A study on Corrosion Performance of Steel in Concrete under Accelerated Condition

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Abstract

Corrosion of rebar embedded in concrete exposed to aggressive environment is one of the significant durability problems encountered in reinforced concrete structures. Exposure of reinforced concrete structures in chloride environment is generally considered as one of the aggressive conditions. In the present work the results of an experimental investigation is presented wherein the performance of concrete specimens made with different types of binder and w/b ratios has been evaluated by performing the accelerated corrosion test. The different types of binder used are ordinary Portland cement (OPC) and OPC with 20% fly ash replacement (OPC+FA). The three w/b ratios included in the study are 0.50, 0.55 and 0.60. Only one type of steel i.e. Thermex TMT steel has been used in the preparation of specimens. The prismatic concrete specimens with a centrally embedded steel bar have been prepared from the above binder, steel and w/b ratios. The specimens were immersed in 3% NaCl solution during the accelerated corrosion test. The measured parameters include the current response at the onset of crack appearance on the surface and the corresponding corrosion initiation time including the chloride content at the rebar level. Further the half-cell potential test was also conducted on the specimens after completion of accelerated corrosion test. On the basis of outcome obtained, the performance of specimens made with two types of binder at different w/b ratios has been evaluated.

Keywords: Chloride, Accelerated Corrosion, Concrete.

1. Introduction

Corrosion of steel reinforcement in concrete is a major durability problem [1, 2]. Concrete durability is associated with its quality. Continuous development of concrete microstructure makes the durability study of concrete difficult [3]. Corrosion of reinforcement steel in concrete is an electrochemical process where at the anode, iron is oxidised to iron ions and goes into solution and at the cathode oxygen is reduced to hydroxyl ions, thereby creating a short circuited corrosion cell between anode and cathode [2, 4, 5]. Presence of chloride ions near steel-concrete interface is the primary cause of steel reinforcement corrosion in concrete [6]. The chlorides are normally contributed by mix constituents of concrete or they penetrate into hardened concrete from surrounding environment [2, 6]. Once the corrosion process is initiated in concrete, the electrochemical process continues till the total deterioration of the reinforced concrete structure [4]. However in good quality concrete due to spontaneous formation of oxide film on the surface of steel reinforcement, the steel reinforcement does not corrode even if sufficient moisture and oxygen are available [5].

Chloride is generally detrimental to the steel in concrete. Only the free chloride (unbound chloride) beyond a certain threshold level is responsible for the corrosion of the reinforcement. The source of chloride (internal or external) in concrete plays a major role on the corrosion of steel. For a given C_3A and chloride content, chloride binding is more when it is present in the mix at the fresh stage (i.e. from the time of mixing as internal chlorides) compared with when it penetrates the hardened concrete from an external environment during the service life of a structure (external chloride). From the view point of steel reinforcement corrosion in concrete, the chlorides that penetrate from surrounding environment in the hardened concrete is more detrimental than chlorides contributed by mix constituents [7].

For performance evaluation of concrete in a shorter period of time, it becomes imperative to find out the parameters viz. corrosion current and cracking initiation time under accelerated condition. Evaluation of all these parameters is possible by carrying out accelerated corrosion test on the reinforced concrete specimens. The accelerated corrosion test provides critical corrosion current and corrosion crack initiation time [1, 3, 8-10].

In the present work, an experimental investigation has been undertaken for performance evaluation of the prismatic concrete specimens made with different types of binders and different w/b ratios under accelerated conditions. In accelerated corrosion test the specimens were immersed in 3% NaCl solution and the corrosion process was initiated by applying a constant voltage of 12 V D.C. to the system. Further the probability of corrosion was checked by carrying out half-cell potential test as per ASTM C876 [11] on the specimens after completion of accelerated corrosion test. After that critical chloride content corresponding to crack initiation was measured by potentiometric titration using drilled concrete powder samples obtained from the test specimens.

2. Experimental Work

2.1 Materials

The parameters of the present experimental investigation include two types of binder viz. ordinary Portland cement (OPC) and OPC with 20% fly ash (class F) replacement, one type of steel and three w/b ratios viz. 0.50, 0.55, and 0.60. Steel reinforcement used is thermo-mechanically treated (TMT) bars made by Thermex process. The diameter of the steel bar used is 12mm. The carbon (C) content, phosphorus (P) content and sulphur (S) content of Thermex TMT steel used in the present investigation are 0.22%, 0.036% and 0.043%, respectively. Coarse aggregates of size 20 mm MSA (maximum size of aggregate) and 10 mm MSA were used in the proportion of 1.94:1. The Coarse aggregates satisfy the recommendations of IS 383-1970 for the overall grading requirement [12]. Land quarried sand conforming to zone II classification of British standard was used as fine aggregate. Laboratory tap water was used for preparation of concrete specimens. To obtain all the mixes with a workability of slump in the range of 40–60 mm, the water content was fixed at 200kg/m^3 by carrying out several trials in the laboratory. The concrete mix proportioning was done as per guidelines specified by British method of mix design (DOE) [13, 14], with some modifications.

2.2 Specimen preparation

Prismatic concrete beam specimens (size: 100mmx100mmx300mm) were prepared with a centrally embedded steel reinforcement of length 300mm. The steel reinforcement was provided at a cover depth of 50mm from bottom and 44mm on all the sides. Thus the embedded length of the steel reinforcement was 250mm inside the prismatic concrete specimen. Before preparation of the specimens the steel bar was cleaned with wire brush to remove the surface scale. With two types of binder and three w/b ratios, a total of 6 prismatic concrete specimens were prepared. For determining the 28 day compressive strength of the concrete mix, cube specimens of size 150mm x 150mm x 150mm were also prepared from each concrete mix. The concrete specimens after casting were kept in moulds for a duration of 24 hours. Then the specimens were moist cured for twenty seven days in a curing tank. On completion of moist curing, the prismatic specimens were kept in the laboratory condition for one week after which they were subjected to accelerated corrosion test; whereas the concrete cubes were tested for compressive strength at the age of 28 days.

2.3 Tests carried out

2.3.1 Compressive strength test

Compressive strength test was conducted at the age of 28days. For each concrete mix three cubes were tested and the average value of compressive strength was determined.

2.3.2 Accelerated corrosion test

In the present study, the corrosion process was accelerated by impressing a constant DC voltage between the steel bar (as anode) and stainless steel plate (as cathode) and the variation of current with time was recorded. The prismatic concrete beam specimen with a centrally embedded steel bar was partly immersed in a 3% NaCl solution. A potential of 12V (DC power supply) was applied across the specimens, the reinforcement steel bar being connected to the positive terminal and stainless steel sheet being connected to the negative terminal of the DC power supply. The current response was measured at 1 minute interval by digital data acquisition system till the cracking of the specimens. The test setup is shown in Fig. 1. The specimens were inspected visually 4-5 times a day to check the appearance of cracks on the surface. A typical beam specimen just at cracking on the surface after accelerated corrosion test is shown in Fig. 2.

Figure 1: Test set-up for accelerated corrosion test

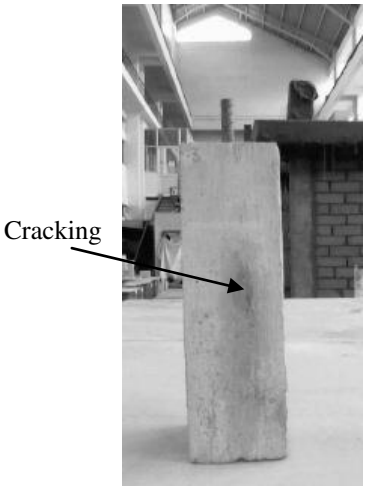

Figure 2: A typical cracked specimen

2.3.3 Half-cell potential test

Half-cell potential test (HCP) is generally considered a non-destructive and rapid indicator to check the probability of steel corrosion in concrete. HCP test was carried out on all the faces of prismatic concrete beam specimens after completion of accelerated corrosion test as per the guidelines specified in ASTM C876 [11]. $Cu/CuSO_4$ electrode was used as the reference electrode.

2.3.4 Chloride content analysis

The chloride content analysis was carried out to determine the free chloride content responsible for crack initiation due to corrosion of steel bar embedded in of the prismatic beam specimen. The concrete powder was collected by drilling on all four sides of the beam specimen i.e. cracked side and

other three uncracked sides. The powder samples were collected at different intervals i.e. 0mm-11mm, 11mm-22mm, 22mm-33mm, 33mm-44mm from the surface. The free chloride content was then determined by potentiometric titration [2] using an automatic titrator (Make Metrohm, model: 848 Titrino plus) for the concrete powder collected at rebar level i.e. in the depth interval 33-44mm.

3. Results and Discussion

3.1 Compressive strength

The results of 28 day cube compressive strength test showed that values of compressive strength of OPC and OPC with fly ash mixes are in the range of 21.8MPa to 35.1MPa and 24MPa to 36MPa respectively. It can be seen that higher compressive strength has been obtained with usage of OPC with fly ash as mineral admixture.

3.2 Corrosion current

The plots showing the variation of corrosion current response with time for two types of binder are shown in Fig. 3, Fig. 4 and Fig. 5 at w/b ratios of 0.50, 0.55 and 0.60 respectively. From these figures it is observed that, the steel reinforcement embedded in concrete mixes made with OPC with fly ash (OPC+FA) exhibited lower corrosion current as compared to that showed by specimens made with OPC irrespective of w/b ratio. The better performance of specimens made with OPC with fly ash may be due to improved passive layer and higher resistivity resulting from the formation of additional C-S-H gel. The corrosion current at the time of crack appearance on concrete surface can be referred to as the critical corrosion current and the corresponding time period can be referred as the crack initiation period. The values of critical corrosion current for both types of binder are shown in Fig. 6. The range of critical corrosion current in OPC and OPC with fly ash (OPC+FA) varied from 117.94mA to 124.87mA and 90mA to 102.19mA respectively at all w/b ratios.

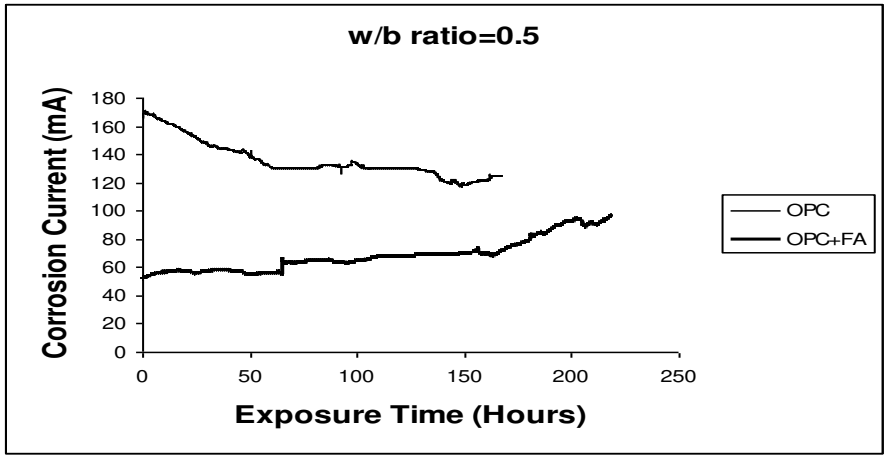

Figure 3: Corrosion current vs. time for two types of binder at w/b ratio of 0.5

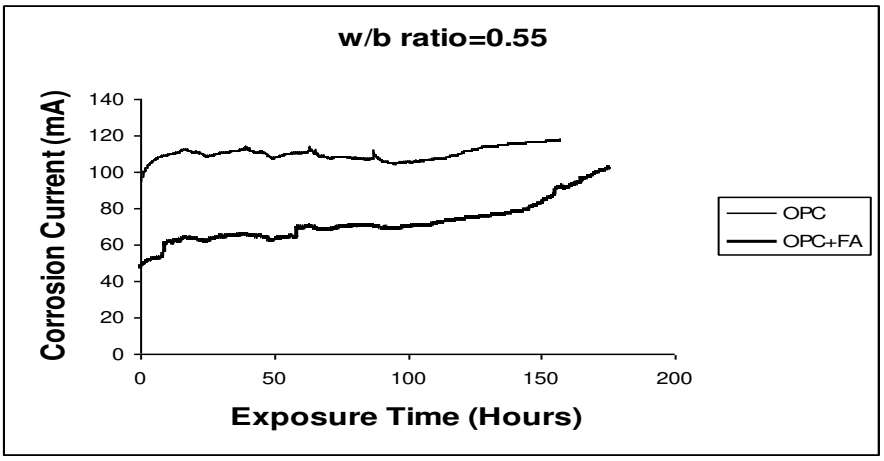

Figure 4: Corrosion current vs. time for two types of binder at w/b ratio of 0.55

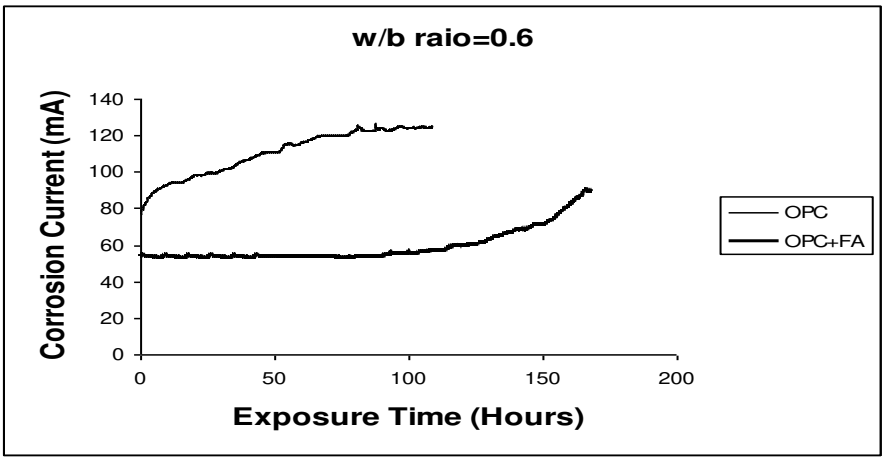

Figure 5: Corrosion current vs. time for two types of binder at w/b ratio of 0.6

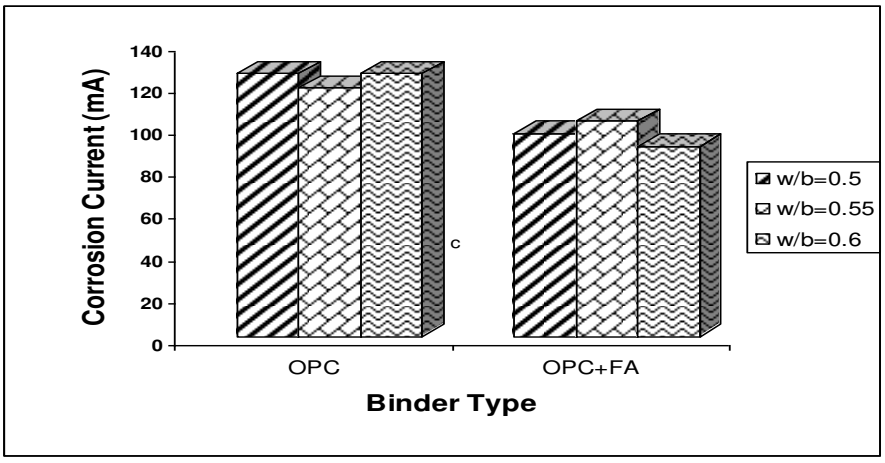

Figure 6: Critical corrosion current

3.3 Crack initiation period

The values of crack initiation period for two types of binder and different w/b ratios are shown in Fig. 7. From this figure, it is observed that, the specimens made with OPC with fly ash (OPC+FA) showed longer crack initiation period than specimens made with OPC. In addition, the specimens made with lower w/b ratio showed longer crack initiation time as compared to the specimens made with higher w/b ratio as evident from Fig. 7. The range of crack initiation period in OPC and OPC with fly ash varied from 108.58hours to 166.67hours and 168.1hours to 218.2hours respectively at all w/b ratios. On an average, the specimens made with OPC with fly ash exhibited 1.3 times longer crack initiation period than those exhibited by OPC.

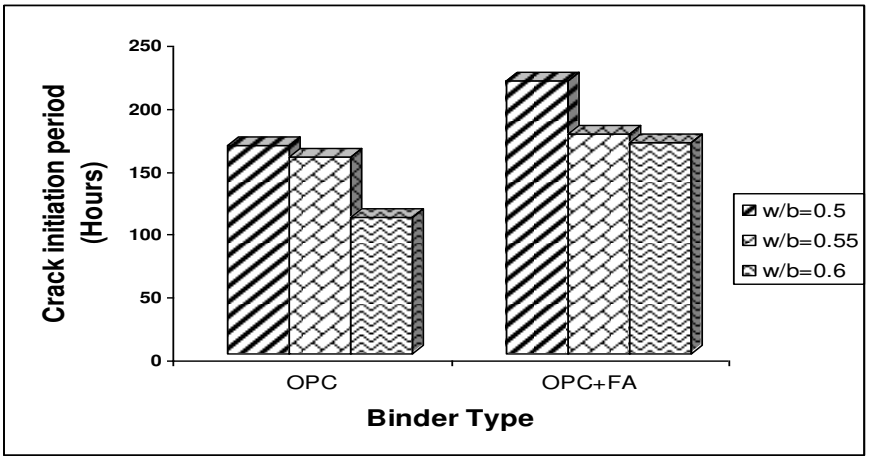

Figure 7: Cracking initiation period

3.4 Half-cell potential

The half-cell potential test was carried out on all four longitudinal faces of all the beam specimens after the completion of accelerated corrosion test. The half-cell potential values obtained for two types of binder are shown in Fig. 8, Fig. 9 and Fig. 10 respectively at w/b ratios 0.50, 0.55 and 0.60. In these figures, the faces of the beam are represented as "F1" for the longitudinal face opposite to the cracked side, "F2" for the longitudinal face left of the cracked side , "F3" for the longitudinal face right of the cracked side and "Cracked face" for the cracked side. From these plots, it is evident that the half-cell potential values for both binder type at all w/b ratios are more negative than -350mV with respect to $Cu/CuSO_4$ electrode (ASTM C876 criteria for greater than 90% probability of reinforcement corrosion) [11]. From the results it is inferred that, the specimens made with OPC exhibited more negative potential values than those exhibited by OPC with fly ash (OPC+FA).

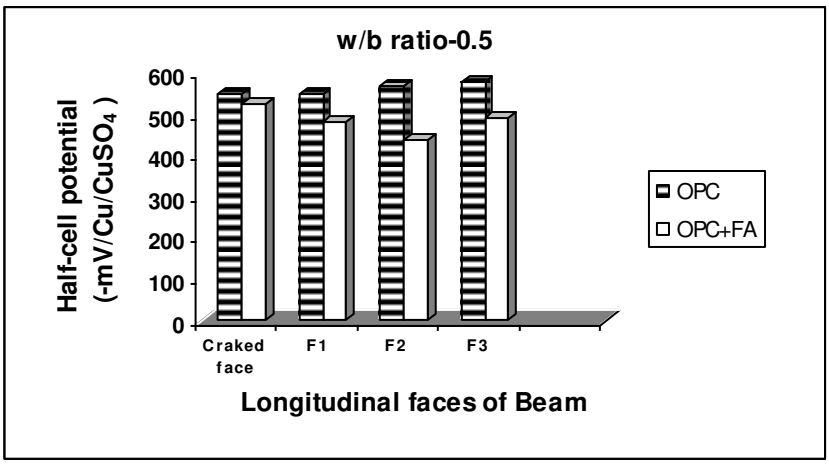

Figure 8: Half-cell potential value at w/b ratio of 0.50

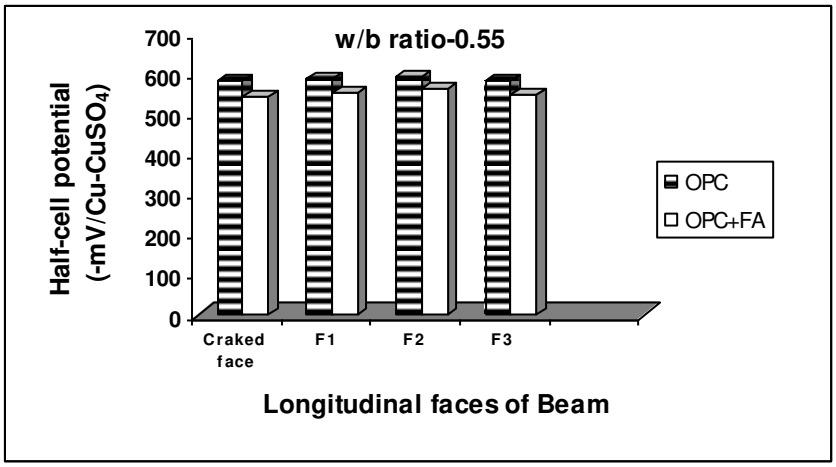

Figure 9: Half-cell potential value at w/b ratio of 0.55

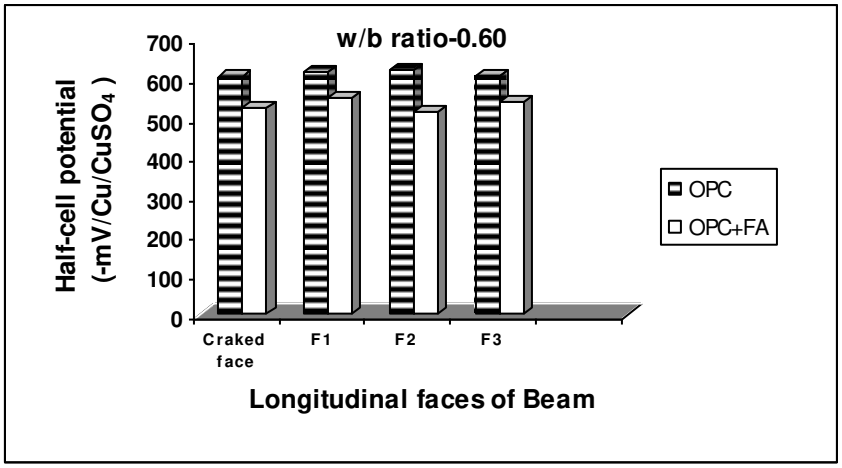

Figure 10: Half-cell potential value at w/b ratio of 0.60

3.5 Critical chloride content

The critical chloride content values at the rebar level of the all longitudinal faces of the beam specimen for OPC & OPC with fly ash (OPC+FA) are shown in Fig. 11 and Fig. 12 respectively. In these figures, the chloride content is expressed as percentage by mass of concrete and the longitudinal faces of the beam are represented in the same manner as in case of plots for half-cell potential values. From these figures it is observed that the specimen made with OPC with fly ash showed higher critical chloride content than specimens made with OPC. The range of average values of critical chloride content in OPC with fly ash and OPC varied from 0.13% to 0.18% and 0.10% to 0.16% respectively for all w/b ratios. This indicates that higher critical chloride content is required for depassivation of steel in specimens made with OPC+FA than specimens made with OPC. It has also been noted that the specimens made with higher w/b ratio exhibited higher chloride content than those made with lower w/b ratios in both the binders. This may be attributed to the fact that the specimens made with higher w/b ratio are comparatively more porous than the specimens made with lower w/b ratio, resulting in higher penetration of chloride ions.

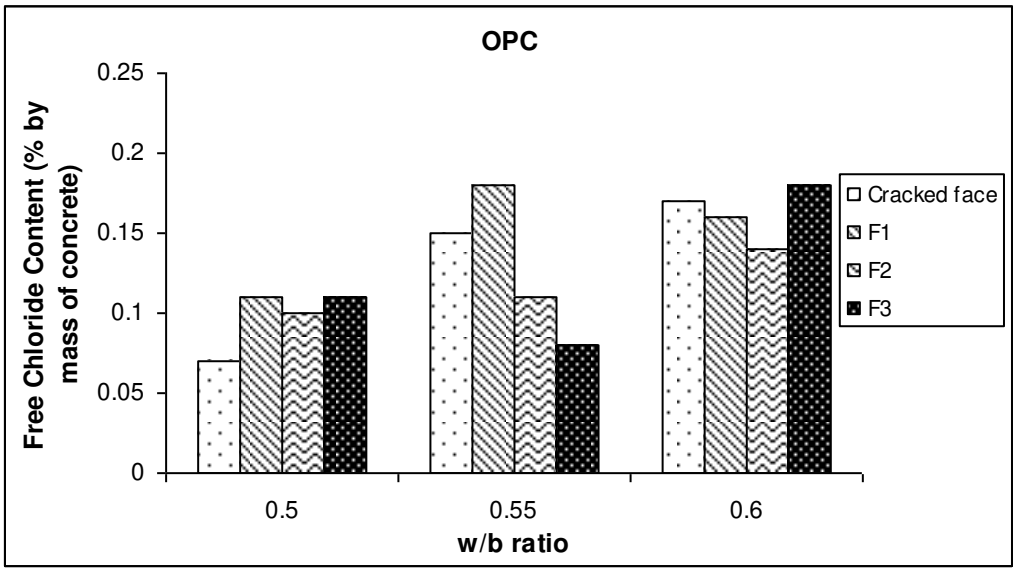

Figure 11: Free chloride content (at rebar lever) at cracking of OPC made specimens at all w/b ratios

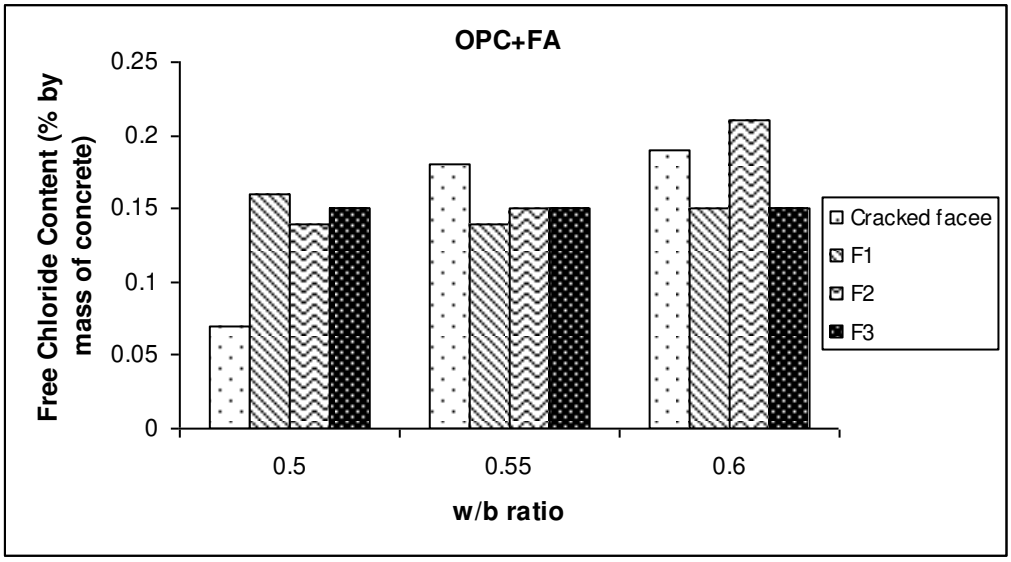

Figure 12: Free chloride content (at rebar lever) at cracking of OPC+FA made specimens at all w/b ratios

4. Conclusion

In the present investigation the accelerated corrosion test was conducted to assess the performance of two types of binder at different w/b ratios. The results of accelerated corrosion test showed that specimens made with OPC with fly ash performed better as compared to the specimens made with OPC in terms of lower corrosion current and longer crack initiation time. Further the specimens made with OPC with fly ash also showed higher critical chloride content than OPC. In addition, the specimens made with lower w/b ratio showed longer crack initiation time than the specimens made with higher w/b ratio. From the half-cell potential measurements the criterion for higher probability of corrosion as per ASTM C876 was reconfirmed from the measured half-cell potential values after completion of accelerated corrosion test.

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