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Durability of Slurry Infiltrated Fiber Concrete to Corrosion in Chloride Environment: An Experimental Study, Part I

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Abstract**—**Slurry infiltrated fiber concrete (SIFCON) is considered as a special type of high strength high-performance fiber reinforced concrete, extremely strong, and ductile. The objective of this study is to investigate the durability of SIFCON to corrosion in chloride environments. Six different SIFCON mixes were made in addition to two refinance mixes with 0% and 1.5% steel fiber content. All mixes were exposed to 10% chloride solution for 180 days. Half of the specimens were partially immersed in chloride solution, and the others were exposed to weekly cycles of wetting and drying in 10% chloride solution. The effectiveness of using corrosion inhibitors, mineral admixture, and epoxy protective coating were also evaluated as protective measures to reduce the effect of chloride attack and to improve the corrosion resistance of SIFCON mixes. Corrosion rates, half-cell potential, electrical resistivity, total permeability tests had been monitored monthly. The results indicated a significant improvement in performance for SIFCON mixes exposed to chloride environment, when using corrosion inhibitor or epoxy protective coating, whereas SIFCON mix contained mineral admixture (metakaolin) did not improve the corrosion resistance at the same level. The cyclic wetting and drying exposure were more aggressive to the specimens than the partial immersion in chloride solution although the observed surface corrosion for the later was clearer.

Keywords**—**Chloride attack, chloride environments, corrosion inhibitor, corrosion resistance, durability, SIFCON, Slurry infiltrated fiber concrete.

I. Introduction

SIFCON is considered a relatively new type of concrete that had used successfully in many applications such as blast resistance structures [1], seismic loads resistance [2], repair, and retrofitting applications [3]. SIFCON is differed from traditional steel fiber reinforced concrete (SFRC) by its high content of steel fiber that can reach 20% of total mix as volume fraction, comparing to relatively limited content of steel fiber not more than 3% in SFRC [4]. Most of the previous researches, those dealt with SIFCON, had focused mainly on investigating the mechanical properties of this unique material [5]. While the research works undertaken in the field of the durability of SIFCON are very limited. However, its exceptional mechanical properties transfer the expected failure of SIFCON to problems associated with durability rather than strength-related problems. This research is aimed to investigate the durability of SIFCON to corrosion in chloride environment.

II. Experimental Program

A. Materials

Two types of cementitious materials were used, ordinary Portland cement type I and metakaolin. The chemical composition and physical properties of each cementitious material was conformed to ASTM C150 [6] and ASTM C 618 [7] respectively. The sand used was confirmed to requirements of ASTM C33 [8]. To ensure a good infiltration of the slurry through the dense steel fiber network, the sand was sieved on 1.18 mm sieve. The absorption, sulfate content, and specific gravity for the sand were 1%, 0.45%, and 2.6 respectively. Hooked end steel fiber with aspect ratio of 58 (length of 35 mm and diameter of 0.6 mm) was used as shown in Fig. 1-a. The tensile strength and density of steel fiber were 1060 N/mm^2 and 7800 kg/m^3 respectively. Steel fiber properties were in compliance with ASTM A820 [9]. The steel reinforcing bars used in this study were low carbon steel reinforcement, grade 60 with 12 mm diameter size. The yield stress, tensile stress, and elongation of steel reinforcement were 457 MPa, 668 MPa, and 14%, respectively. The steel reinforcement properties were confirmed to ASTM- A615 [10]. The steel reinforcement was cut in suitable dimensions to fit the designed forms and had partially coated with epoxy to protect the parts that are not intended to expose to aggressive conditions as shown in Fig. 1 (b). Two types of chemical admixtures were used, high range water reducing admixture (HRWRA) commercially known as Hyperplast PC200 which complied with ASTM C494 [11] type A & G and calcium nitrite based corrosion inhibiting admixture commercially known as Flocrete CN30 confirmed to ASTM C494 [11] Type C. Moreover, solvent free non-toxic epoxy resin commercially known as Strongcoat 400 was used as surface coating for concrete specimens of one of SIFCON mixes as well as steel reinforcing bars to provide external protection from aggressive environments. This product was selected due to its heavy-duty protection for concrete and steel and its high chemical resistance. The mechanical and chemical properties were complied with the requirements of B. S. 6920 [12]. Tap water

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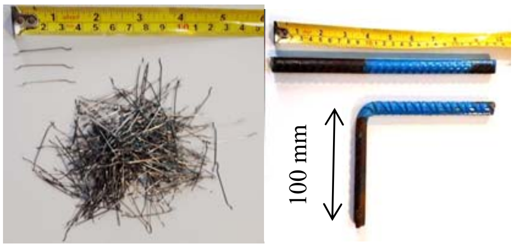
was used for mixing and curing of specimens up to 28 days. Sodium chloride salt that available at local market was used to prepare the 10% chloride solution which is used as aggressive solution.



(a) (b)

Fig. 1 (a) Steel fiber, (b) preparation of steel reinforcement bars

B. Mixes Proportions and Mixing Procedure

Six SIFCON mixes were cast with different steel fiber content (6, 8, and 10%) as volume fraction. In addition to two reference mixes with 0 and 1.5% of steel fiber content were cast for comparison reasons. Two types of exposure conditions were investigated wet and dry cycles and partial immersion in chloride solution.

The resistance of SIFCON mixes to chloride environment was evaluated monthly by monitoring the corrosion rates, half-cell potential, electrical resistivity, total permeability for six months of exposure to 10% chloride solution. It is intended to continue observing the specimens for longer period and the results will be included in another publication in the future. Table I shows the mixes descriptions and proportions. Mixing procedure adopted in this work was based on ASTM C192 [13]. All dry materials of the reference mix (R) were mixed together for 3 minutes, and then HRWRA was dissolved in water and added to the mixer and mixed for additional 5 minutes. The same procedure was made with SFRC mix (F1.5) except that the steel fiber was added randomly to the mixer after ensuring homogeneity of the mix, mixing had extended for additional 2 minutes. While for SIFCON mixes the steel fiber was placed in the molds and then infiltrated with the slurry. The slurry was prepared by mixing all dry materials together then chemical admixtures (HRWRA & corrosion inhibiting admixture) were dissolved in water and added to the mixer and mixed for 5 minutes or until a homogenous slurry was obtained. After casting all specimens were covered with nylon sheet for 24 hours, and then they were demolded and cured in tap water for 28 days before exposing them to chloride environment. The specimens that intended to be coated with epoxy were moved outside the tap water curing tank at age of 28 days and left to dry at lab temperature for 2 days. Two layers of epoxy coating were applied by roller on clean dry concrete surface as shown in Fig. 2. The painted specimens cured for 7 days at 25±2 °C in the lab before exposing them to aggressive solution.

Fig. 2 Epoxy coating for the concrete specimens

C. Designing the Corrosion Test Specimens

The plywood forms with interior dimensions of 300 mm × 200 mm × 62 mm were made to cast the specimens for corrosion tests. The dimensions of the mold were selected to fit the dimensions of the sensor of the corrosion rate device as shown in Fig. 3. Each specimen had two embedded reinforcing bars, one vertically aligned and the other horizontally aligned. Reinforcing bars were coated by epoxy except 100 mm length of each bar leaved without any treatment as shown in Fig. 1 (b). The surface area of this part was used to calculate the corrosion rate.

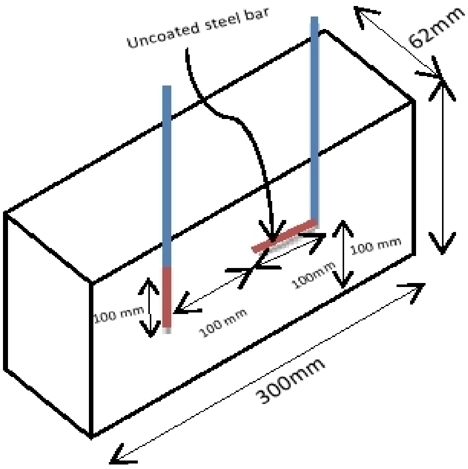


Fig. 3 Corrosion test specimens

III. Test Results and Discussion

A. Corrosion Rate

This test was carried out by using "Gecor 6" device (sensor A) as shown in Fig. 4. The principle of work of this device is based on linear polarization technique [14]. The corrosion rate was monitored monthly for 6 months. Figs. 5 and 6 show the partial immersion in chloride solution respectively. The results are corrosion rate (µA/cm^2) for cyclic wetting and drying and of exposure to chloride environment. It is clear that all mixes were in passive state up to 150 days (120 days of exposure to aggressive solution) whereas the corrosion rate values were less than 0.2 µA/cm^2 [15]. This could be attributed to the fact that the corrosion process need for specific time to initiation and that time depend on many factors such as concrete permeability and chloride ion diffusion. Then, different behaviors were observed for each mix, using corrosion inhibitor admixture and epoxy protective coating improved the resistance to corrosion at all ages in both exposure types. While SIFCON mix with metakaolin (M) showed high corrosion rate results at later age compering to mixes C and E, this could be attributed to the role of mineral admixture in reducing pH value of concrete due to pozzolanic reaction. Hence this mix was more susceptible to corrosion. It is also observed that SIFCON mixes F6 and F8 showed better performance compared to mix R and F1.5. This is due to the tie effect of steel fiber although SIFCON mix with higher steel fiber content (F10) showed a relatively high corrosion rate values, this could be due to increase the voids and permeability when using such high content of steel fiber. On the other hand, the results proved that the effect of wet and dry cycles was more distractive to the specimens compering to partial immersion in chloride solution except for mixes F8, F10 and M, where they showed a relatively higher corrosion rate when partially immersed in chloride solution. This behavior was clearly observed during the visual monitoring of the specimens as presented in Fig. 7. The horizontal alignment of steel reinforcing bars slightly increases the corrosion rate relative to vertical alignment especially with specimens that exposed to partial emersion in chloride solution. This is because the horizontal reinforcing bar totally located in the tidal zone.

TABLE I
MIXES PROPORTIONS AND DESCRIPTIONS

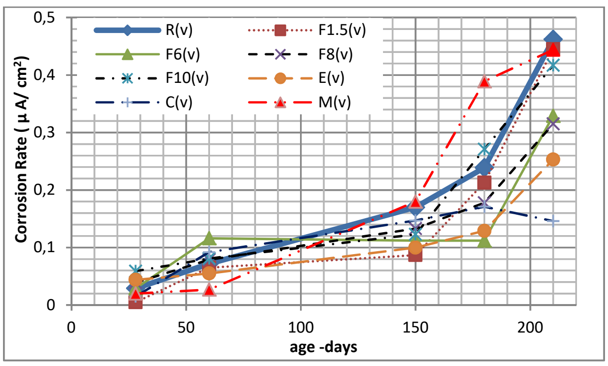
Mix Designation	Mix description	Cement kg/ m³	Fine Aggregate kg/ m³	MK kg/ m³	Water/ cement %	HRWRA % by wt. of cement	Corrosion Inhibitor l/ m³	Steel fiber % vf
R	Reference mix with0% SF	885	885	-	0.32	0.5	-	0
F1.5	Steel fiber concrete with1.5% SF	885	885	-	0.32	0.5	-	1.5
F6	SIFCON with 6 % SF	885	885	-	0.32	1	-	6
F8	SIFCON with 8 % SF	885	885	-	0.32	1	-	8
F10	SIFCON with 10 % SF	885	885	-	0.32	1	-	10
C	SIFCON with 8 % SF and corrosion inhibitor admixture	885	885	-	0.32	1.2	20	8
M	SIFCON with 8 % SF and Metakaolin	799.5	885	85.5	0.32	1.2	-	8
E	SIFCON with 8 % SF, specimens were coated with epoxy protective coating	885	885	-	0.32	1	-	8

B. Corrosions Potential

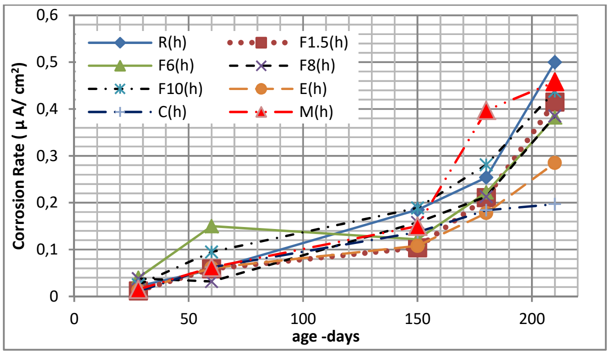
Corrosion potential was carried out by using copper-copper sulfate electrical half-cell. This operation was performed by means of Gecor 6 device, sensor A as shown in Fig. 4. Half-cell potential was measured in (mV) and monitored monthly for 6 months. Corrosion potential test results for specimens exposed to wet and dry cycles and partial immersion in chloride solution are presented in Figs. 8 and 9, respectively. The results showed a gradual reduction in corrosion potential with time for all mixes which considered an indication to increase the probability of corrosion. In accordance to ASTM C876 [16] criteria, when corrosion potential is less than -350 mV the possibility of corrosion is about 90%. It is obvious that most of the recorded values of corrosion potential were less than -350 mV at age of 150 days, which indicate a high possibility for corrosion. But depending on the corresponding corrosion rate result at the same age, it can be concluded that no corrosion occur at that age although the possibility to corrosion was high.

It was also observed that increasing steel fiber content will adversely affect the corrosion potential at all ages. SIFCON mix coated with epoxy protective coating (E) had the best corrosion potential values at later age followed by SIFCON mix with corrosion inhibitor admixture (C) which confirms the importance of using protection methods when there is a possibility to expose to corrosive environments. No significant differences were recorded between corrosion potential specimens exposed to wet and dry cycles and partial immersion in chloride solution. The effect of steel reinforcing bar alignment was not clear up to the late age of the test.

Fig. 4 Gecor 6 device and the setup of corrosion rate measurement

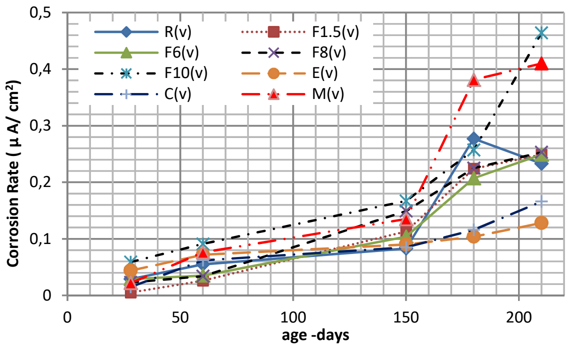


(a) Steel bars were vertically aligned

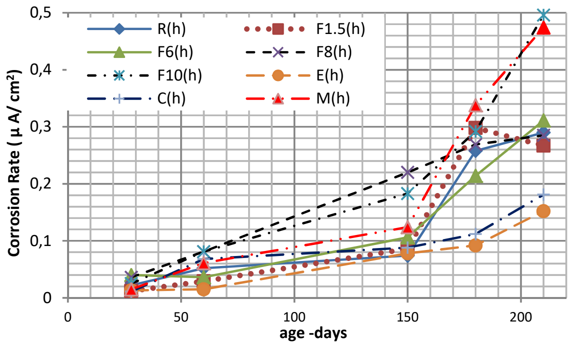


(b) Steel bars were horizontally aligned

Fig. 5 Corrosion rate for mixes exposed to wet and dry cycles in chloride solution

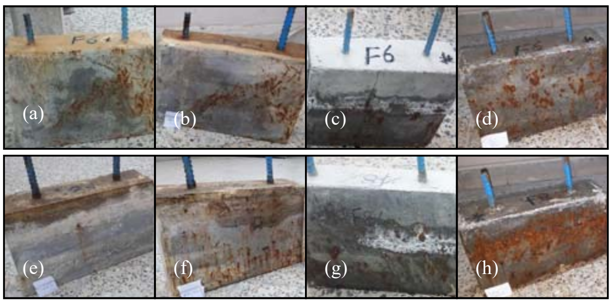


(a) Steel bars were vertically aligned



(b) Steel bars were horizontally aligned

Fig. 6 Corrosion rate for mixes exposed to partial submersed in chloride solution



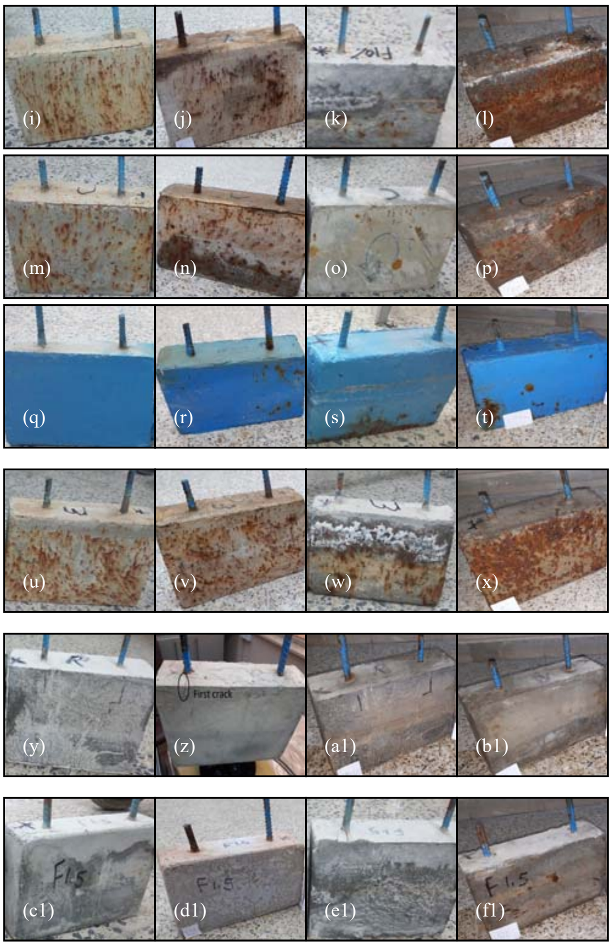
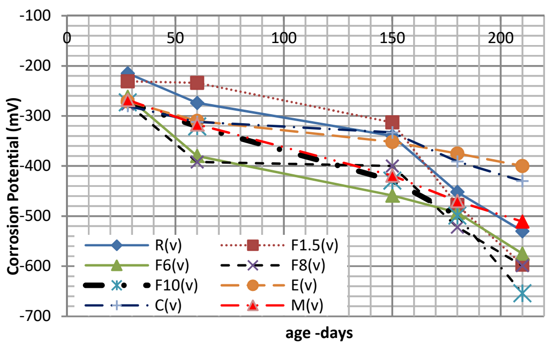
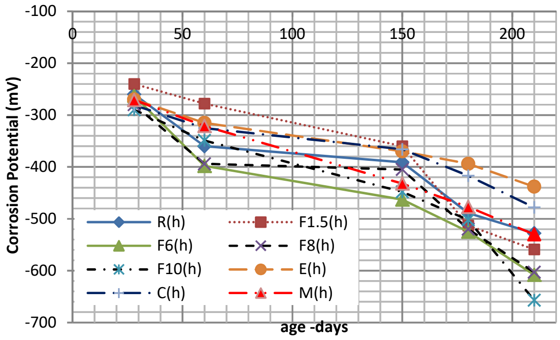


Fig. 7 Visual monitoring for specimens exposed to wet and dry cycles and partial submersed in chloride solution up to 180 days of exposure. (a), (e), (i), (m), (q), (u), (y), and (c1) are mixes F6, f8, F10, C, E, M, R, and F1.5 respectively after 28 days of exposing to wet and dry cycles in chloride solution. (b), (f), (j), (n), (r), (v), (z), and (d1) are mixes F6, f8, F10, C, E, M, R, and F1.5 M respectively after 180 days of exposing to wet and dry cycles in chloride solution. (c), (g), (k), (o), (s), (w), (a1), and (e1) are mixes F6, f8, F10, C, E, M, R, and F1.5 respectively after 28 days of exposing to partial submersed in chloride solution. (d), (h), (l), (p), (t), (x), (b1), and (f1) are mixes F6, f8, F10, C, E, M, R, and F1.5 respectively after 180 days of exposing to partial submersed in chloride solution

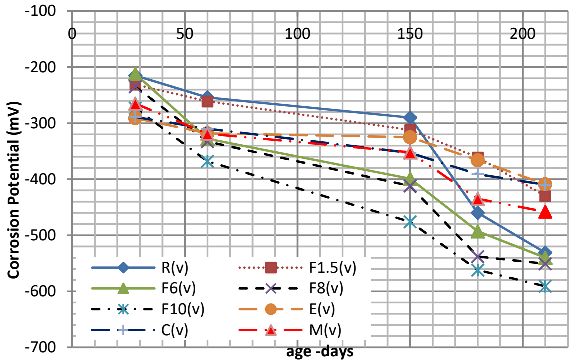


(a) Steel bars were vertically aligned

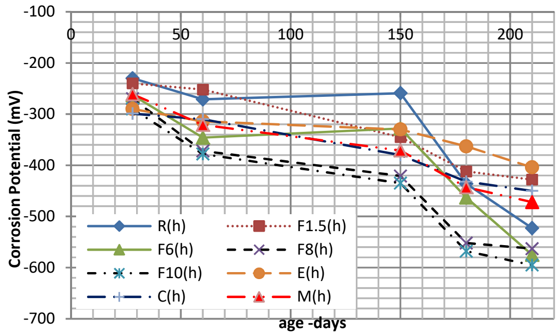


(b) Steel bars were horizontally aligned

Fig. 8 Corrosion potential for mixes exposed to wet and dry cycles in chloride solution



(a) Steel bars were vertically aligned



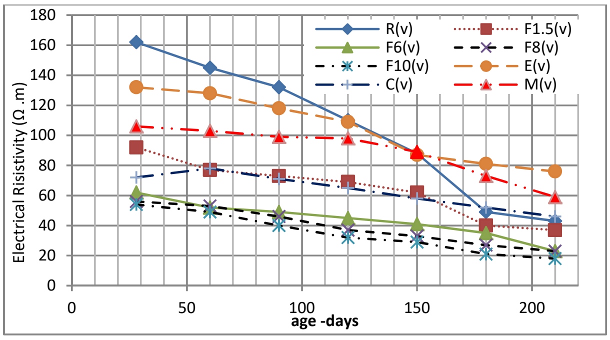
(b) Steel bars were horizontally aligned

Fig. 9 Corrosion potential for mixes exposed to partial submersed in chloride solution

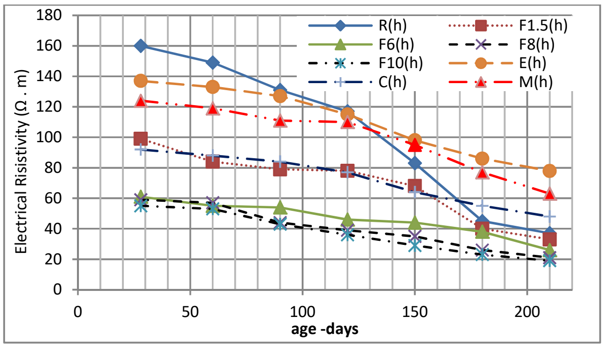
C. Electrical Resistivity

The electrical resistivity can be defined as the ability of material to resist the transfer of charge through it. For concrete the electrical resistivity depend on the porous system and ion migration. The porosity and pore characteristic of concrete strongly affect the values of concrete resistivity and give a wide range of values that vary between few tens of Ω.m to many thousands of Ω.m [17]. The electrical resistivity of SIFCON was measured monthly by using Gecor 6 device, sensor B as presented in Fig. 10. The test results for resistivity of concrete specimens exposed to cyclic wetting and drying and partial immersion in chloride solution are depicted in Figs. 11 and 12, respectively. The results showed that the electrical resistivity decreases significantly when steel fiber content increased to a certain extent and then increasing fiber content did not significantly affect the electrical resistivity of the matrix. This is because electrical charges moved through the steel fibers faster than that passing through the concrete porous. Electrical resistivity strongly affected by the degree of connectivity of steel fiber, hence when the steel fiber content increased more than 6 % it is supposed that a continuous path of steel fiber is available to transfer the electrical charges so no more reduction in electrical resistivity were recorded with SIFCON mixes contained higher amount of steel fiber. The epoxy coated SIFCON specimens (E) showed higher electrical resistivity in comparison with other fiber reinforced mixes, this is due to the impermeable membrane provided by epoxy coating which will reduce the surface absorption. SIFCON mix with metakaolin (M) also showed high electrical resistivity compared to corresponding SIFCON mix without treatment (F8). This is attributed to the pozzolanic effect of metakaolin that reduced the permeability of the matrix. No significant differences in results were recorded between the two types of chloride exposure and between the vertical and horizontal aligned of steel bars reinforcement up to the later age of the test.

Fig. 10 Electrical resistivity measurement

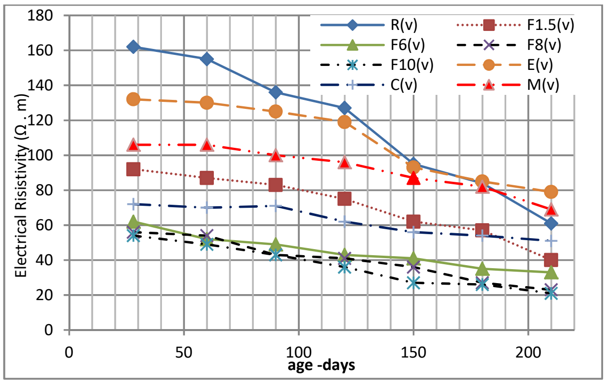


(a) Steel bars were vertically aligned

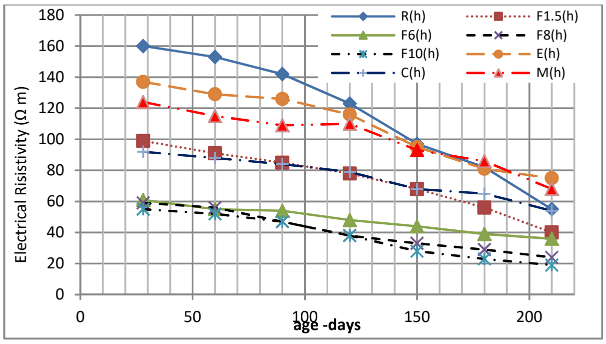


(b) Steel bars were horizontally aligned

Fig. 11 Electrical resistivity for mixes exposed to wet and dry cycles in chloride solution



(a) Steel bars were vertically aligned

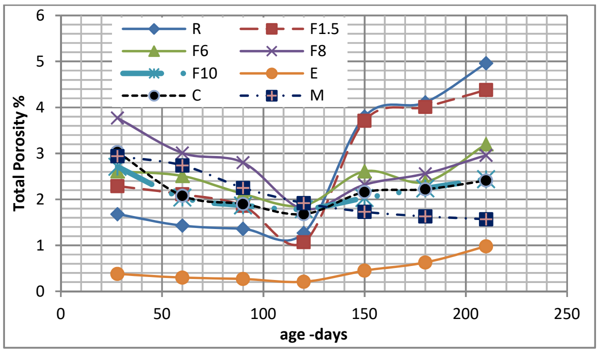


(b) Steel bars were horizontally aligned.

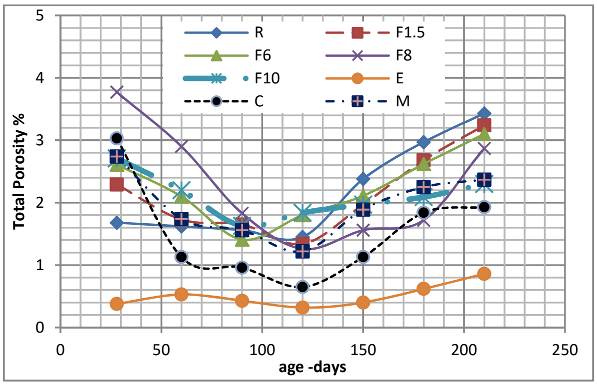
Fig. 12 Electrical resistivity for mixes exposed to partial submersed in chloride solution

D.Total Porosity

The concrete durability characteristic is mainly depending on the total porosity which is related to permeability and ionic movement in concrete. Total porosity (ρ) is defined as the ratio of voids volume to total volume. The total porosity was determined according to experimental technique of ASTM-C642 [18], the test results of total porosity are presented in Fig. 13. All mixes showed a reduction in porosity up to 120 days, this is due to hydration progress which leads to pores refinement and permeability reduction. After that, the result showed a steady increase in total porosity where the steel fibers near surface were directly exposed to chloride solution and started to corrode as seen in Fig. 7, the corroded parts of steel fiber were more susceptible to decompose in water leading to increase the porosity. SIFCON mix coated with epoxy showed superior performance compere to other mixes due to the efficiency of epoxy coating in reduce the permeability of the concrete. Specimens exposed to wet and dry cycles showed higher porosity than specimens exposed to partial submersed in chloride solution especially at later ages.



(a) Specimens exposed to wet and dry cycles in chloride solution



(b) Specimens exposed to partial submersed in chloride solution

Fig. 13 Total porosity

IV. Conclusions

1. All concrete mixes show low to moderate corrosion rate at 180 days of exposing to chloride solution.
2. The steel fiber significantly decreases the electrical resistivity of concrete even before exposing to chloride solution.
3. Using epoxy protective coating and corrosion inhibitor admixture approves their efficiency in protecting SIFCON mixes in corrosive environment.
4. SIFCON mix with metakaolin shows lower resistance to corrosion compared to other treated SIFCON mixes although metakaolin reduces the permeability of SIFCON mix.
5. SIFCON mixes performance in chloride solution is slightly differ between the two types of exposer adopted

in this study.

6. No significant differences in corrosion resistance test results are recorded between vertical and horizontal alignments for steel bar reinforcement.

REFERENCES

[1] R. W. Lucky, “Automatic equalization for digital communication,” *Bell Syst. Tech. J.*, vol. 44, no. 4, pp. 547–588, Apr. 1965.
[2] P. Chun, S. Lee, S.H. Cho, and Y. Lim, "Experimental study on blast resistance of SIFCON," Journal of Advanced Concrete Technology, Vol. 11, pp.144-150, 2013.
[3] B. T. Wood, "Use of slurry infiltrated fiber concrete (SIFCON) in hinge regions for earthquake resistant structures," Ph. D. thesis in Civil Engineering submitted to North Carolina State University, USA, 2000.
[4] Y. N. Dhamak, and M. R. Wakchaure, " Use of precast SIFCON laminates for strengthening of RC beams," International Journal of Engineering and Computer Science, Vol. 4 Issue 9, pp. 14261-14266, Sep. 2015.
[5] A. M. Gilani, "Various durability aspects of slurry infiltrated fiber concrete," Ph.D. thesis in Civil Engineering submitted to Middle East Technical University, Turkey, 2007.
[6] M. A. Ali, “Properties of slurry infiltrated fiber concrete (SIFCON),” Ph. D. Thesis in Civil Engineering submitted to the University of Technology, Iraq, 2018.
[7] ASTM C150, “Standard specification for Portland cement1,” Vol.04.01, 2015.
[8] ASTM C 618, “Coal fly ash and raw or calcined Natural pozzolan for use in concrete1,” Vol.04.02, 2015.
[9] ASTM C 33 “Standard specification for concrete aggregates1,” Vol.04.02, 2015.
[10] ASTM A820, “Standard specification for steel fibers for fiber-reinforced concrete,” Vol.01.04, 2015.
[11] ASTM A615, “Standard specification for deformed and plain carbon-steel bars for concrete,” Vol.01.04, 2015.
[12] ASTM C 494, “Standard specification for chemical admixtures for concrete,” Vol.04.02, 2015.
[13] B. S. 6920-1, “Suitability of non-metallic products for use in contact with water intended for human consumption with regard to their effect on the quality of the water, Specification,” 2000.
[14] ASTM C192, “Making and curing concrete test specimens in the laboratory1,” Vol.01.04, 2015.
[15] A. Poursaee, “Corrosion of steel in concrete structures,” Woodhead Publishing is an imprint of Elsevier, 2016.
[16] James Instrument INC., “Non-destructive testing system,” https://www.ndtjames.com/.
[17] ASTM C876, “Standard test method for half-cell potentials of uncoated reinforcing steel in concrete,” 2015.
[18] C. G. Berrocal, K. Lundgren, and I. Löfgren, “Influence of steel fibers on corrosion of reinforcement in concrete in chloride environments: a review,” Fiber Concrete Journal, 2013, Prague.