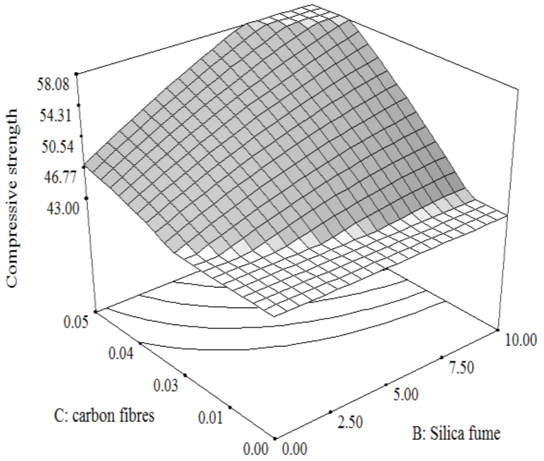

Figure 3: *Response surface graph with silica fume and carbon fibres*

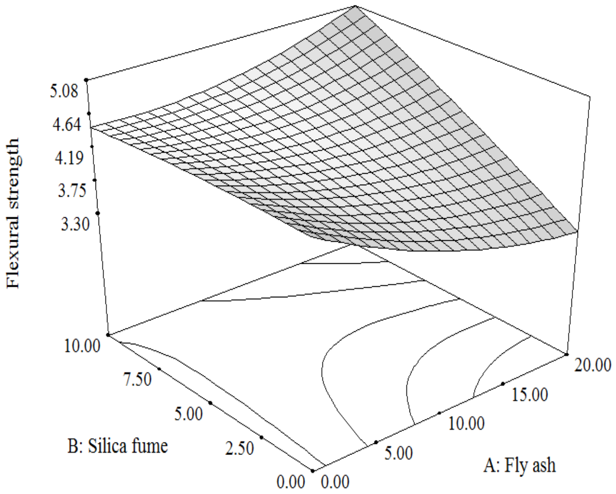

Figure 4: *Response surface graph with fly ash and silica fume*

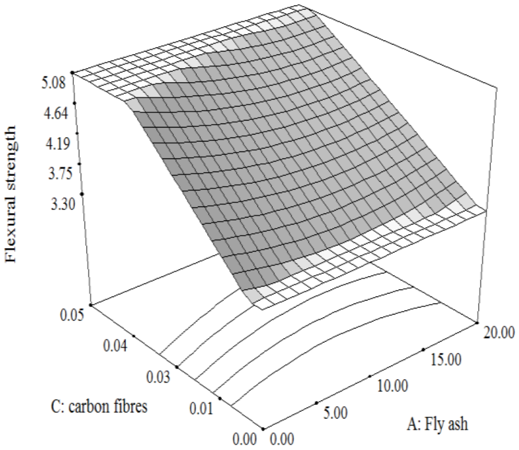

Figure 5: *Response surface graph with fly ash and carbon fibres*

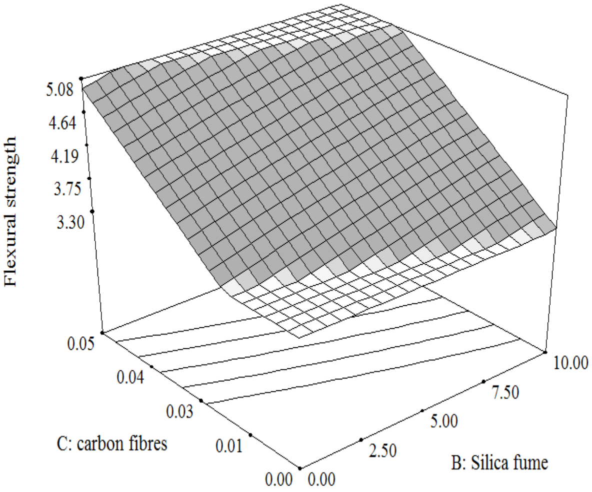

Figure 6: *Response surface graph with silica fume and carbon fibres*

Finally the software optimises a mix based on the experimental results entered in Table-1 for the maximum strength criteria keeping the factors within the range and also predicts the results for the optimised mix proportion. The combination of the optimised mix is again tested in the laboratory for compressive strength and flexural strength and the observed value is compared with the predicted value by the software. The optimized mix proportion is given in Table 2 and the predicted value from the software and observed value through experimental results are given in Table 3. The observed values were closer to the predicted values.

Table 2: *Optimized Values*

Fly ash (%)	Silica fume(%)	Carbon fibres(%)
17.87	7.8	0.05

Table 3: *Confirmatory tests*

	Compressive strength(MPa)	Flexural strength (MPa)
Predicted	62.90	6.10
Observed	60.6	5.89

This mix proportion was further used to perform the corrosion testing and service life prediction as explained in the paper.

3.2 Service Life Prediction

3.2.1 Initiation of Corrosion

Service Life prediction was done using the following equations and procedure:

The chloride diffusion model, which predicts the time to initiation of corrosion, is based on Fick’s second law.

$$T_{\mathrm{i}} = \frac{x^2}{4\,D_{\mathrm{a}}\left[\mathrm{erf}^{-}(1-(C_x/C_{\mathrm{s}}))\right]^2} \qquad (1)$$

where Ti is the time for chloride to reach Cx (x,t) at cover depth, x(s); x is the cover of concrete (cm); Da is the diffusion coefficient of chloride (cm^2/s);Cs is the surface chloride concentration (% by weight of cement); and Cx is the threshold chloride concentration at which corrosion initiates on the rebar (% by weight of cement). The governing parameters of this diffusion-based corrosion initiation time using Equation 1 are the concrete cover depth, the chloride diffusion coefficient in the concrete, the surface chloride concentration and the chloride threshold level.

3.2.2 Corrosion Rate Measurement

Weight loss method was used for determining the corrosion rate. Initial weight of the rods was recorded before embedding into concrete specimens. The rods were embedded in concrete (optimized mix was used) and the concrete specimens were cast. The specimens were cured in steam chamber as mentioned in the methodology section. Then the specimens were immersed in diluted hydrochloric acid to accelerate the corrosion process. At the end of 180, 365, 545 and 730 days of exposure, the concrete specimens were broken and the rods were visually examined for the extent of rust. After pickling the rebars in inhibited hydrochloric acid as specified in ASTM G1 (ASTM, 1995), the final weights were measured. From the initial and final weight, the corrosion rate in m/year was calculated as:

$$\text{Corrosion rate } (\mu\text{m/year}) = \frac{87\,600 \times w}{DAT} \tag{2}$$

where w is the loss in weight (mg); D is the density of iron (g/cm^3); A is the area (cm^2); and T is the time (h).

An alternative approach for calculating the corrosion measurement is using electrochemical impedance spectroscopy (EIS) technique. Using the electrochemical work station polarization resistance (Rp) can be calculated by determining the initiation and propagation of corrosion (Ti and Tp). Based on this, the enhancement of service life of cement concretes was estimated quantitatively in the presence of chloride levels of 0.5 and 1%.The time to initiation of corrosion (Ti) is the time at which the rebar attained a Rp value of less than 230 k cm^2: This Rp value is equal to the icorr of 0.1 A/cm^2.

3.2.3 Chloride concentration

Using Fick's law, the value of Da was calculated by the following equation

$$C_x = C_s\left(1 - \operatorname{erf}\left[\frac{x}{2\sqrt{Da\ \ t}}\right]\right) \tag{3}$$

where Cx is the chloride concentration at known depth (%); Cs is the surface chloride concentration (%); x is the cover in concrete (cm); Da is the apparent diffusion coefficient (cm^2/s); and t is the time (s). The water-soluble chloride content (Cx) was determined by volumetric analysis using the silver nitrate method (Mangat and Molloy, 1991; Muralidharan et al., 2005). In the present study, the mathematical model developed by Maaddawy and Soudki (2007) was used to predict the time to cracking. The Maaddawy model relates the internal radial pressure created by the corrosion product on the cover concrete to Faraday's law to predict the time from the time of initiation of corrosion to cracking and derives Tp in days as

$$T_p = \left[\frac{7117{\cdot}5(D + 2\delta_0)(1 + \gamma + \psi)}{i_{corr}\ E_{cf}}\right] \left[\frac{2Cf_{ct}}{D} + \frac{2\delta_0 E_{cf}}{(1 + \gamma + \psi)(D + 2\delta_0)}\right] \tag{4}$$

where D is the diameter of the rebar (mm); C is the cover (mm); i_{corr} is the corrosion current density (µA/cm^2); Ecf is the effective elastic modulus of concrete, which is equal to Ec/(1+ ϕ_α) (N/mm^2); Ec is the elastic modulus of concrete, Ec =5000√ f_{ck} (N/mm^2); ϕ_{cr} is the concrete creep coefficient assumed as 2.35 as given in the CSA standard (CSA, 1994); γ is Poisson's ratio of concrete assumed as 0.18 as per CSA standard; δ_0 is the porous layer assumed to be 10 μm thick; ψ is the $(D + 2\ \delta_0)2/2C(C + D')$; where $D' = D + 2\ \delta_0$ (mm); f_{ct} is the tensile strength of concrete, $f_{ct} = 0{:}7\ \sqrt{f_{ck}}$ (N/mm^2);f_{ck} is the compressive strength of the concrete at the end of 365 days (N/mm^2). The appearance of crack width of 0.05 and 0.1 mm on the cover concrete was assumed that the service life of the structure will end at this stage. The failure time of the structure (Tf) was taken as the time taken to reach 40 μm thickness of metal loss from the weight loss method. The experimental results for all the times that were calculated are given in Table 4.

Table 4: *Time to failure for 0.5% chloride exposed concrete*

Concrete type	Initiation period (Ti) days	Propagation period (Tp) days	Time to failure (Tf=Ti+Tp), Years	Time taken to reach 40 μm of metal loss
Control concrete	65	385	1.23	1.42
Concrete composite with carbon fibres	540	685	3.35	>2

4. Conclusions

The properties of concrete incorporating silica fume, fly ash and copper slag were found to be superior to the conventional concrete.

- Optimised mix proportion using mineral admixtures like fly ash and silica fume with carbon fibres have been identified to produce a concrete for attaining high strength
- Accelerated corrosion testing was performed to identify the initiation of corrosion and the chloride concentration within the concrete
- The test results of corrosion are compared with a conventional concrete without mineral admixtures and carbon fibres and it is evident that the concrete customised in this paper is resistant to corrosion.
- The given model is found to be appropriate in service life prediction with the adopted methodology.

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References

Andrade, C., Diez, J., and Alonso, C. (1995). Modelling of skin effects on diffusion processes in concrete. In L.-O. Nilsson and J. Ollivier (Eds.), Chloride Penetration into Concrete pp. 182–194.

Baroghel-Bouny, V., Kinomura, K., Thiery, M., Moscardelli, S., Easy assessment of durability indicators for service life prediction or quality control of concretes with high volumes of supplementary cementitious materials, Cement & Concrete Composites 33 (2011) 832–847 https://doi.org/10.1016/j.cemconcomp.2011.04.007

Clifton, J. (1993). Predicting the service life of concrete. ACI Materials Journal, 90 (6), 611–617.

Collins, F., and Grace, W. (1997). Specifications and testing for corrosion durability of marine concrete: the Australian perspective. In V. Malhotra (Ed.), Durability of Concrete, ACI SP–170 Vol 1, pp. 757–776). Detroit.

Geetha, S. and Selvakumar Madhavan, (2017). High Performance Concrete with Copper slag for Marine Environment, Materials Today: Proceedings, 4, 3525–3533 https://doi.org/10.1016/j.matpr.2017.02.243

Gulikers, J. (1996). Experimental investigations on macrocell corrosion in chloride contaminated concrete. Heron, 41(2), 107–123.

Lopez, W., and Gonzalez, J. (1993). Influence of the degree of pore saturation on the resistivity of concrete and the corrosion rate of steel reinforcement. Cement and Concrete Research, 23(2), 368–376. https://doi.org/10.1016/0008-8846(93)90102-F

Maaddawy EIT and Soudki KA (2007) Model for prediction of time from corrosion initiation to corrosion cracking. Cement and Concrete Composites 29(3): 168–175. https://doi.org/10.1016/j.cemconcomp.2006.11.004

Mangat PS and Molloy BT (1991) Influence of PFA. slag and micro-silica on chloride induced corrosion of reinforcement in concrete. Cement and Concrete Research 21(5): 819–834. https://doi.org/10.1016/0008-8846(91)90177-J

Muralidharan S, Vedalakshmi R, Saraswathy V and Palaniswamy N (2005) Studies on the aspects of chloride ion determination in different types of concrete under macro cell corrosion condition. Building and Environment 40(9): 1275–1281. https://doi.org/10.1016/j.buildenv.2004.10.005

Rosenberg, A., Hansson, C., and Andrade, C. (1989). Mechanisms of corrosion of steel in concrete. In J. Skalny (Ed.), Materials Science of Concrete I (pp. 285–313). Westerville,OH: The American Ceramic Society, Inc.

Shamsad Ahmad (2003), Reinforcement corrosion in concrete structures, its monitoring and service life prediction—a review, Cement & Concrete Composites, 25, pp 459–471 https://doi.org/10.1016/S0958-9465(02)00086-0

Tuutti, K. (1982). Corrosion of steel in concrete (Tech. Rep.). Stockholm: Swedish Cement and Concrete Research Institute. (469 pp.)

Tuutti, K. (1993). The effect of individual parameters on chloride induced corrosion. In L.-O. Nilsson (Ed.), Chloride Penetration Into Concrete Structures (pp. 18–25). Goteborg, Sweden.

Wael Slika, George Saad, An Ensemble Kalman Filter approach for service life prediction of reinforced concrete structures subject to chloride-induced corrosion, Construction and Building Materials 115 (2016) 132–142 https://doi.org/10.1016/j.conbuildmat.2016.04.025

Young Cheol Choi, Byoungsun Park, Gi-Sung Pang, Kwang-Myong Lee, Seongcheol Choi. Modelling of chloride diffusivity in concrete considering effect of aggregates. Construction and Building Materials 136 (2017) 81–87. https://doi.org/10.1016/j.conbuildmat.2017.01.041