Experimental investigation on protection methods of Slurry Infiltrated Fiber Concrete in corrosive environments

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Abstract. Many innovations had been achieved in concrete technology since the last decades to meet the ongoing needs for new types of concrete. Slurry infiltrated fiber concrete (SIFCON) is a special type of high strength high-performance steel fiber reinforced concrete. This new type of concrete characterized by its high strength and ductility is encouragingly used in many heavy duties applications. This research is carried out to study the efficiency of using different protection methods to protect SIFCON in chloride corrosive environments. Where, corrosion inhibitor admixture, mineral admixture (local metakaolin) and epoxy protective coating were used to provide either internal or external protection for SIFCON mixes. All mixes were evaluated for more than 390 days of exposing to chloride solution. Corrosion rates, half-cell potential, concrete resistivity, and chloride concentration tests were performed. The results indicated that all SIFCON mixes showed low to moderate corrosion rates. Also it was found that using of epoxy protective coating, corrosion inhibitor and mineral admixture can reduce the rate of corrosion as compared to unprotected mixes. The cyclic wetting and drying exposure to chloride environments was more aggressive to the specimens than the partial immersion in chloride.

Keywords
Chloride attack, corrosion inhibitor, corrosion resistance, epoxy protective coating, Slurry infiltrated fiber concrete, SIFCON.

1. Introduction
Slurry infiltrated fiber concrete (SIFCON) is considered as special type of steel fiber concrete (SFC) with high volume fraction of steel fiber. It possesses high ductility and high mechanical properties and had used successfully in many applications such as blast resistance structures [1], seismic loads resistance [2], repair, and retrofitting applications [3]. SIFCON mixes characterized by their high steel fiber content that can reach upto 20% of mix’s volume, and by their special production techniques [4].

Though many researches were conducted to investigate the corrosion resistance of different types of concrete, no research was carried out to study the corrosion resistance of SIFCON mixes. Most of the works were focused on mechanical properties of SIFCON rather than its durability.

2. Objective and scope
The main objective of this study is to investigate the effectiveness of using different protection methods on corrosion performance of SIFCON. 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, these were cast for comparison purpose. Different types of protection methods were used by either internal or external treatment. The internal protection technique was performed by using mineral admixture (local available metakaolin) in one of SIFCON mixes, and by using of chemical admixture (calcium nitrite inhibiting admixture) which was used in another SIFCON mix. While the external protection technique was assessed by coating specimens of one of SIFCON mixes with epoxy protective coating.
coating. All mixes were cured by immersing them in tank filled with tap water for 28 days, and then exposed to 10% chloride ion solution for 390 days. Corrosion rates, half-cell potential and concrete resistivity tests had been monitored monthly. Chloride concentration was also checked after 360 days of exposure. Two types of exposure were implemented, cyclic wetting and drying in chloride solution and partial immersion in chloride solution.

3. Experimental Program

3.1 Materials

a- Cementitious 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 in conformance to ASTM C150 [5] and ASTM C 618 [6] respectively.

b- Fine aggregate: The fine aggregate used was uniformly graded with max size of 1.18 mm to ensure a good infiltration of the slurry through the dense steel fiber network. The absorption, sulfate content, and specific gravity for the sand were 1%, 0.45%, and 2.6 respectively and it was conformance to requirements of ASTM C33 [7].

c- Steel Fiber: Hooked end steel fiber with aspect ratio of 58 (length of 35 mm and diameter of 0.6 mm) was used as shown in Figure 1-(a). The tensile strength and density of steel fiber were 1060 N/mm² and 7800 kg/m³ respectively. Steel fiber properties were in conformance to ASTM A820 [8].

d- Steel Reinforcement: Low carbon steel reinforcing bars of grade 60 and 12 mm diameter size was used. The yield stress, tensile stress and elongation of steel reinforcement were 457 MPa, 668 MPa and 14% respectively. The steel reinforcement properties were conformance to ASTM A615 [9]. The steel reinforcement was cut in suitable dimensions to fit the designed forms and was partially coated with epoxy to protect the parts that are not intended to expose to aggressive conditions as shown in Figure 1-(b).

e- High range water reducing admixture (HRWRA): High range water reducing admixture (HRWRA) commercially known as Hyperplast PC200 was used, which complied with ASTM C494 [10] type A and G.

f- Corrosion inhibiting admixture: Calcium nitrite based corrosion inhibiting admixture commercially known as Flocrete CN30 was used, it was conforming to ASTM C494 [10] Type C.

g- Epoxy protective coating: 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 in compliance to the requirements of B. S. 6920 [11].

h- Water: Tap water was used for mixing and curing of specimens up to 28 days.

i- Chloride salt: Sodium chloride salt available at local market was used to prepare the 10% chloride solution which is used as aggressive solution.

3.2 Mixes proportions, mixing and curing procedures:

The details of mixes proportions are presented in Table 1. The mixing procedure that adopted in this work is in compliance with ASTM C192 [12]. SIFCON mixes were cast by placing steel fiber in the mold then infiltrated with the slurry as shown in Figure 2. All dry consistent of the slurry were mixed for 3 minutes then the liquid consistent (mixing water, high range water reducing admixture, and corrosion inhibiting admixture) were added and mixed for additional 5 minutes. For SFC mix (F1.5), the same procedure of preparing slurry was applied except that the steel fibers were added to the mixer after ensuring the homogeneity of the mix and the mixing time was extended for additional 2 minutes.
After cast, 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 solution. The specimens that intended to be coated with epoxy were moved out of 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 Figure 3. The painted specimens cured for 7 days at 25º ± 2 C in the lab before exposing them to aggressive solution. Two types of exposure to chloride solution were implemented; cycles of wetting and drying, each cycle consist of 7 days of total immersion in chloride solution followed by 7 days of drying in lab temperature. The second type of exposure was partial submersed in chloride solution.

**Figure 1.** (a): steel fiber, (b): the coated steel bars  
**Figure 2.** Cast of SIFCON mixes

| 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                |

**3.3 Design of Corrosion Test Specimens**

In order to study the corrosion of SIFCON, simple plywood forms were designed with adequate dimensions to fit the sensor of the corrosion rate tester machine. The interior dimensions of the forms were (300mm x mm *62 mm) as detailed in Figure 4. Two reinforcing bars were embedded in each specimen, one vertically aligned and the other horizontally aligned. Both reinforcing bars are coated
with an epoxy protective coating except 100 mm length of each bar left without any treatment as shown in Figure 1-b. The surface area of this part was used to calculate the corrosion rate.

![Figure 3](image3.png) Coating SIFCON specimens with epoxy protective coating

![Figure 4](image4.png) Design of corrosion specimens

4. Results and discussion

4.1 Corrosion Rate

This test is based on linear polarization technique (LPT) and carried out by using "Gecor 6" tester as shown in Figure 5. Corrosion rate was calculated in (µA/cm²) over a specified area of steel bars. More details about LPT and Gecor 6 tester are given by Salih et al [13] The corrosion rate was monitored monthly for 14 months. The test results are presented in Figures 6 and 7, the results indicate that the corrosion rates were increased with time, but in all cases, they were less than 1 µA/cm², which indicated a low to moderate corrosion rate. A better performance was observed for SIFCON mixes coated with epoxy or containing corrosion inhibitors, while SIFCON mixes containing metakaolin didn't show the same resistance to corrosion, this is attributed to the pozzolanic effect of metakaolin in reducing the alkalinity of concrete. The highest corrosion rate was recorded with reference mix, while the use of steel fiber in other mixes showed a lower corrosion rate at a later age compared to reference mix. This phenomenon was attributed to the crack arresting role of steel fiber which leads to reduce the permeability and thereby reduce the effect of aggressive environments. The results showed that the effect of exposing to wetting and drying cycles in chloride solution was more harmful to specimens than partial immersion in chloride solution, this could be attributed to the physical deterioration that caused by chloride crystallization upon drying of the specimens. On the other hand, the different alignment of steel reinforcing bars didn’t show significant change in the corrosion rate results.

![Figure 5](image5.png) (a): Gecor 6 device,(b): the setup of corrosion rate measurement and (c) electrical resistivity test
4.2 Corrosion potential

Corrosion potential was carried out by using copper-copper sulfate electrical half-cell. This operation was performed by means of Gecor 6 tester equipment by using sensor A as shown in Figures 5. Half-cell potential was measured in (mV) and monitored monthly for 14 months. The test results are depicted in Figures 8 and 9. The results indicated that the corrosion potential for all mixes was increased with time suggesting a higher probability of corrosion especially at later ages. In accordance to criteria of ASTM C876 [14], when corrosion potential is less than -350 mV the possibility of corrosion is about 90% where all mixes showed corrosion potentials less than -350 mV after 6 months of exposing to chloride solution except the treated SIFCON mixes (E, C and M). It was also observed that there was a harmony between the corrosion rate test results and corrosion potential. Mixes E, C and M showed better performance than other mixes without treatment. This is indicating the efficiency of these protection methods in improving the corrosion resistance of SIFCON. Also, it was clear that as the steel fiber content increased as the potential increased even at early ages. Mixes that exposed to partial immersion in chloride solution showed better performance relative to the corresponding mixes that exposed to cycles of wetting and drying in chloride solution, which can be attributed to the same reason mentioned in 4.1.

4.3 Electrical resistivity

The electrical resistivity of a material describes its ability to withstand the transfer of charge. In the case of plain concrete it can be directly related to the ion migration in the porous concrete microstructure. The resistivity of concrete may vary between few tens of $\Omega \cdot m$ to many thousands of $\Omega \cdot m$ depending on the porosity and pore characteristics [15]. The electrical resistivity of SIFCON was measured monthly for 14 months by using Gecor 6 tester equipment (sensor B) as shown in Figure 5. The test results are presented in Figures 10 and 11. The results indicated that the electrical resistivity decreased significantly when steel fiber content increased up to a certain extent, and then no significantly affect the electrical resistivity of the matrix. This is because electrical charges move through steel fiber faster than through the concrete porous. Electrical resistivity is strongly affected by the degree of connectivity of steel fiber. 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. Hence, no more reduction in electrical resistivity was recorded with SIFCON mixes contained higher amount of steel fiber. All mixes showed a reduction in electrical resistivity with time although SIFCON specimens that coated with epoxy were less affected by chloride solution comparing to other mixes flowed by SIFCON specimens containing corrosion inhibitor and metakaolin respectively. The cycles of wetting and drying in chloride solution were more detrimental to concrete mixes than partial exposing to chloride solution while the alignment of steel reinforcing bar had a minor effect on the recorded results.
Figure 6. 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.
Figure 7. Corrosion rate for mixes exposed to partial submersed in chloride solution, (a): steel bars were vertically aligned, (b): steel bars were horizontally aligned.
**Figure 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.
Figure 9. Corrosion potential for mixes exposed to partial submerged in chloride solution, (a): steel bars were vertically aligned, (b): steel bars were horizontally aligned.
Figure 10. 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.
4.4 Chloride Concentration

This test was carried out in accordance with ASTM C 1152 [16]. The chloride concentration was calculated after 12 months of exposing to chloride solution, for all mixes in both exposure types and at depth of 25mm from specimens surface. For concrete mixes that exposed to partial immersion in chloride solution, the chloride concentration calculated at the tidal zone. Figure 12 shows the test results, the results indicate a lower chloride concentration for all treated SIFCON mixes which indicate the efficiency of the adopted protection methods. The best performance was recorded with mix E that coated with epoxy. The chloride concentration for mixes exposed to cyclic wetting and drying in chloride solution was slightly higher than corresponding mixes that exposed to partial immersion in chloride solution. This could be attributed to the physical deterioration that caused by chloride crystallization upon drying of the specimens and the corresponding increase in the permeability. The critical chloride threshold value that cause corrosion in steel fiber concrete is not well define, although there is a general agreement that steel fiber concrete remained free of corrosion for chloride contains up to 1.7 % by weight of cement [17]. The chloride concentration results of SIFCON mixes showed that the chloride concentration was less than this value which is attributed to low permeability and these result explain the high resistance to corrosion that recorded with SIFCON mixes.
5. Conclusions
1- All concrete mixes show low to moderate corrosion rate after 390 days of exposing to chloride solution.
2- The steel fiber significantly decreased the electrical resistivity of concrete even before exposing to chloride solution.
3- Using epoxy protective coating and corrosion inhibitor admixture proved 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.
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 shown between vertical and horizontal alignments for steel bar reinforcement.

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