Relationship between steel mass loss and accelerated corrosion regimes in reinforced concrete columns

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Abstract. Present study aims to observe the consequence of varying the intensity of the accelerating impressed electrical current and situations of wetting-drying as hybrid accelerated corrosion regime on synthetically corroded concrete specimens, especially the loss of steel mass. Small-scaled reinforced concrete columns were fabricated and synthetically corroded by altered accelerating corrosion situations by applying an impressed current with intensity ranging between (50 and 500 µA/cm²). Moreover, the impressed current joined with two dissimilar durations of wetting- drying cycles for assessment. The steel mass losses during and at the end of the accelerated corrosion process were calculated, also, cracking configuration and damage shape were observed for accelerating corrosion. The outcomes designated that the hybrid method (impressed current joined with cycles of saline solution wetting and drying series) can be employed adequately to simulate the regular corrosion process in the reinforced concrete structure. The steel mass loss is mostly influenced by the intensities of the impressed accelerating current, while the crack appearance and the pattern of surface cracks, is influenced by wetting and drying cycles as well as the impressed accelerating current. Yet, increasing the current intensity produce a considerable growth in the cracking owing to the reinforcing steel corrosion in shorter stage.

1. Introduction

Steel corrosion in every situation is an electro-chemical process wherein Fe (iron) is eliminated from the corroded steel, dissolving within the nearby solution, to form Fe + (ferrous ions). Intended for embedded steel in concrete structures, the dissolving activity occur in the bounded quantity of water solution existing in the concrete pores neighboring the steel. The dissolving ions (Fe+) in the pore solutions of concrete generally rejoin with the ions of hydroxide (OH⁻) and dissolved particles of oxygen (O₂) to create one or a combination of numerous kinds of rust, namely as a solid byproduct of the reaction of corrosion. The rust is typically precipitated on the boundary of the reinforcement steel bars and the concrete. It’s formation within this constrained space leads to cracking in the concrete cover due to the extensive stresses. These cracks take place above the steel reinforcing bars and arrange in a line with them, this is associated to a severe durability distress [1]–[3].

Natural steel corrosion is extremely slow, requiring more than (10 years) to make severe structural damage. For example, Zhang et al [4]–[6] allowed the laboratory reinforced concrete specimens to corrode naturally, they were required to wait for more than (4 years) for steel corrosion to being and an additional (two years) for the appearance of first cracking. It required 20 years to reach the level of dangerous structural damage. Many efforts were done to practice numerous regimes to accelerate the corrosion of embedded steel in concrete for attempting to shrink the time that required for tests. Numerous literatures have been specified on acceleration the corrosion process in reinforced concrete
using Galvano-Static Method (otherwise known as Impressed Current System) joined with solution of saline. El Maaddawy et al. [7], carried out an experimentation on full-scaled reinforced concrete beams that were affected by attacks of the chloride at altered intervals of subjecting a constant impressed current at density of (215 mA). The results revealed that the average steel mass loss fluctuated around (8.9 % to 31.6%). Though, the width of maximum cracks varied from (0.9 to 2.9) mm at subjecting periods ranging between (50 to 310 days) correspondingly. Malumbela et al. [8], examined a different strength full-scaled reinforced concrete beams put under (5% NaCl) solution wetting and drying cycles to accelerate the embedded steel corrosion. An impressed constant current of density (189,µA/cm²) was applied. A 0.04 mm crack width in the reinforced concrete due to corrosion products caused by (1%) steel mass loss. Similarly in the other experimental investigation accomplished by Elghazy et al.[9], approved a comparable process for accelerating steel corrosion with (180 µA/cm²) impressed current and (5% NaCl) solution of identical cycles of wetting and drying were employed in the reinforced steel bars. Wang et al. [10], experimentally examined the corrosion effect on reinforced concrete slabs by impressing of a constant current of (50-200 µA/cm²) with different arrangements (half soaking in solution of (5% NaCl), full soaking in solution of (5% NaCl), and wet dry cycling). It was found that the applicable manner of accelerated corrosion was governed by the goal of the research. The small impressed current with the cycles of wetting and drying process and half soaking were selected if study was on corroded steel rebar reinforcement itself, whereas, if research was on the bond between corroded steel reinforcement and the damaged concrete or expansive rusts products that led to the concrete cover cracking, wet dry cycles with a slight impressed accelerating current is used. However, the partial soaking accelerating corrosion manner (soaking up to two-third of the height of the specimen in saline solution with concentration of 3.5 %) with great impressed accelerating current at (1Am) to achieve the expansive products that form the cracks in corroded specimens have been nominated in the another research directed by Kashi et al.[11] .

Kearsley and Joyce [12] employed great impressed current with regular intensity of (1087 µA/cm²) and fully soaked reinforced concrete specimens in (5%, NaCl) solution for accelerating the process of steel corrosion. Furthermore, Sanz et al [13], designated impressed current regime using great constant current concentration of (400 µA/cm²) and fully soaked specimens in CaCl solution for accelerating the loss of bonding concerning the reinforcement steel bar and concrete. Kashani et al. [14], inspected the performance of steel reinforcement bars through corrosion process and they accomplished noticeable corrosion rate by applying (1100 – 2400 µA/cm²) with complete soaking in (3% NaCl) solution. Even though, Pritzl et al. [15], implemented accelerated corrosion approach by applying little impressed current concentration at series between ( 30 and 45 µA/cm²) joined (6% NaCl) solution wetting and drying cycles.

Previously local studies, Al-Galawi et al.[16], employed the impressed current accelerating corrosion method so as to achieve simulating exposure intervals equivalent of (5 and 25 years) regular exposure of corrosion situations and the applied current concentrations of (50-100 µA). Besides, further local experimental investigation on embedded steel accelerated corrosion by Hassan [17], studied the influence of a ( 600 µA/cm²) impressing current to accelerate the steel reinforcing bars corrosion on reinforced concrete beams. The author reaches steel mass loss of 26% afterward (60 days) from beginning the accelerating corrosion practice. Regardless of various investigations being presented in the accelerated steel corrosion regime for, there are no identical Standard specification ways for accelerating corrosion of the embedded steel on laboratory reinforced concrete samples. Therefore, it necessitates further investigations for recognizing the applicable arrangements for accelerating corrosion in the research laboratory experiments that make appropriate simulation of the ordinary corrosion of embedded steel in the reinforced concrete. The reinforced concrete columns comprising columns in marine structure, reinforced concrete piles, and highways bridges columns, are more relevant structural elements, which are mostly susceptible for embedded steel corrosion owing to subjecting for the moisture and severe environment, producing dangerous drops in the capacity of the
load transport and structural reliability of the elements. In the existing research work, six small-scaled reinforced columns were synthetically corroded by applying altered impressed accelerating current arrangements joined with two sorts of wetting and drying cycles of the saline solution demanding to realize the variances among them, from the steel mass loss standpoint, finally to conclude the most suitable.

2. Constituents and experimental works
A total of six small-scaled circular reinforced concrete columns (100 mm diameter and 300 mm height) were considered with altered patterns of accelerating corrosion. The identified cube concrete strength at 28 days age was 40 MPa (about 32 MPa for cylinder).

2.1 Constituents
This subdivision reviews the properties of reinforced concrete production and constituents were utilized in the existing study including cement, aggregate, and reinforcing bars. Al-Jeser karbala high sulfate-resistance cement was utilized in fabrication concrete compatible to ASTM-C150. Tables (1) and (2) display the properties of utilized cement. Al-Ukhaider Karbala natural sand was utilized as fine aggregate compatible to ASTM-33, with 2.93 fineness modulus and 0.3 sulfate content. Al-Nebai black crushed gravel was used as coarse aggregate compatible to ASTM-C33, with 9.5 mm maximum and 0.07 sulfate content. 6 mm diameter deformed bars and 4 mm diameter plain bars were used for the main and spiral stirrup reinforcements, respectively. The used steel bars meeting the requirements of ASTM A-1064. The approved concrete mix proportion was (1: cement 1.75 sand: 3.5 gravel) and the water-to-cement ratio 0.38, the mix for plain concrete was designed agreeing to ACI 211. Figure (1) displays the details of the reinforced column. Tap water was utilized for curing the reinforced specimens for 28 days.

2.2 Accelerating corrosion regimes
Previously, researchers have utilized exterior impressed electrical current methods for accelerating the steel bars corrosion in reinforced concrete. The basic principle of applying the external D.C. electrical current is quite easy and comprises of forming an electrochemical circuit via an exterior D.C. power source. In an electric cell, the steel bars in reinforced concrete play as an anode and another material plays as the cathode [18][19]. After tap water curing for 28 days, the reinforced concrete circular columns were plunged in a solution of NaCl (3.5% salt concentration) for 3 days to eliminate passivity of steel bars, then, the columns were enclosed in a mesh of stainless-steel, the gap between columns and stainless-steel mesh was filled by sponge material. A constant current was supplied between the anode (reinforcing bars in the columns) and the cathode (exterior stainless-steel mesh) from a D.C. power device. The applied currents were 500, 200, and 50 μA/cm². The wetting- drying cycles of the NaCl solution, with concentration of 3.5%, were combined with impressed current. Two arrangements of cycles were implemented, half of the reinforced columns were subjected to wetting for 1 day followed by drying for a 3 day and the remaining columns were subjected to wetting for 1 day followed by drying for 6 days. In the drying days, the impressed current was turned-off and the columns were taken away and exposed to room air for drying days. Table (3) demonstrates the details of accelerated corrosion regimes for all the reinforced circular columns in the present study. The arrangements of the regimes of acceleration corrosion process were as described in Radhi et. al. [20]. The corroded reinforced columns were discovered twice for each day. The current of corrosion and surface cracking were detected over the phase of accelerated corrosion to conclude the amount of steel loss; the scale of damage caused by rusts and the cracks pattern.
Table 1. Chemical characteristics for the utilized cement.

| Oxide composition | Abbreviation | % by weight | Parameters of ASTM 150 |
|-------------------|--------------|-------------|------------------------|
| Lime              | CaO          | 62.52       | -                      |
| Silica            | SiO₂         | 21.85       | -                      |
| Alumina           | Al₂O₃        | 3.86        | -                      |
| Iron oxide        | Fe₂O₃        | 4.67        | -                      |
| Sulphate          | SO₃          | 1.68        | ≤ 2.3%                 |
| Magnesia          | MgO          | 1.58        | ≤ 6%                   |
| Loss on Ignition  | L.O.I.       | 0.93        | ≤ 3%                   |
| Lime saturation factor | L.S.F. | 0.97        | 0.66-1.02              |
| Insoluble residue | I.R.         | 0.70        | ≤ 0.75                 |

Main compounds (Bogues eq.) % by weight of cement

| Compound                      | % by weight of cement |
|-------------------------------|-----------------------|
| Tricalcium silicate (C₃S)     | 51.05                 |
| Diacalcium silicate (C₂S)     | 24.14                 |
| Tricalcium aluminate (C₃A)    | 2.31                  |
| Tetracalcium aluminoferrite. (C₄AF) | 14.2                 |

Table 2. Physical characteristics for the utilized cement.

| Physical properties             | Test result | Parameters of ASTM 150 |
|---------------------------------|-------------|------------------------|
| Specific surface area, Blaine   | 305         | >260                   |
| Method, (m²/kg)                 |             |                        |
| Setting time (Vicat's method)   |             |                        |
| -Initial setting (min.)         | 200         | ≥ 45 min.              |
| -Final setting (min.)           | 290         | ≤ 375 min.             |
| Compressive strength (MPa):     |             |                        |
| 3-days                          | 30.5        | ≥ 15                   |
| 7-days                          | 37.5        | ≥ 21                   |

Figure 1. Reinforced columns information.
Table 3. The accelerated corrosion regimes for each sample.

| Column Description | current Intensity μA/cm² | Wetting and Drying series |
|--------------------|---------------------------|---------------------------|
| C050W3D            | 50                        | 1 days Wetting -3 days Drying |
| C050W6D            | 50                        | 1 days Wetting -6 days Drying |
| C200W3D            | 200                       | 1 days Wetting -3 days Drying |
| C200W6D            | 200                       | 1 days Wetting -6 days Drying |
| C500W3D            | 500                       | 1 days Wetting -3 days Drying |
| C500W6D            | 500                       | 1 days Wetting -6 days Drying |

2.3 Steel mass loss

Many earlier researchers have effectively employed the Faraday’s law to theoretically calculate steel mass loss or estimate the required time for acquiring a specific level of corrosion in the reinforced concrete samples. In the current study, the Faraday’s law was adopted to estimate the steel mass loss due to the steel corrosion process from the accelerated regimes in the corroded reinforced columns based on the impressed current density, Faraday’s law as follow (eq. 1) [21]:

$$\Delta m = \frac{M \cdot i \cdot t}{F \cdot Z}.$$  (1)

Where:

- \(\Delta m\) theoretical steel mass loss caused by the accelerated corrosion regime,
- \(M\) is the steel molar mass which about 56 g,
- \(i\) is the impressed accelerated corrosion regime in Am.
- \(t\) is the required time for corrosion in second.
- \(F\) is the Faraday’s law constant 96500 A/s,
- \(Z\) is the ionic charge in iron equal 2.

3. Discussion of results

The succeeding subdivisions display the outcomes acquired after about 90 days of accelerated steel corrosion for the six columns. Steel loss, observable first crack appearance and cracks configuration were adopted as indicators for steel corrosion damage. Table 4 summarizes the observation of the steel corrosion in the current study.

Table (4) the outcomes of the steel corrosion in all RC columns.

| Column Description | Theoretical Steel mass loss % | observable first surface cracks |
|--------------------|-------------------------------|--------------------------------|
|                    | Cumulative                    | Per cycles | Duration (Days) | Total of cycles |
| C050W3D            | 2.55                          | 0.127      | ---             | 20              |
| C050W6D            | 1.27                          | 0.127      | ---             | 10              |
| C200W3D            | 9.72                          | 0.511      | 76              | 19              |
| C200W6D            | 4.60                          | 0.511      | 63              | 9               |
| C500W3D            | 10.84                         | 1.204      | 36              | 9               |
| C500W6D            | 4.82                          | 1.204      | 28              | 4               |

3.1 Steel mass loss and observable cracks

Steel mass losses were determined by applying Faraday’s Law (mentioned earlier). In using this equation the effectiveness of the impressed current was supposed to be 100% indicating that all the impressed current was distributed to each specimen. Investigations by previous researchers have also revealed that steel mass loss assessed by applying Faraday’s Law appeared to overestimate the real steel mass loss. [22] et al. stated the overestimation of steel mass loss by Faraday’s law associated with real steel mass loss. They found that the alteration between the actual steel mass loss and the
theoretical steel mass loss depend on the applied voltage and concrete cover. Although, all the corroded columns detected similar shape of damage and cracking pattern, which side observable surface cracks equivalent to the main column reinforcement bar direction, as shown in figures (2) and (3). While, as mentioned earlier in table 4, the observable first surface crack for the columns C200W3D and C200W6D acquired on steel mass loss percent 9.72 % and 4.64% at 76 and 63 days respectively. The observable first surface crack for the columns C500W3D and C500W6D acquired on steel mass loss percent 10.84 % and 4.82% at 36 and 28 days individually, as shown in figure (4). This tendency in the variation of steel mass loss fo attaining the observable cracks may be attributed to the alteration in rust compounds depending on available oxygen and moisture besides the impressed current density, as identified by [21]. On the contrary, at the end of the accelerated steel corrosion the steel mass loss percent for the columns C050W3D and C050W6D are 2.55% and 1.204% without any observable first surface crack, and may acquire the observable first surface crack, depending on Faraday’s Law, after 320 days and 279 days, respectively.

Figure 2. The observable crack in column.  
Figure 3. The damage pattern in the columns.

Figure 4. the cracks appearance time in the all columns.

3.2 Steel mass loss and accelerated corrosion regime
As stated earlier in experimental part in this study the hybrid accelerated steel corrosion regime was adopted, which that intersection between the impressed current technique (three current density, 50, 200, and 500 μA/cm²) and wetting drying cycles system (1 day wetting -3days wetting and 1 day
wetting-6 days wetting). As stated in table 6, the outcomes revealed that the impressed current increased the rate of steel mass loss increases. The steel mass loss percentage for 500, 200, and 50 μA/cm² are 1.204%, 0.511, and 0.127 % per wetting drying cycle, respectively. Although, the effect of each impressed current density equal for steel mass loss in the different wetting-drying system, but the rate of the damage in the concrete columns was somewhat different. This trend may be attributed to the different rust products volumes depending on the availability of oxygen in the 1 wetting-6 drying cycle more than 1 wetting-3 drying cycle.

4. Conclusions

The correlation between the steel mass loss and altering the accelerating impressed current for corrosion of reinforced concrete columns specimens was examined. The study evaluated the steel mass loss applying Faraday’s Law, observable first crack appearance and cracks configuration. The succeeding leading findings from this experimental study are:

1- For the corroded reinforced concrete columns, the steel mass loss depend mainly on the impressed current density, and the rate of steel mass loss increases noticeably with an increase in the impressed current density.

2- Intended for the corroded reinforced concrete columns, the damage rate and observable first crack appearance depend on the type of rusts produced as well as the impressed current density.

3- Changing the wetting drying cycles, has no influence on the steel mass loss of corroded reinforced concrete columns, but effect on the corrosion products nature, the higher drying period the higher in the size of the corrosion produced.

4- The type of the accelerated corrosion regime has no influence on the damage shape and cracks pattern. For all corroded columns, the observable surface cracks were equivalent to the steel reinforcing bars unrelatedly of the wetting and drying cycles or the subjected impressed current level.

5- Reduction in the required time of the appearance of the observable first crack on the corroded reinforced columns with increase in the density of the impressed current in accelerated corrosion regimes.

6- The hybrid accelerated steel corrosion regime by joining the impressed current with alternative drying wetting process is recognized to be an operative method to inspect the growth of the corrosion of steel bars in the reinforced concrete buildings, and its impacts of the cover damage in concrete element.

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