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Research Article

Six Years of Experimental Investigation on Corrosion Resistance of Concrete with Corrosion Inhibitors

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Abstract

Much time and effort has gone into the development of the corrosion inhibitors process. Corrosion undermines the physical integrity of structures and can lead to destruction of property and loss of life. Corrosion inhibitors are one means of protection for reinforced concrete structures. This investigation was carried out to evaluate long-term effect of corrosion inhibitors for concrete specimens made of ordinary and sulfate-resistant cement. Three commercial corrosion inhibitors were evaluated in this study: two anodic inhibitors based on calcium nitrite in both powder and liquid form, and mixed inhibitor reactions (anodic and cathodic reaction) based on nitrogen containing organic and non-organic substances. Three dosages of each type of corrosion inhibitors and two types of cement were considered in this study. Corrosion test was conducted using cylindrical specimen of 75 mm diameter and 150 mm length, with a high tensile strength deformed steel bar of 12 mm diameter. Test specimens were subjected to weekly wetting (in salt solution) and drying cycles for 3 years and kept dry for other 3 years. The whole testing period was 2244 days. Corrosion was monitored by obtaining half-cell potentials of the embedded steel. Results indicated that the addition of anodic corrosion inhibitor based on calcium nitrite with the producer recommendation dosage to OPC or SRC concrete have an insignificant effect on the corrosion potentials throughout the whole testing period. The use of corrosion inhibitors based on calcium nitrite and mixed reaction corrosion inhibitors based on nitrogen containing organic and non-organic substances decreases the percentage of steel weight loss for OPC concrete.

Keywords: *Anodic inhibitors, mixed reaction, cathodic reaction, corrosion potentials, protection.*

1. Introduction

The corrosion of concrete reinforcement is a very expensive problem, amounting in billions of dollars of damage worldwide. Several solutions have been proposed to enhance the corrosion resistance of concrete. The use of corrosion inhibitors is one of these solutions (Richard E. W. et al., 1998). A corrosion inhibitor is defined as a substance that will prevent or minimize corrosion. Most inhibitors act by chemically stabilizing the steel surface, although some also act to reduce the permeability of the concrete. Several researchers deal with the reinforcement corrosion problem by using corrosion inhibitors in the aim to inhibit the onset of chloride- induced corrosion of concrete reinforcement. Two issues need to be addressed in the use of corrosion inhibitors. First and foremost is the efficiency of inhibiting action which is the most obvious concern, and second, but of no lesser importance, is the influence of this inhibitor on concrete properties. According to some researchers (Jamil H. E. et al, 2004) ‘‘an inhibitor adequate to control or to prevent corrosion of reinforcing steel must be a suitable chemical admixture, which when added to concrete in the correct proportions, should be able to stop or delay the reinforcement corrosion without adverse effects in the mechanical and physical–chemical properties of concrete (Fayala et al 2013).

Corrosion inhibitors are typically divided into three categories: anodic inhibitors, cathodic inhibitors, and organic inhibitors. Anodic inhibitors react with the ions of the corroding metals increasing the polarization of the anode and producing thin passive film or salt layers which coat the anode. Two types of anodic corrosion inhibitors are important for steel, those which are oxidizing agents and those which require dissolved oxygen to be effective (Trethewey K. R. et al., 1988; Justnes H. , 2006). These inhibitors form an insoluble protective film on anodic surfaces to passivate the steel. Some anodic inhibitors, such as nitrites, can cause accelerated corrosion and pitting if they are not used in large enough quantities (Virmani Y. P. et al., 1998; Chambers B. D. et al., 2003; Cement Concrete & Aggregates Australia, 2009).

Cathodic inhibitors form an insoluble film on the cathodic surfaces of the steel. They are usually less effective than anodic inhibitors, but are also safer because the active cathode area is reduced even if too little inhibitor is added. Organic inhibitors (both the anodic and cathodic reaction) block the entire surface of the metal (Virmani et al., 1998). Organic inhibitors can also act as pore blockers, reducing the permeability of the concrete. After 10 years exposure, the inorganic admixture system

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Table 1 Mix proportions of concrete mixes

Mix No.	Mix Type	Mix proportions for concrete with 350 kg/m^3 ordinary Portland cement (Kg/m3)						Mix No.	Mix Type	Mix proportions for concrete with 350 kg/m^3 sulfate-resisting cement (Kg/m3)					
		water	sand	Corse agg.	Inhi.	Adm.	NaCl			water	sand	Corse agg.	Inhi.	Adm.	NaCl
1	Control	195	683	1025	0	3.5	0	15	Control	195	683	1025	0	3.6	0
2	Control + 0.5%salt	195	683	1025	0	3.5	1.75	16	Control + 0.5%salt	195	683	1025	0	3.6	1.75
3	0.289% INH1*	195	683	1025	1	3.6	0	17	0.289 % INH1*	195	683	1025	1	3.6	0
4	0.429% INH1*	195	683	1025	1.5	3.6	0	18	0.429 % INH1*	195	683	1025	1.5	3.7	0
5	0.571% INH1*	195	683	1025	2	3.7	0	19	0.571 % INH1*	195	683	1025	2	3.8	0
6	0.429% INH1 + 0.5 % salt*	195	683	1025	1.5	3.6	1.75	20	0.429 % INH1+ 0.5 % salt*	195	683	1025	1.5	3.7	1.75
7	0.289% INH2*	195	683	1025	1	3.1	0	21	0.289 % INH2*	195	683	1025	1	3.15	0
8	0.429% INH2*	195	683	1025	1.5	3.1	0	22	0.429 % INH2*	195	683	1025	1.5	3.15	0
9	0.571% INH2*	195	683	1025	2	3	0	23	0.571 % INH2*	195	683	1025	2	3.1	0
10	0.429% INH2 + 0.5 % salt*	195	683	1025	1.5	3.1	1.75	24	0.429 % INH2 + 0.5 % salt*	195	683	1025	1.5	3.15	1.75
11	2.0 % INH3*	195	683	1025	7	0	0	25	2.0 % INH3*	195	683	1025	7	0	0
12	3.0 % INH3*	195	683	1025	10.5	0	0	26	3.0 % INH3*	195	683	1025	10.5	0	0
13	4.0 % INH3	195	683	1025	14	0	0	27	4.0 % INH3*	195	683	1025	14	0	0
14	3.0 % INH3 + 0.5 % salt*	195	683	1025	10.5	0	1.75	28	3.0 % INH3 + 0.5 % salt*	195	683	1025	10.5	0	1.75

* The percentage value written before mix type containing inhibitor represents the dose of inhibitor as a percentage by weight of cement.

gave consistently good performance, with a reduced risk of corrosion, followed by other organic concrete admixtures in comparison to the control system (Cusson D. and Qian S., 2007). Recent migrating corrosion inhibitors are based on amino carboxylate chemistry and the most effective types of inhibitor interact at the anode and cathode simultaneously (Bavarian B. and Reiner L., 2004; Bjegovic D. et al., 1999; Rosignoli D. et al., 1995). Migrating corrosion inhibitors are able to penetrate into existing concrete to protect steel from chloride. The inhibitor migrates through the concrete capillary structure, first by liquid diffusion via the moisture that is normally present in concrete, then by its high vapor pressure and finally by following hairlines and microcracks. The diffusion process requires roughly 120 days to reach the rebar surface and to form a protective layer (Bavarian B. and Reiner L., 2004).

Concrete penetrating corrosion inhibitors based on bipolar inhibitor mechanism is a new generation corrosion inhibition. They can penetrate even dense concrete by virtue of their vapor pressure and natural affinity for the embedded steel in concrete. Further, the new generation corrosion inhibitor is eco-friendly and non-toxic (Limaye R. G. et al., 2000).

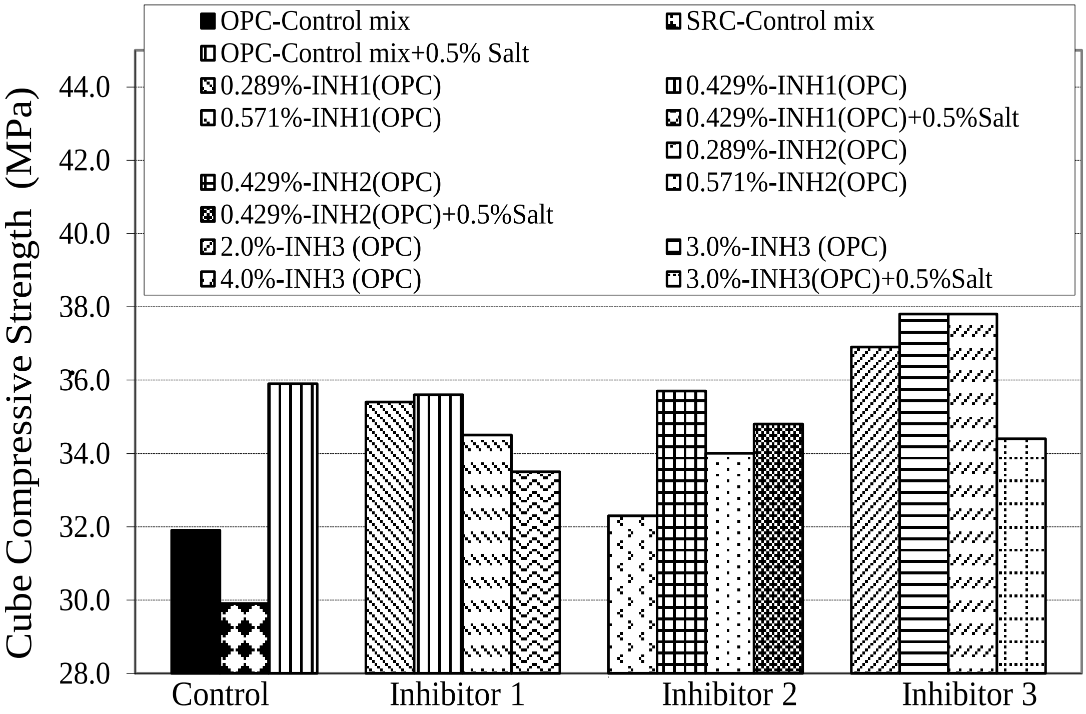
For rehabilitation of the concrete structures suffering severe corrosion, corrosion inhibitor is regarded as one of the simplest and most cost-effective techniques (Cabrera JG. and Al-Hasan AS 1997;d Ormellese M. et al 2009). As one of most commonly used inhibitive admixtures, nitrite can react with ferrous ions generating a Fe_2O_3 protective layer and reducing the corrosion rate of rebar (Berke NS and Hicks MC, 2004). Passive film on steel is a highly defective oxide film similar to n-type semiconductor (Li W.S. and Luo J.L., 2002; Ze Hua Dong et all 2011), and the electronic properties of passive film have strong ties with their stability in the presence of Cl^- ions. Freire et al recently found that the ratio of Fe^{2+}/Fe^{3+} in passive film decreased with the increase of applied potential (Freire L. et al, 2010). Cheng investigated the passive film formed on iron in borate buffer solution and concluded that the donor density decreased exponentially with the increase of film forming potential (Cheng Y.F. et al, 2002).

Also, electrochemical injection of corrosion inhibitors has been to alleviate carbonation-induced reinforcement corrosion in aging reinforced structures. This method involves application of aqueous solutions of organic base corrosion inhibitors onto the concrete surface with controlled current densities passed between anodes placed within the inhibitor solutions and the embedded steel bars acting as cathodes (Junichiro K. et al, 2013).

This study aims to evaluate the effect of different types of corrosion inhibitors that are used commercially in Egypt on the long-term corrosion resistance of reinforced concrete made of ordinary and sulfate-resistant cement.

2. Experimental program

Natural siliceous sand with a specific gravity of 2.60 and fineness modulus of 2.625, pink limestone with a nominal maximum aggregate size of 9.53 mm and a specific



1a) Concrete made of OPC

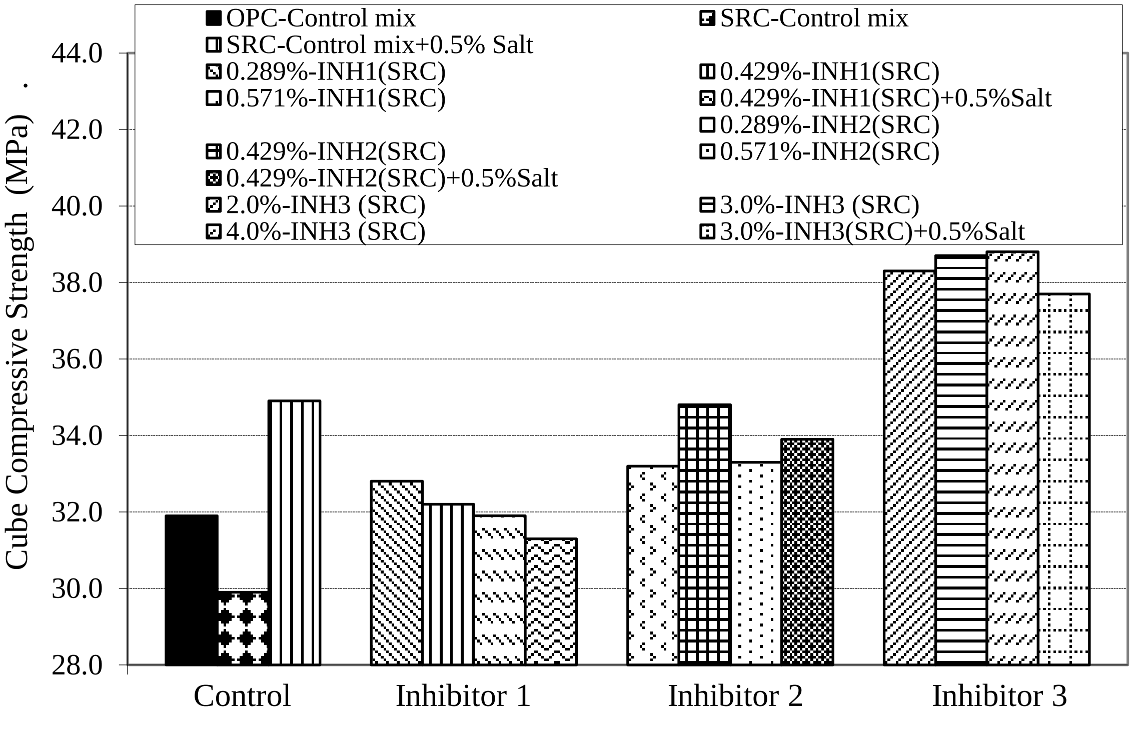
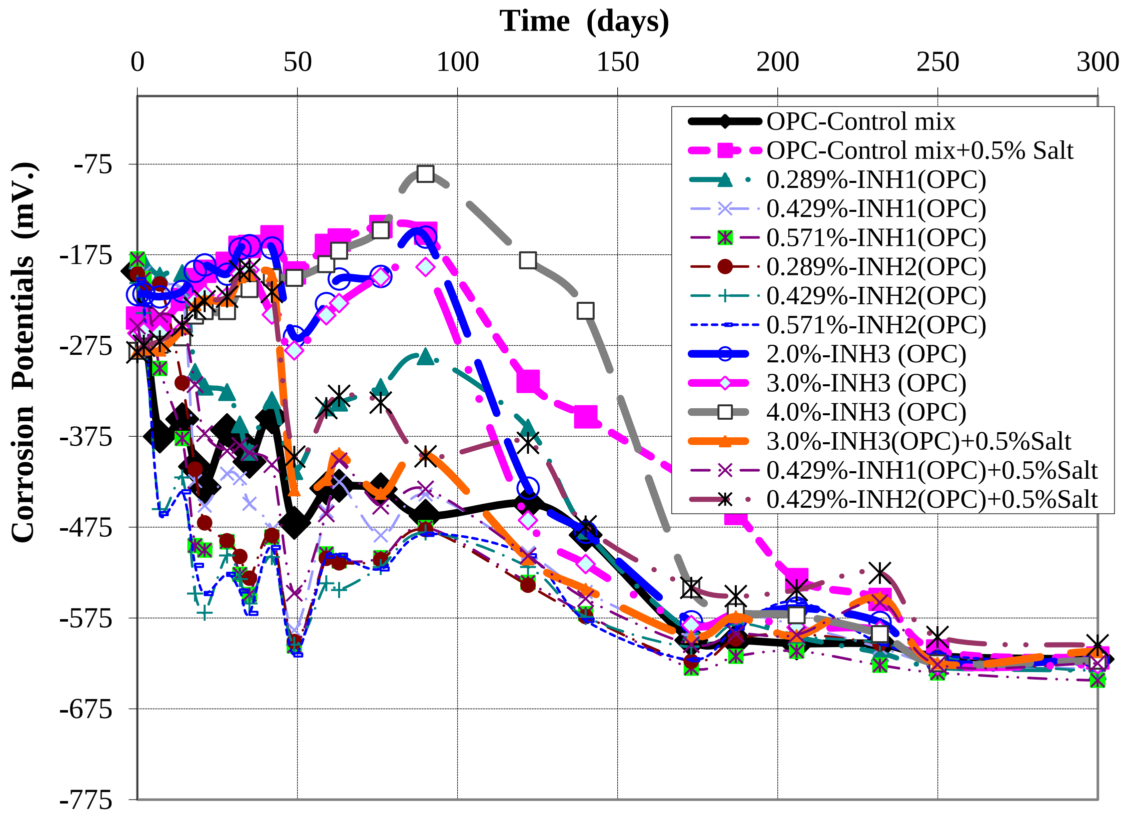


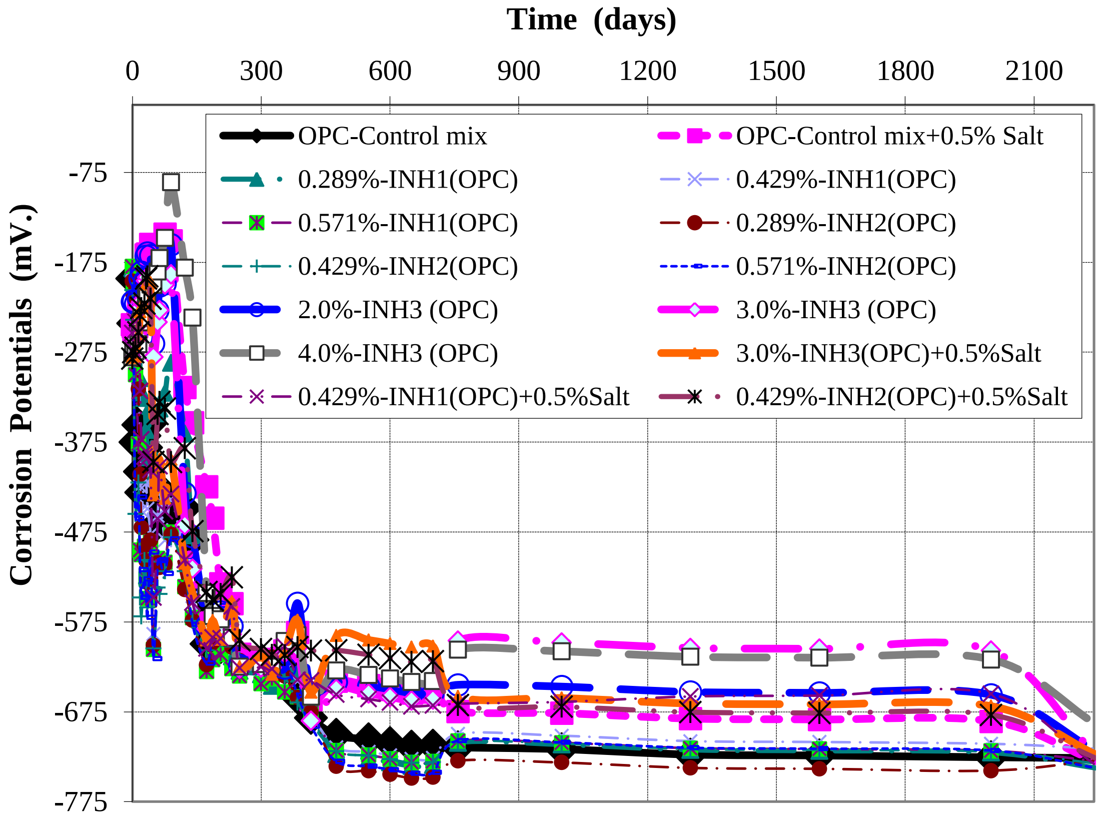
Fig. 1 Results of 28- day cube compressive strength of control mixes and concrete containing corrosion inhibitors for both concrete made of OPC and SRC.

gravity of 2.50, and both ordinary Portland cement (OPC) and sulfate-resisting cement (SRC) were used. These materials meet the requirements of Egyptian Standard Specification; ESS 1109/2002 for fine and coarse aggregate, ASTM C150 for OPC and for SRC.

Four variables were used which included type of cement, type of corrosion inhibitors, dosage of corrosion inhibitors, and the presence of sodium chloride in concrete mix. Both ordinary Portland cement and sulfate-resisting cement with 350 kg/m^3 cement content and three commercial corrosion inhibitors were considered in this study. The types of corrosion inhibitors included two anodic inhibitors based on calcium nitrite in both powder (INH1) and liquid form (INH2), and mixed inhibitor reactions (anodic and cathodic reaction) based on nitrogen

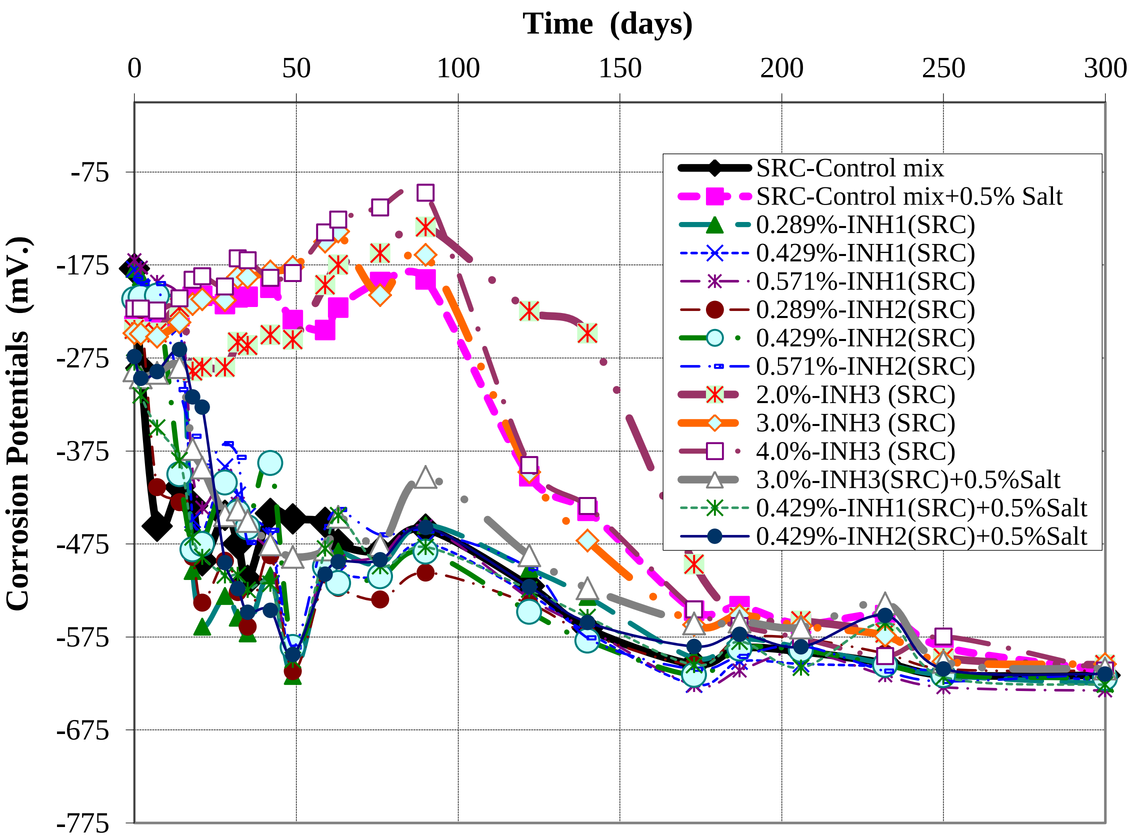


2a) Corrosion potential results up to 300 days

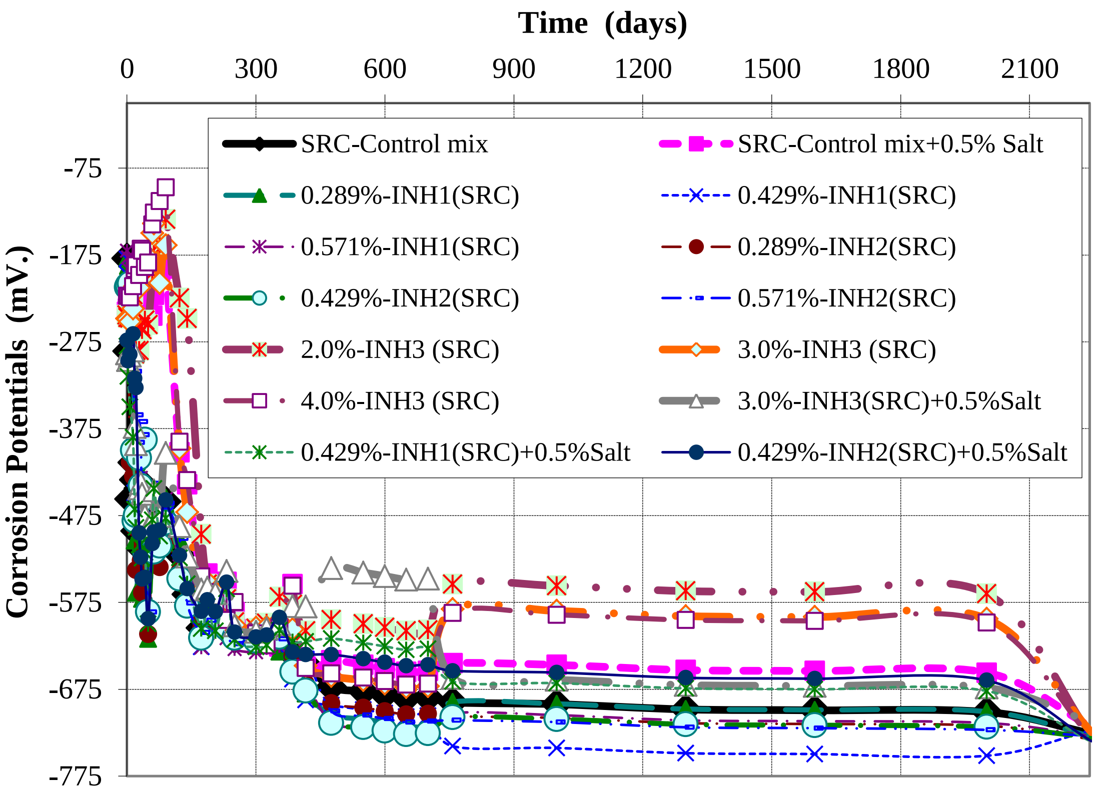


2b) Corrosion potential results up to 2200 days

Fig. 2 Results of corrosion potential measurements for OPC control mix and OPC concrete containing corrosion inhibitors.

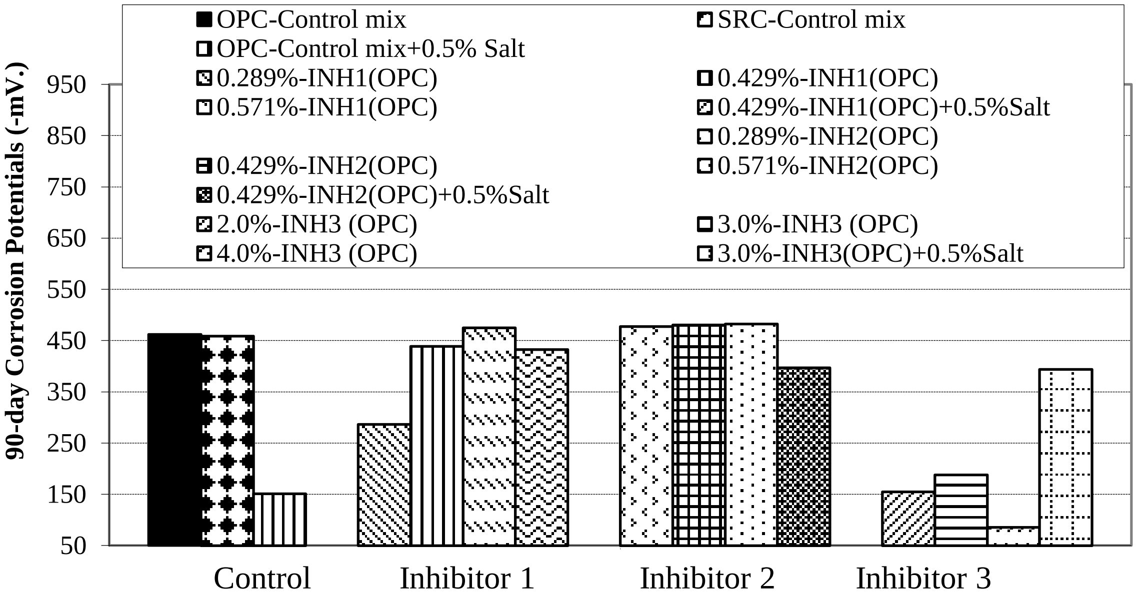


3a) Corrosion potential results up to 300 days

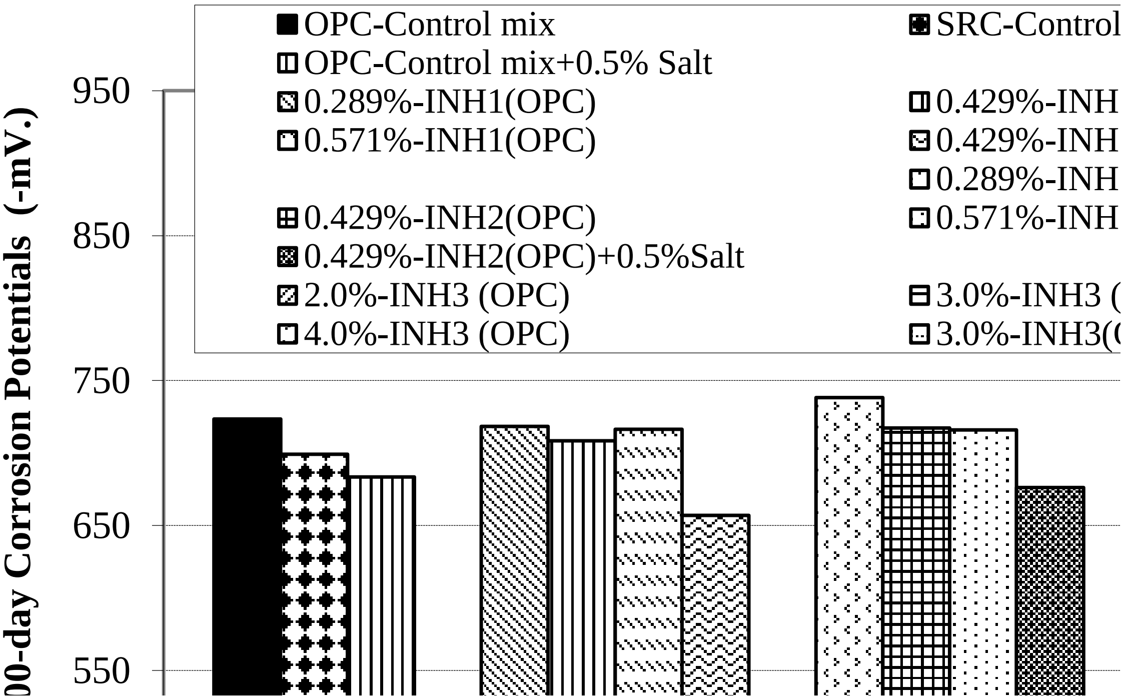


3b) Corrosion potential results up to 2200 days

Fig. 3 Results of corrosion potential measurements for SRC control mix and SRC concrete containing corrosion inhibitors.



4a) 90-day Corrosion potential

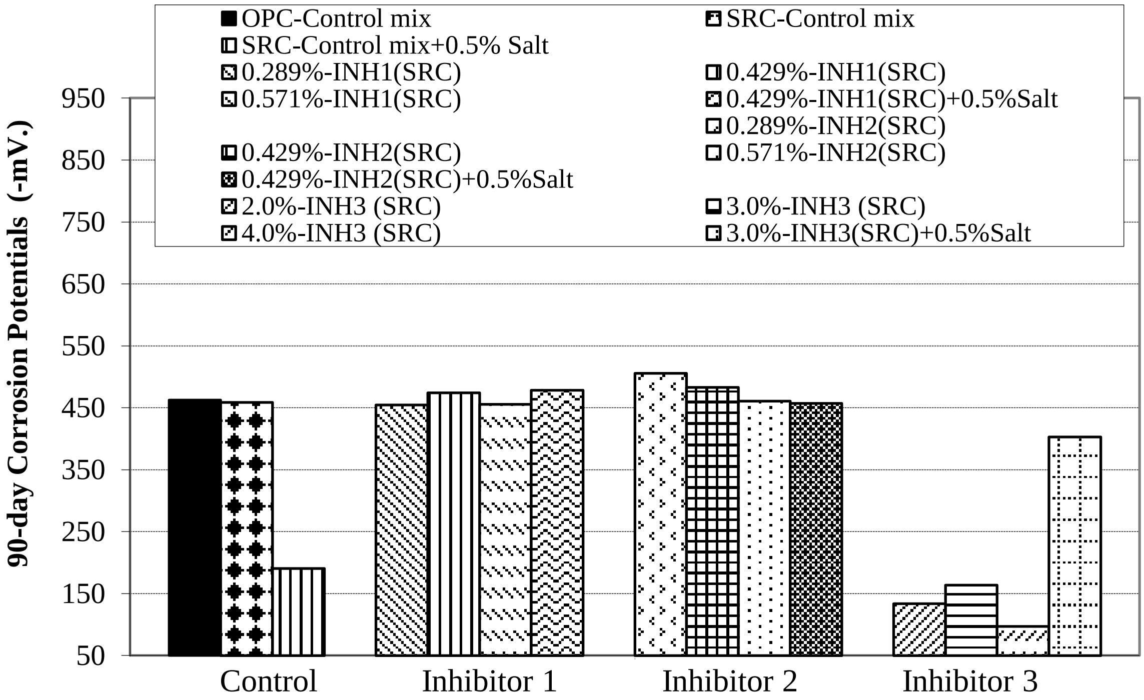


4b) 1600-day Corrosion potential

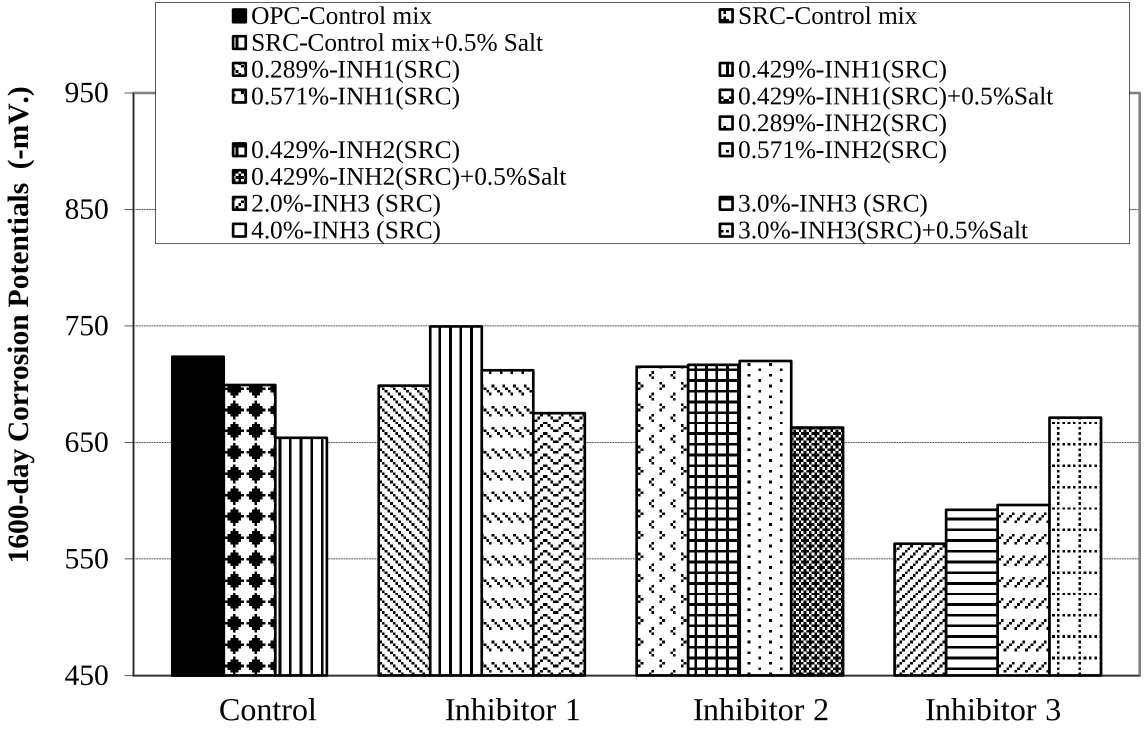
Fig. 4 Results of 90 and 1600-day corrosion potential for OPC control mix and OPC concrete containing corrosion inhibitors.

containing organic and non-organic substances (INH3). Three dosages for each used type of corrosion inhibitors that are in the range of producer recommendation were considered. Also, 0.5% sodium chloride (NaCl) was added directly in the mixture for control mixes and concrete mixes containing average dosage of the used inhibitors. These variables were included in 28 concrete mixes. All mixes had constant water content and high water reducing type F with different doses was added to mixes with INH1 and INH2 to fulfill a constant slump of 10 cm, while the used doses of INH3 gave the same previous slump without addition of high water reducing. Table 1 shows the used variables and mix proportions of 28 concrete mixes.

Compression tests (using 100*100*100 mm cube) were carried out at age of 28 days. Cylindrical concrete specimens (75x150 mm) were used in corrosion test. A reinforcing steel bar (360/520 MPa) of 12 mm diameter and 200 mm length was embedded centrally in the used concrete specimens. For each mix, three specimens were cast. A uniform concrete cover of 31.5 mm thickness was kept constant from the bottom and the sides of cylinder for the used steel bar. A thick layer of zinc rich primer coating was applied to protect the external part of the steel bar. The specimens were cured in potable water up to the test age of 42 days. After curing, the specimens were subjected to weekly wetting and drying cycles for 3 years



5a) 90-day Corrosion potential



5b) 1600-day Corrosion potential

Fig. 5 Results of 90 and 1600-day corrosion potential for SRC control mix and SRC concrete containing corrosion inhibitors.

and left dry for more than other 3 years at laboratory environment. In the wetting cycle, the specimens were partially immersed in 5% sodium chloride solution where the level of solution was kept constant at three times the cover thickness (94.5 mm). Corrosion was monitored by obtaining half-cell potentials of the embedded steel at different times using a voltmeter (ASTM 876-80). The whole testing period was 2244 days. After the end of the test, pH value, chloride content of concrete as a percentage of cement weight, crack width and length, and steel weight loss were determined. This program represents a real exposure condition to corrosion.

Figs 1a and 1b represent the 28-day cube compressive strength of control mixes and concrete containing corrosion inhibitors for both concrete made of OPC and SRC. From these figures, the 28-day cube compressive strength for concrete containing mixed inhibitor reactions (INH3) is higher than that of both control mixes (made of OPC and SRC) and concrete containing INH1 and INH2. The type of cement slightly affects the 28-day cube compressive strength.

3. Test results and discussion

3.1 Corrosion monitoring test results

Figs 2a and 2b show the half–cell corrosion potential measurements of OPC control mix and OPC concrete containing corrosion inhibitors up to 300 days and 2200 days, respectively while Figs 3a and 3b show these results for SRC control mix and SRC concrete containing corrosion inhibitors. In OPC and SRC control mixes, the absolute values of corrosion potentials are initially seen to increase and then continue increasing with different rate up to 250 days. After this time, the absolute values of corrosion potentials still increase with a very slow rate. Generally, in both OPC and SRC concrete containing corrosion inhibitors INH1 and INH2, the corrosion potential readings gives almost the same result of control mixes. Throughout the initial testing period up to 100 days, in both OPC and SRC concrete containing INH3, the absolute values of corrosion potential readings decrease with the increase of time. After this time, the absolute values of corrosion potentials increase as the time increases up to 250 days. Throughout the later testing period, the results of corrosion potentials for both OPC and SRC concrete containing INH3 give the same results of control mixes although their results are still less than those of both control mixes and concrete containing corrosion inhibitors INH1 and INH2. Also up to the first 100 days, the addition of 0.50 % sodium chloride to the control mixes (mix constituent) decreases the absolute values of the corrosion potentials as the time increases. The sodium chloride works as a filler in this stage. The effect of dosage of corrosion inhibitors and type of cement on the corrosion potential readings is not clear as shown in Figs 2a, 2b, 3a and 3b.

Figs 4a and 4b show the corrosion potentials for OPC control mix, SRC control mix and OPC concrete containing corrosion inhibitors at 90 and 1600 days, respectively while Figs 5a and 5b represent the same relation for SRC concrete. From these results and Figs 4b and 5b, the use of inhibitors based on calcium nitrite does not affect the corrosion potentials at 90 and 1600 days. According to the ASTM classification of corrosion half-cell potentials (ASTM C-876), the corrosion potential measurement of OPC, SRC concrete mixes and concrete with inhibitors based on calcium nitrite indicates that a 90 % statistical risk of corrosion is occurring before 90 days, where the threshold potential for corrosion (reflecting the initiation of corrosion) is taken at -250 millivolts. Also, these figures showed that OPC and SRC concrete containing mixed inhibitor reactions (INH3) have significant effect on corrosion activity at 90 days. This inhibitor is observed to reduce the 90-day corrosion potential of OPC concrete by approximately 66, 59 and 81 % for dosage 2, 3 and 4%, respectively. Also, the reduction of corrosion potential for SRC concrete due to the addition of 2, 3, and 4% of INH3 is about 71.0, 64.0 and 79.0 %, respectively. In addition, the use of 0.5 % sodium chloride in OPC and SRC mix constituent reduces the corrosion potential at 90 days by 67.0 and 58.0 % for these concretes, respectively due to the filling effect.

The effect of INH3 on the corrosion potential at 1600 days is less than that at 90 days. OPC concrete with 2, 3 and 4% INH3 is observed to reduce the 1600-day corrosion potential for OPC concrete by 9.6, 16.4 and 15%, respectively, while the reduction of the 1600-day corrosion potential for SRC concrete due to the addition of 2, 3 and 4% of INH3 is 19.5, 15.4 and 14.7%, respectively. So, only, the use of mixed reaction inhibitor INH3 improves the corrosion resistance for both OPC and SRC concrete.

3.2 Corrosion resistance factor

Corrosion resistance factor (CRF) is proposed to evaluate the reinforcement corrosion activity and could be expressed as the inverse of the area under the time-corrosion potential relation. The unit of this factor is $(\text{mV. day})^{-1}$. If the absolute value of CRF increases the corrosion resistance of steel improves. Figs 6 and 7 represent the relation between corrosion resistance factor and time for OPC and SRC concrete containing different types of corrosion inhibitors. Also Fig 8a shows the results of corrosion resistance factor for OPC concrete mixes at 49 days while Figs 8b shows the results of corrosion resistance factor at the same time for SRC concrete. These figures showed that as the time increases the CRF absolute values decrease. This result is logic as the time increases the corrosion increases.

The CRF values for both OPC and SRC concrete containing anodic inhibitors corrosion inhibitor (INH1 and INH2) are very close for those of control mixes throughout the whole testing period. So the addition of INH1 and INH2 to concrete does not improve the corrosion resistance of embedded steel and occasionally they have adverse effect on the corrosion resistance especially for concrete made of OPC while the addition of these inhibitors generally improves slightly the initial corrosion resistance factor of concrete made of SRC. For example, the ratio of 49-day corrosion resistance factor for OPC concrete with 0.289, 0.429 and 0.571% INH1 and that of OPC control mix is 1.26, 1.0 and 0.84 respectively, while this ratio of CRF for INH2 with the same previous dosage is 0.90, 0.77 and 0.76, respectively. Also, ratio of the 49-day corrosion factor for SRC concrete with 0.289, 0.429 and 0.571% INH1 and that of SRC control mix is 1.0, 1.15 and 1.18, respectively, while this ratio for INH2 with the same previous is 0.93, 1.11 and 1.20, respectively.

These results may be due to the decrease of the used dosage recommended by producer, of INH1 and INH2 where the relative concentrations of nitrite and chloride ions are important. The ratio of CL^-/NO_2^- should be less than or equal 1.1 (Smith et al., 2000 and Virmani, 1988). So, anodic inhibitors are said to be dangerous because the corrosion rate will increase if too little inhibitor is used (Trethewey et al., 1988). The CRF absolute values of both

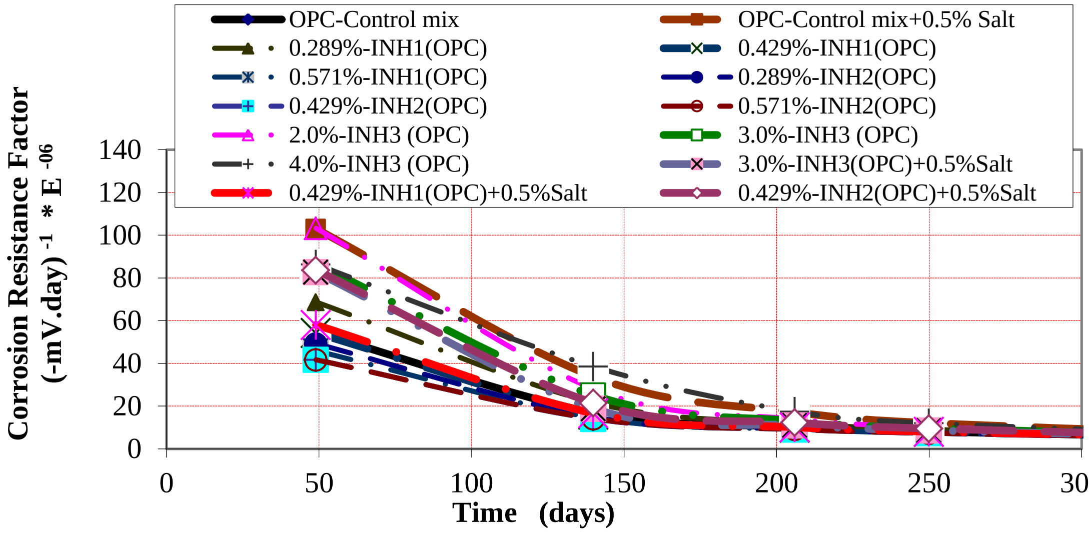


Fig. 6 Results of corrosion resistance factor up to 300 days for OPC control mix and OPC concrete containing corrosion inhibitors.

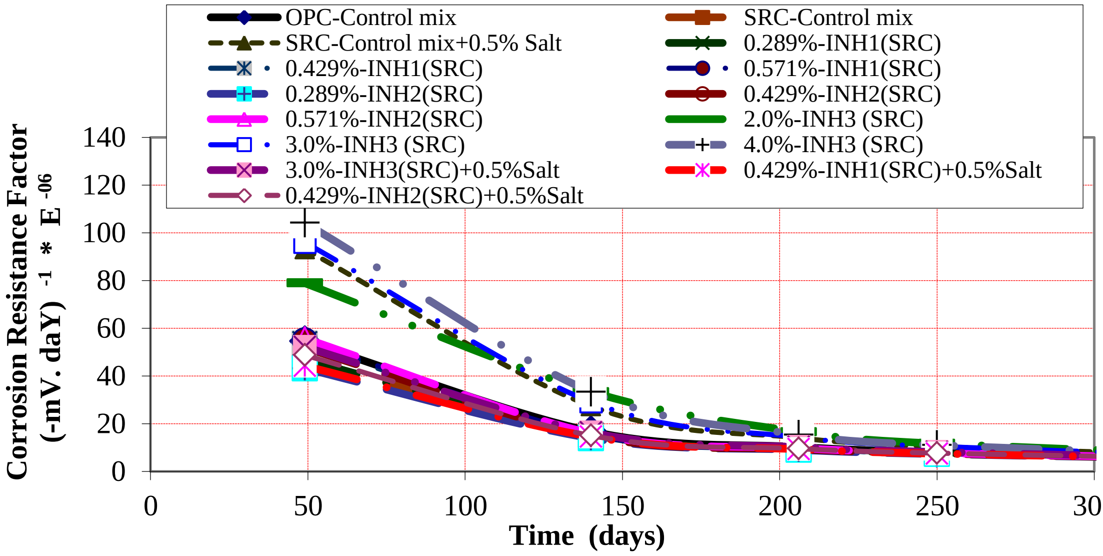
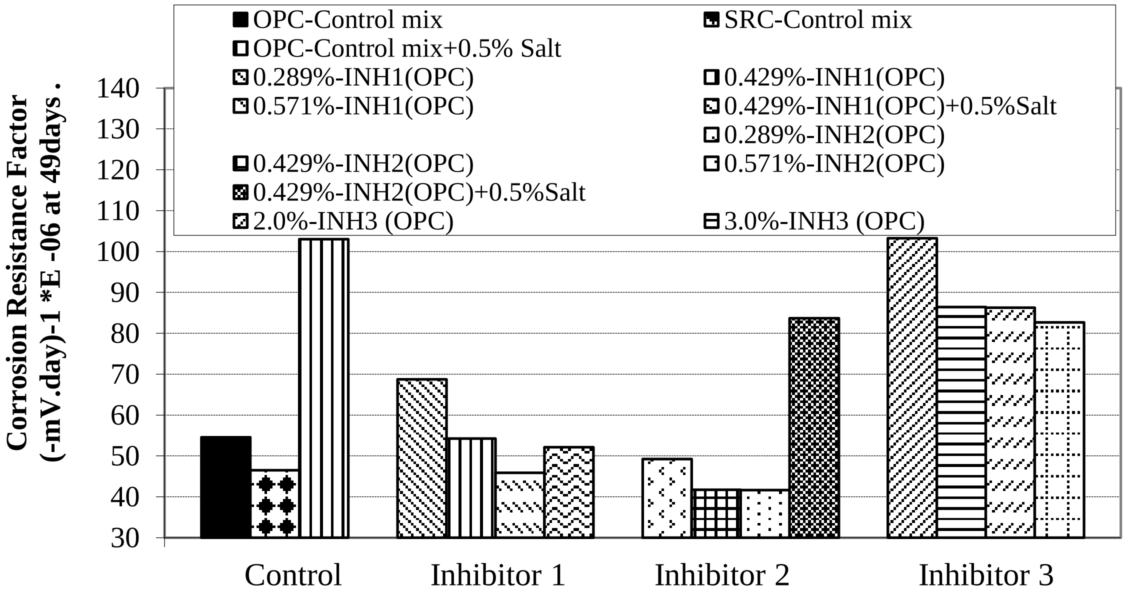
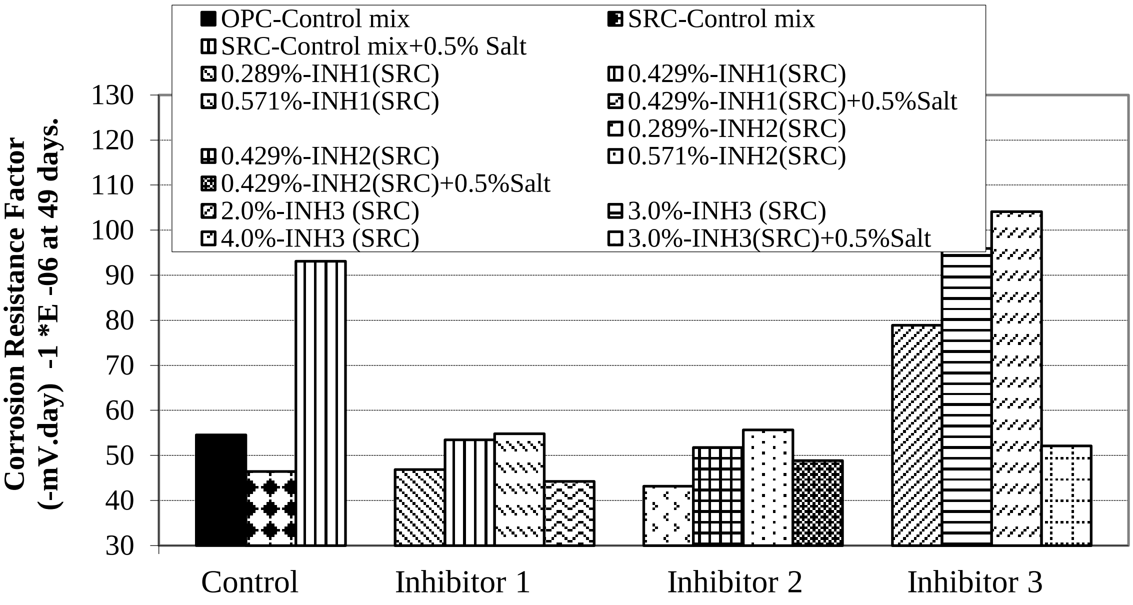


Fig. 7 Results of corrosion resistance factor up to 300 days for SRC control mix and SRC concrete containing corrosion inhibitors.



8a) 49-day CRF for OPC concrete



8b) 49-day CRF for SRC concrete

Fig. 8 Results of 49 -day corrosion resistance factor for both OPC and SRC concrete.

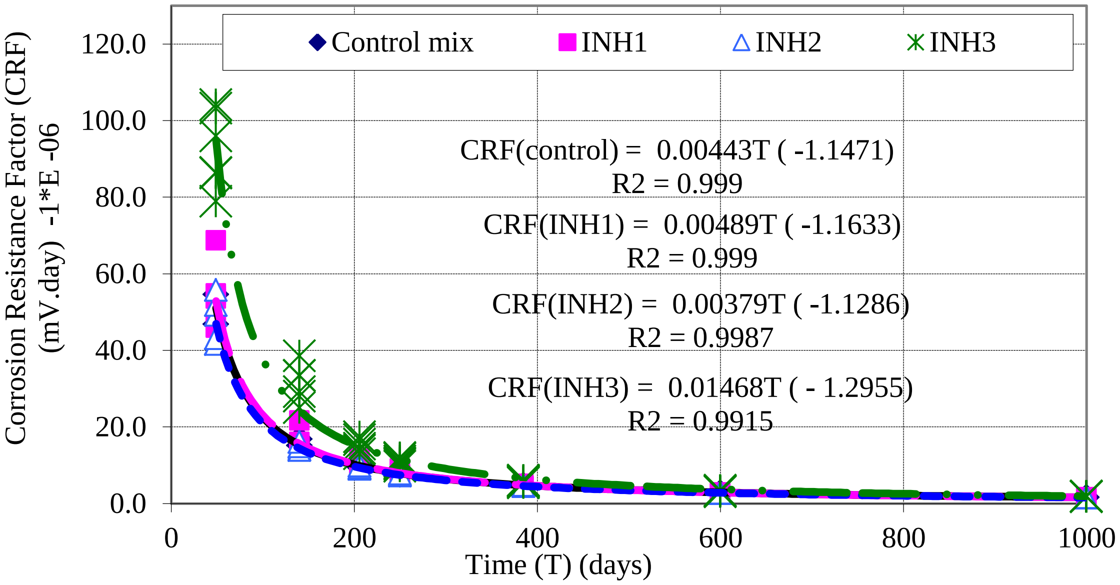


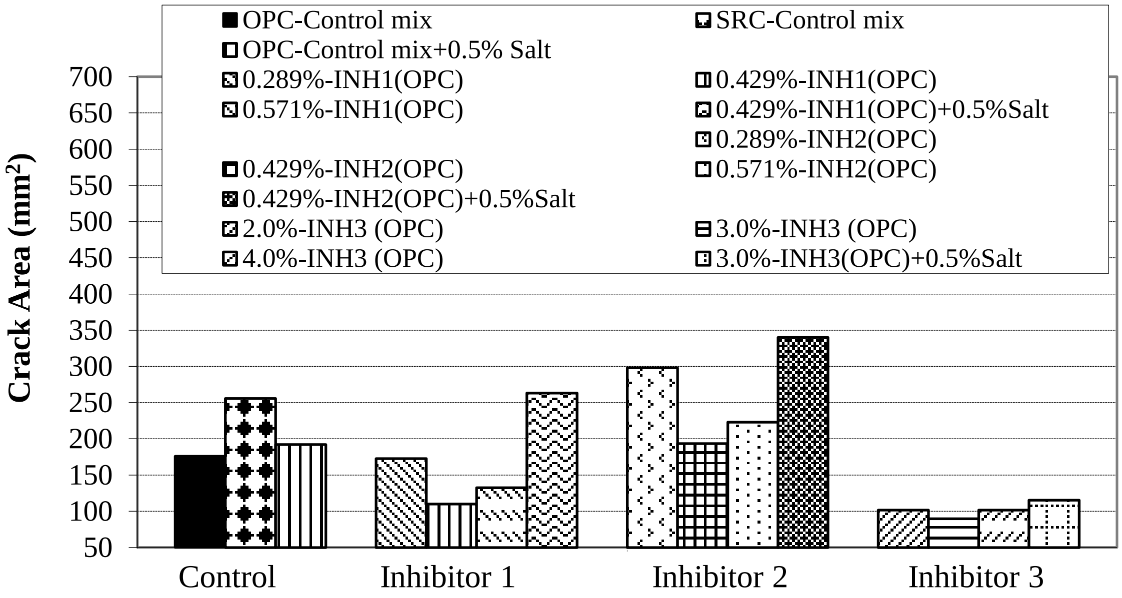
Fig. 9 Relation between absolute values of corrosion resistance factor and time

OPC and SRC concrete containing mixed inhibitor reactions (INH3) are higher than those of control mixes during the initial testing period up to 300 days and they are very close for those of control mixes after this time. INH3 with dosage of 2.0, 3.0 and 4.0 % is observed to improve the 49-day corrosion resistance factor of OPC concrete by 89.0, 58.0 and 58.0 %, respectively, while this improvement of SRC concrete by using the same previous dosage is 70.0, 106.5 and 124.0 %, respectively. The increase of dosage of INH3 improves the 49-day corrosion resistance factor for SRC concrete while the effect of dosage of INH3 on the 49-day corrosion resistance for OPC concrete is not clear (see Figs 8a and 8b). The 49-day CRF absolute value of OPC control mix is higher than that of SRC control mix by 17.4%. The addition of 0.5% sodium chloride improves the 49-day corrosion resistance factor of OPC and SRC control mix by 89.0 and 100.0%, respectively due to the filling effect. At 2100-days, the presence of chloride decreases the corrosion resistance factor.

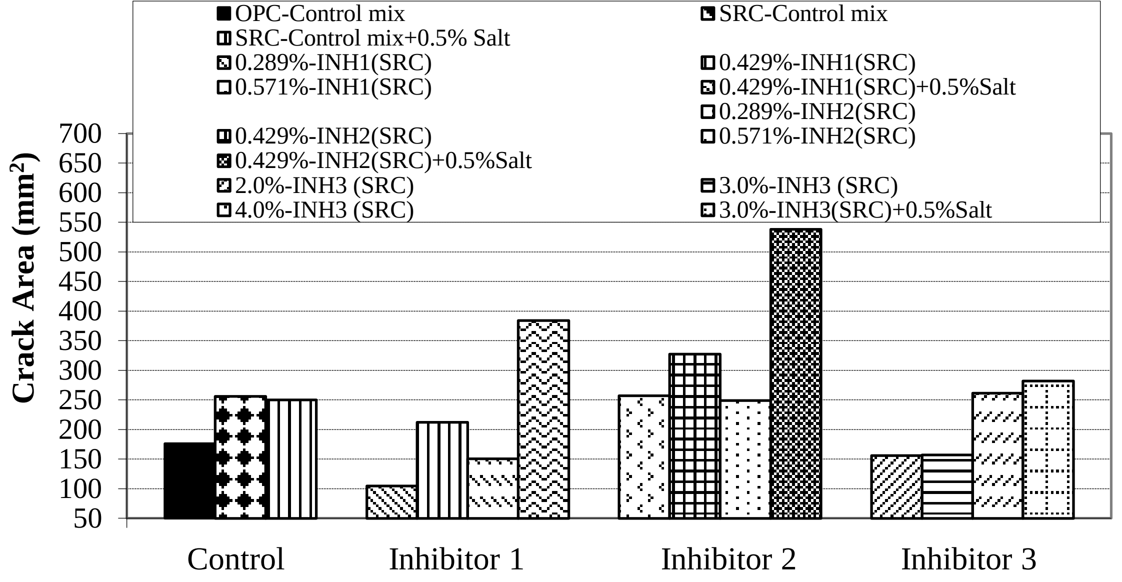
Due to the close results of corrosion resistance factor for OPC concretes and that for SRC concretes (see Figs 6 and 7). So, one can derive the relation between time and absolute value of corrosion resistance factor for control mixes and concrete containing used corrosion inhibitors as shown in fig 9. These relations take the following formula:

$CRF_{(control)} = 0.00443T^{(-1.1471)}$ for control mixes (1)
$CRF_{(INH1)} = 0.00489T^{(-1.1633)}$ for inhibitor 1 (INH1) (2)
$CRF_{(INH2)} = 0.00379T^{(-1.1286)}$ for inhibitor 2 (INH2) (3)
$CRF_{(INH3)} = 0.01468T^{(-1.2955)}$ for inhibitor 3 (INH3) (4)

Where CRF and T are the absolute value of corrosion resistance factor in $(mV.day)^{-1}$ and time in days, respectively. From these equations, it can be noticed that



10a) Crack area of OPC concrete



10b) Crack area of SRC concrete

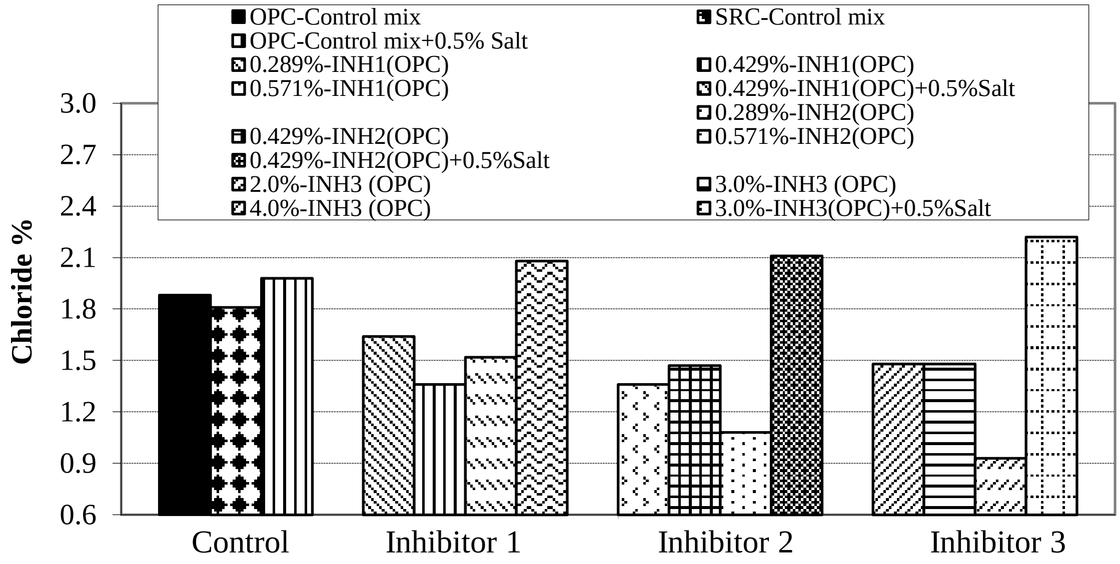
Fig. 10 Results of crack area for both OPC and SRC concrete

the equation of CRF for control mixes and the two equations of CRF for both INH1 and INH2 based on calcium nitrite with the producer recommendation dosage is very close. From the previous results, the effect of corrosion inhibitor based on calcium nitrite (INH1 and INH2) with the producer recommendation dosage on the corrosion activity (corrosion potentials and corrosion resistance factor) is negligible while the use of mixed reaction corrosion inhibitor based on nitrogen containing organic and non-organic substances (INH3) with the producer recommendation improves the corrosion resistance of embedded steel especially during the initial testing period.

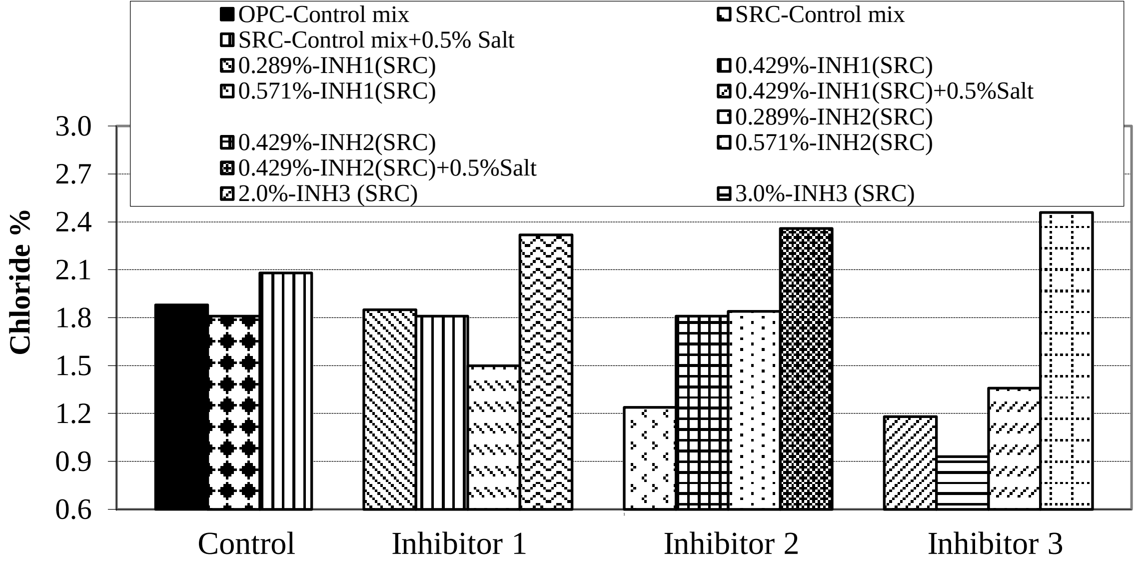
3.3 Crack area

After 2244 days, the specimens were taken out from the tank that were subjected to weekly wetting and drying cycles for 3 years and left dry for more than other 3 years at laboratory environment. It was noticed that most specimens had one crack and other specimens had more than one crack with different length and width. Also there were no cracks in some specimens. The crack width and length for any crack for each specimen was measured and the crack area of these cracks was determined. Each plotted result in Figs 10a and 10b is an average of crack areas obtained from three specimens. Figs 10a and 10b show the crack area of both OPC concrete and SRC concrete, respectively.

From these figures, the use of 2, 3 and 4% INH3 reduces the crack area of OPC control mix by 42.0, 49.0 and 42.0%, respectively, while this reduction of crack area for SRC control mix using the same previous dosage is 39.0, 38.5 and ~ 0.0 %, respectively. Generally, the use of



11a) Chloride percent of OPC concrete



11b) Chloride percent of SRC concrete

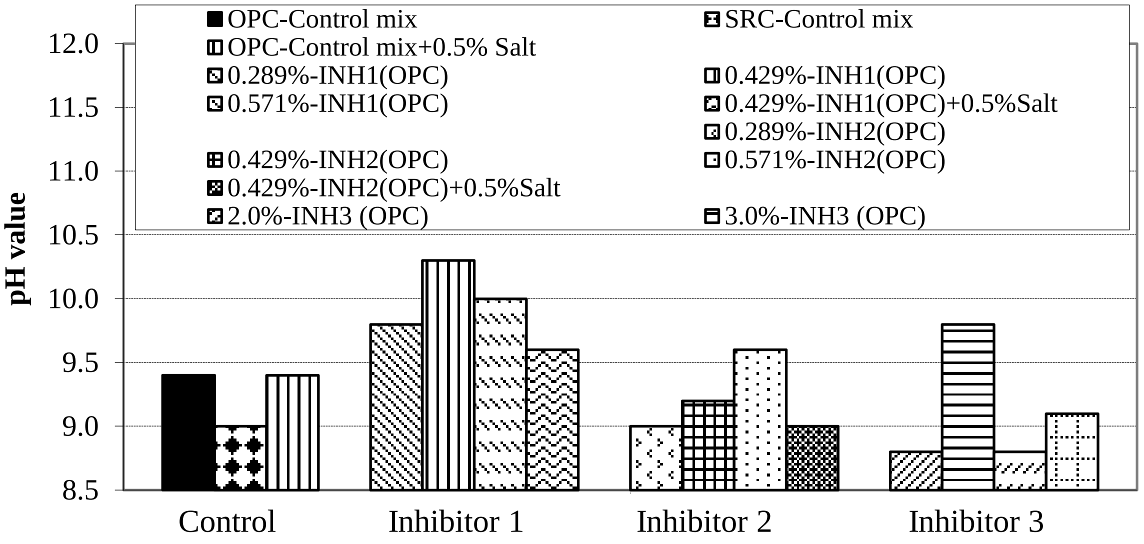
Fig. 11 Results of chloride percent for both OPC and SRC concrete.

INH1 also reduces the crack area of OPC and SRC concrete. The use of INH2 increases the crack area of both OPC and SRC concrete. The use of SRC and the addition of 0.5 % sodium chloride to the mix constituent have an adverse effect on the crack area for all studied concrete specimens as shown in Figs 10a and 10b.

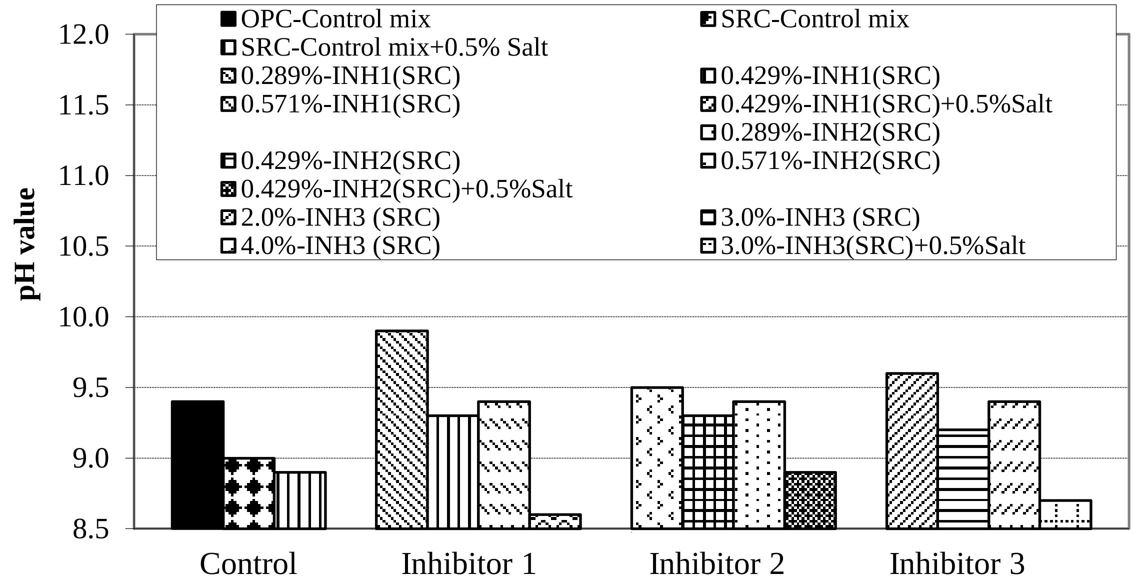
The crack area of OPC control mix is less than that of SRC control mix by 31.0 %. Also, the crack area of OPC concrete with 2, 3 and 4% INH3 is less than that of SRC concrete with the same dosage of inhibitor by 34.8, 42.8 and 61.0 %, respectively. From the previous discussion, the crack area of concrete specimens due to corrosion of embedded steel depends upon the cement type, the presence of salt (CL^- ion) in concrete mix and the type of corrosion inhibitor. Still, the use of INH3 gives better results of crack area compared with that of control mix and concrete with anodic corrosion inhibitor (INH1 and INH2) with the producer recommendation dosages.

3.4 Chloride percent and pH value

After the end of test, the chloride percent (the chloride diffused from salt solution) and pH values of all studied concrete specimens were obtained. Figs 11a and 11b show the chloride percent of OPC and SRC concrete with and without used corrosion inhibitors, respectively. Generally, from these figures, the use of corrosion inhibitor decreases the chloride percent of OPC and SRC concrete. The addition of 0.5 % sodium chloride to OPC and SRC concrete with and without corrosion inhibitors increases the chloride percent. Only, the use of 0.571 % of INH1 and 0.289 % of INH2 reduces of chloride percent of SRC concrete by 17.0 and 32.0 % respectively, while the use of other dosage of INH1 and INH2 does not affect the chloride percent of SRC concrete. In addition to, the use of 2, 3 and 4 % of INH3 reduces the chloride percent of SRC concrete by 35.0, 49.0 and 25.0 % respectively.



12a) pH values of OPC concrete



12b) pH values of SRC concrete

Fig. 12 Results of pH values for both OPC and SRC concrete.

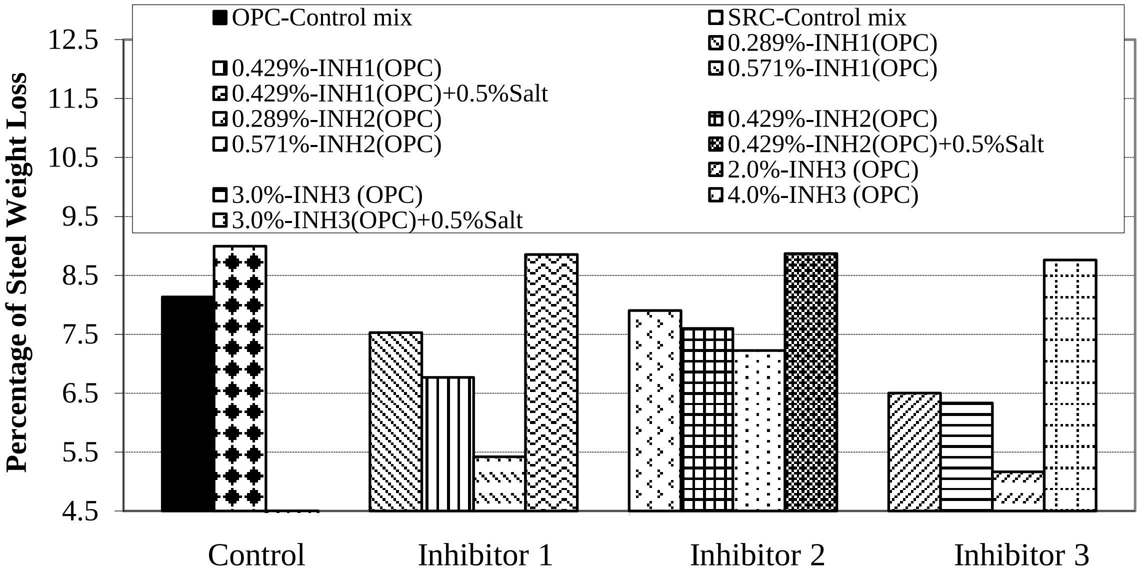
Generally, one can conclude that the addition of corrosion inhibitors to concrete reduces the chloride percent of both OPC and SRC concrete. This result agree with the result of Buffenbarger et al, where they reported that organic inhibitors help to decrease the chloride content in concrete and to promote a decrease on the chloride ion diffusion (Buffenbarger J.K. et al, 2000).

Figs 12a and 12b represent the pH values of OPC and SRC concrete, respectively. It can be noticed that effect of used corrosion inhibitors on the pH values of OPC concrete is not clear. Some of used inhibitors such as inhibitor 1 gives slightly higher values of pH values compared with that of OPC control mixes, while the use of INH2 and INH3 gives generally lower values of pH values compared with that of OPC control mix. Generally, the use of all studied corrosion inhibitors improves slightly the pH values of SRC concrete. Generally, the addition of 0.50 % sodium chloride to concrete has an adverse effect on the pH values.

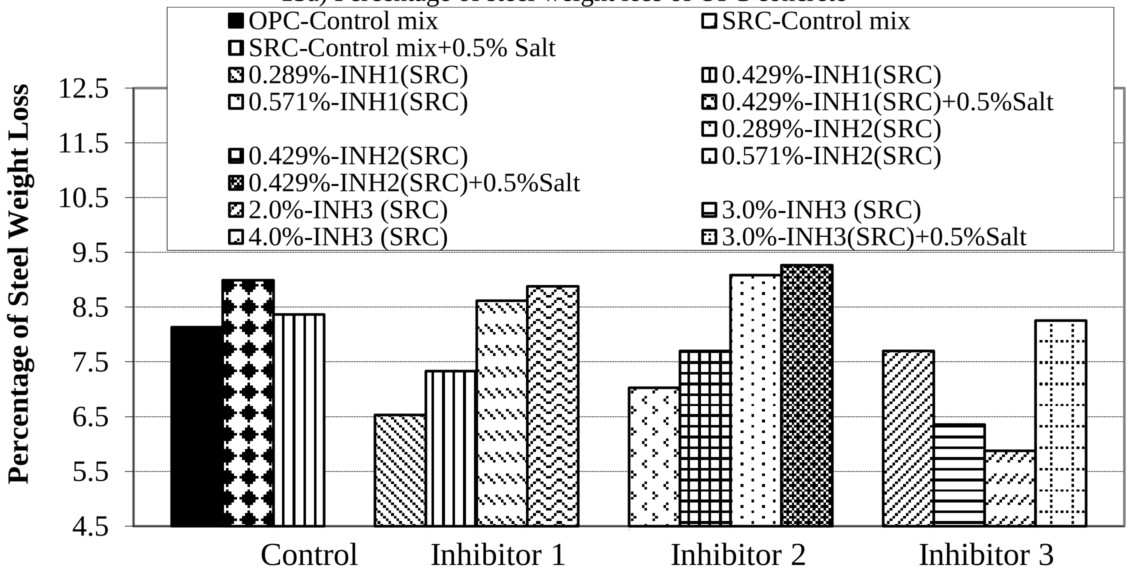
3.5 Percentage of steel weight loss

After the end of the test, the embedded part of steel bars was cleaned from the corrosion and weighed. Then, the average percentage of steel weight loss of three specimens was calculated. Figs 13a and 13b represent the percentage of steel weight loss for OPC and SRC concrete with and without corrosion inhibitors. Generally, the use of corrosion inhibitors decreases the percentage of steel weight loss for OPC and SRC concrete. Also, the addition of 0.50 % sodium chloride to concrete mix increases the percentage of steel weight loss. It can be noticed that the use of 0.289, 0.429 and 0.571 % of INH1 decreases the percentage of steel weight loss of OPC concrete by 7.4, 16.8 and 33.3 %, respectively, while this decrease by using the same previous dosage of INH2 is 2.8, 6.8 and 11.2, respectively. Also the use of 2, 3 and 4 % of INH3 improves the percentage of steel weight loss of OPC concrete by 20.0, 22.1 and 36.5 %, respectively.

The ratio of the percentage of steel weight loss of SRC concrete with 0.289, 0.429 and 0.571 % INH1 and INH2 to that of SRC control mix is 0.73, 0.82 & 0.95 and 0.78, 0.86 & 1.01, respectively. Also the steel weight loss of SRC concrete with 2, 3 and 4 % INH3 is less than that of SRC control mix by 8.7, 27.9 and 32.9 %. The percentage of steel weight loss of OPC control mix is less than that of SRC control mix by 9.60 %. From these results, the percentage of steel weight loss due to corrosion may be reduced using corrosion inhibitors. This result does not coincide with the result obtained using accelerated corrosion test (50 volts were used) (Diab A., and Elyamany H., 2000). This may be due to the high temperature accompanied to the accelerated corrosion test where this temperature may destroy the insoluble protective film on anodic surfaces.



13a) Percentage of steel weight loss of OPC concrete



13a) Percentage of steel weight loss of SRC concrete

Fig. 13 Results of percentage of steel weight loss of both OPC and SRC concrete.

As the dosage of corrosion inhibitor increases, the percentage of steel weight loss embedded in OPC concrete decreases. In addition to, the use of OPC concrete gives better values of percentage of steel weight loss compared with that of SRC concrete due to the decrease of C3A %. Traditionally, the binding capacity of cement for chloride ions has been considered to be directly related to the C3A content of the cement. This is because the chloride ions can react to form insoluble chloroaluminates. The chloride ions, however, cannot be totally removed from solution by chemical binding. An equilibrium is always established between the bound and the free chloride ions, so that even with high C3A contents, there will always be some free chloride ions in solution. There is increasing evidence that a reaction with C3A is only one of several mechanisms for effectively removing chloride ions from solution. In ordinary Portland cements, there is no direct relationship between the concentration of bound chloride ions and the C3A content. There is, however, a qualitative relationship with both the (C3A + C4AF) content and pH of the pore solution (ACI 222R-01, 2001). The addition of 0.50 % sodium chloride has an adverse effect on the steel weight loss as it is expected.

From the previous discussions, the half-cell potentials of reinforcing steel in concrete according ASTM C 876 does not show clearly the effect of type of cement, the presence of salt (CL^- ion) in concrete mix, the type of corrosion inhibitor, and the dosage of corrosion inhibitors on the corrosion activity of the reinforcing steel. Also, there are some contradictions between the results obtained using this method and the results obtained using the percentage of steel weight loss which is more accurate. So, one should not depend completely on the half-cell results for evaluation the corrosion activity

4. Conclusions

Based on the results obtained in this study (whole testing period was 2244 days), the following conclusions can be drawn:

- The addition of anodic corrosion inhibitor based on calcium nitrite (INH1 and INH2) with the producer recommendation dosage to OPC or SRC concrete has an insignificant effect on the corrosion potentials throughout the whole testing period.
- The use of mixed reaction corrosion inhibitors based on nitrogen containing organic and non-organic substances with the producer recommendation dosage (INH3) has significant effect on the corrosion potentials in the early testing period up to 200 days for OPC and SRC concrete. However, throughout the later testing period, this inhibitor has an insignificant effect on the corrosion potentials.
- The addition of mixed reaction corrosion inhibitors based on nitrogen containing organic and non-organic substances with the producer recommendation dosage (INH3) to OPC and SRC concrete improves clearly corrosion resistance factor in the early testing period up to 300 days.
- The addition of anodic inhibitors based on calcium nitrite with the producer recommendation dosage (INH1 and INH2) to SRC concrete does not improve the corrosion resistance factor of embedded steel. The relative concentrations of nitrite and chloride ions for these inhibitors are important.
- The crack area of concrete specimens due to corrosion of embedded steel and percentage of steel weight loss depend upon the cement type, the presence of salt (CL^- ion) in concrete mix and the type of corrosion inhibitor.
- The use of corrosion inhibitors based on calcium nitrite (INH1 and INH2) and mixed reaction corrosion inhibitors based on nitrogen containing organic and non-organic substances (INH3) decreases the percentage of steel weight loss due to corrosion for OPC concrete.
- The use of corrosion inhibitors based on calcium nitrite (INH1 and INH2) and mixed reaction corrosion inhibitors based on nitrogen containing organic and non-organic substances (INH3) has an insignificant effect on pH values for OPC and SRC concrete.

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