Assessment of Corrosion in Rebars by Impressed Current Technique

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1 Introduction

In the construction industry, reinforced concrete has its own significance as the most used material due to its economic value, versatility and performance [1–3]. Today, durability has become a critical issue in the management of RC structures [4]. RC structures get deteriorated in many ways. Corrosion of steel rebar is the costliest mechanism which affects the service life and integrity of these structures [5, 6]. Bhaskaran et al. [7] studied economic loss in India due to corrosion during the period of 2011–12 using NBS input/output economic model. This study explained the capital loss as a result of corrosion sectorwise. In 2011–12, the cost of corrosion was $26.1 billion as the direct cost expenses which was 2.4% of Indian gross domestic product (GDP) and indirect expenses was $39.8 billion which was 3.6% of Indian GDP. According to NACE International IMPACT Study 2016, India's total cost of corrosion is $70.3 billion, which is 4.2% of GDP of $1260 billion. As corrosion is an electrochemical process, it is to be noted that steel rebar in good quality of concrete is never going to corrode in the higher alkaline environment, even if the ample amount of oxygen and moisture is available required for the reactions to take place as a result of the formation of a passive layer (iron oxide film) [8, 9]. This film is protective in nature to steel rebar blocking the ion exchange between steel and concrete needed for corrosion, thereby decreasing its rate and preventing the damage to steel [6]. But there are some reasons which can cause the destruction of this passive layer such as the introduction of chlorides in the concrete environment or any cause due to which pH could be reduced in surrounding concrete such as carbonation or acid [2, 5, 6, 9]. The corrosion process has so many steps, but it starts in imperfect regions where there is higher or lower density in rebar's crystal structures. Corrosion products such as iron oxide could be 2–4 times in volume of iron which causes pressure on the concrete

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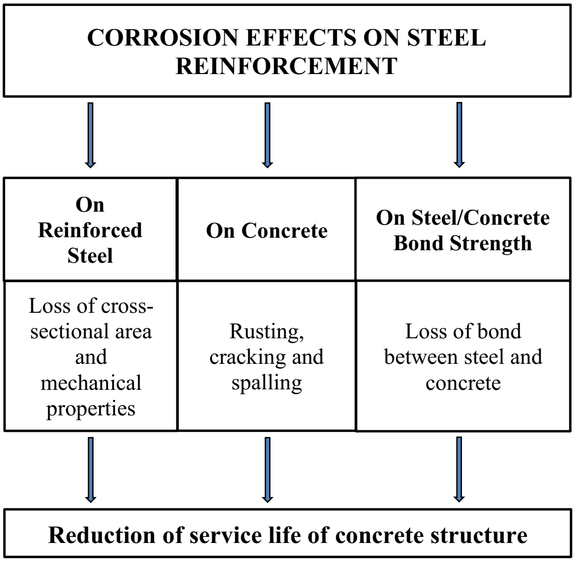

Fig. 1 Effect of corrosion on a reinforced concrete structure

and eventually results in spalling and cracking of concrete which can further cause the ultimate failure of the whole structure [10, 11]. So, the formation of corrosion products on the rebar's surface causes the reduction in its cross section which results in the lesser load bearing capacity and affects the durability and service life of the structure. The process of corrosion can be completely stopped by restricting the entry of dissolved oxygen in the pore water which is not practical. The corrosion products formed initially on the steel surface first increase the bond between steel and concrete, but as corrosion further increases, the bond weakens that ultimately results in cracking in concrete [12, 13]. Figure 1 explains the effect of corrosion on concrete, steel and their bond strength.

There have been so many attempts made by researchers to explore the ways to detect, monitor, and protect the concrete from corrosion. The conventional methods adopted by researchers take a long time span of a structure to monitor the corrosion process. Researchers have adopted various accelerated corrosion techniques to get fast results [14–20]. Impressed current technique is one of them, which gives the results in the short time span. Austin et al. [14] assessed impressed current technique and concluded it an effective method to accelerate chloride-induced corrosion. Caré et al. [15] recommended that while performing ICT concrete specimens should be immersed in sodium chloride solution and not in pure water, then only the corrosion of steel rebars will follow Faraday's law. Ha et al. [16] investigated the corrosive effect of steel rebars in concrete made by fly ash cement using ICT. Yuan et al. [17] concluded that the corroded surface characteristics of the embedded steel bar are different when corrosion is induced by ICT than when corrosion occurs in the natural environment. Benito et al. [18] investigated the corrosive effect of fresh water and brackish water and concluded that corrosion in RC specimens in fresh water is not so active compared to brackish water. Nguyen et al. [19] demonstrated that higher current densities cause more localized corrosion. Also, the degree of corrosion by calculating the loss in diameter is not a reliable method as it is very difficult to measure the diameter with utmost precision after corrosion. Zhang et al. [20] analyzed that there is a decrease in coefficients of expansion of corrosion products when the applied impressed current density increases.

The main aim of this study is to find the corrosive effect in reinforced steel by using ICT as an accelerated corrosion method. The main benefit of using the ICT is that the occurrence of corrosion in rebar is fast, so mass loss also is estimated in RC in lesser days. It can be said that ICT's results are more noticeable and in a controlled manner.

2 Experimental Program

2.1 Preparation of Specimen

Cylindrical-shaped specimens with M30 grade of concrete were casted using 20 mm diameter size steel reinforcement. Two sets of cylindrical specimens dimensioning 100 mm diameter and 200 mm height providing 40 mm cover and 120 mm diameter and 200 mm height providing 50 mm cover were made. The length of reinforcement is not greater than length plus ten times diameter embedded concentrically in a concrete cylinder and here taken as 35 mm.

2.2 Impressed Current Technique Setup Used for Inducing Reinforcement Corrosion

The corrosion of steel rebars in RC structures is generally a long-term process and sets aside a long opportunity to research. Hence, ICT is used to permit accelerated corrosion in a shorter period. Impressed current technique used for inducing corrosion in steel rebar embedded in concrete comprises of a direct current power supply source, a counter electrode (cathode) and an electrolyte solution. The positive terminal of direct current power supply is directly connected to rebar acting as the anode, and the negative terminal is attached to the copper plates acting as cathode in 3% sodium chloride (NaCl) solution as the electrolyte. The current is impressed from copper plates to the rebars embedded in concrete with the help of NaCl solution. Following immersion of specimens in the electrolyte, accelerated corrosion process (impressed current) starts applying constant current till the advancement of the first noticeable surface crack. The ammeter to screen and control the current was attached to DC source. The electrolyte solution in the tank is replaced with new after every 3 days. The setup is made with the aim that the reinforcement steel works as an anode and

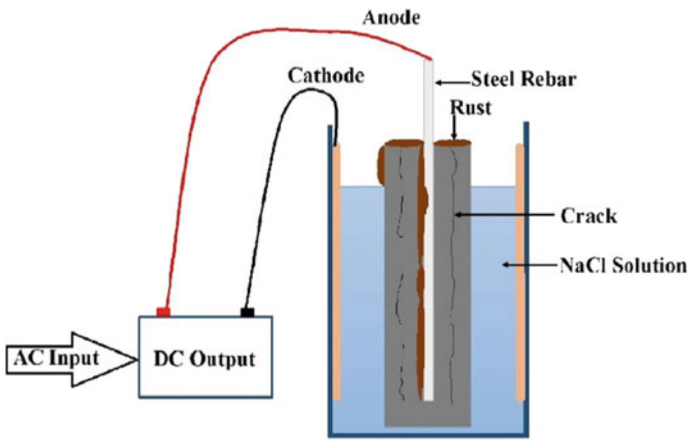

Fig. 2 Impressed current technique setup

copper plates as cathode placed in sodium chloride solution, and the arrangement is shown in Fig. 2. Each RC specimen was studied for corrosion with different applied currents varying from 2 to 4 mA/cm^2 at experiment days after casting and curing.

3 Results and Discussions

3.1 *Time for the First Crack Development*

Time for the first crack development on the surface of RC specimen is taken by visual inspection. Cracks generated were oriented parallel to the embedded rebar in most of the specimens visible through naked eye as shown in Fig. 3.

Figure 4 represents a plot between applied current density and time taken for the first surface crack development after 7, 14 and 28 days of casting and curing of specimens. It shows that the time is continuously decreasing as the applied current density increases despite different casting and curing days. Also, time taken is increased when the cover is increased.

3.2 *Mass Loss*

Theoretical mass loss as a result of corrosion is evaluated using Faraday's law. It can be modeled such that it is directly proportional to applied current per unit surface area of steel rebar and time taken for the development of the first surface crack in RC specimen. The steel rebar is extracted from concrete specimen by breaking it

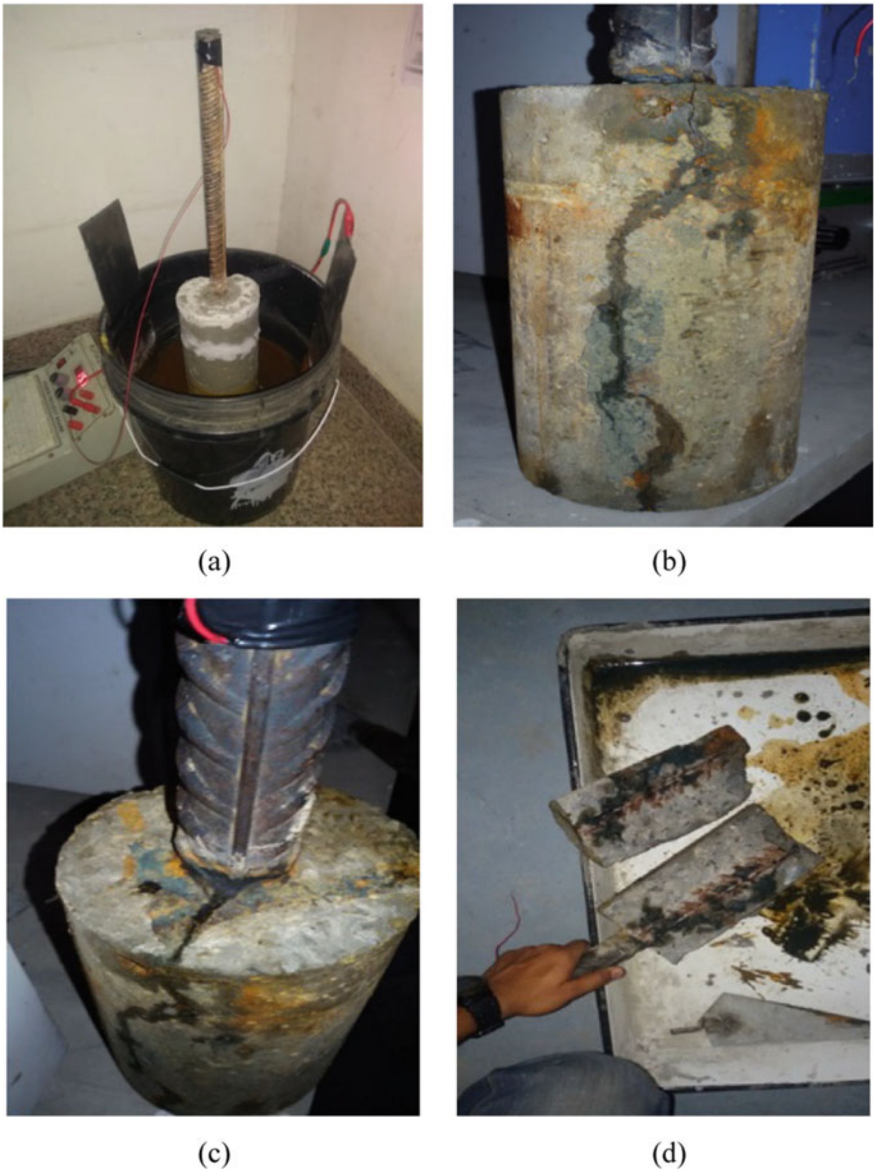

Fig. 3 (**a**) Laboratory ICT setup, (**b**) crack propagation along the surface, (**c**) crack initiation from free top surface along the steel bar, (**d**) steel bar removal after breaking of RC specimen

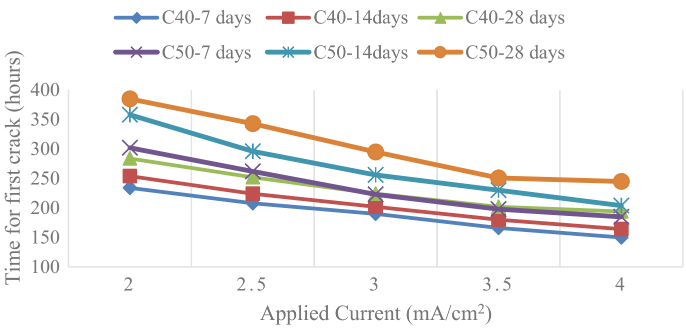

Fig. 4 Time for the first crack at different applied current densities after 7, 14 and 28 days of casting and curing for 40 and 50 mm cover

after the first noticeable crack on the surface of the specimen and cleaned. The actual mass loss of rebar or the actual mass of rust (corrosion product) per unit surface area of rebar is evaluated by gravimetric test.

Figures 5 and 6 represent plot between applied current density and mass loss (theoretical and actual) after 7, 14 and 28 of casting and curing of specimens for 40 mm and 50 mm cover, respectively. Actual mass loss that is measured by gravimetric analysis is always smaller than theoretical mass loss. Considering actual to theoretical mass loss ratio and the fact that concrete specimen gains its strength after every passing day up to 28 days, applied current density of 3.5 mA/cm^2 can be taken as optimum to give satisfactory results.

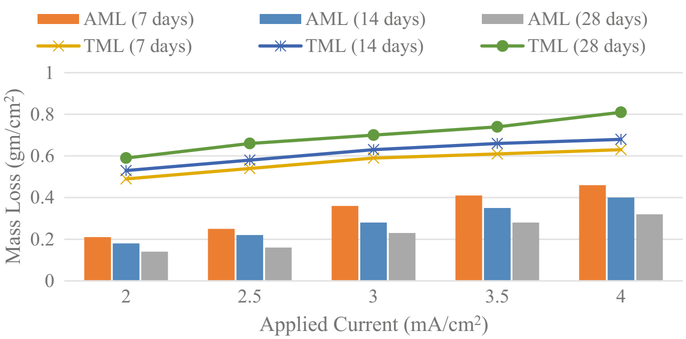

Fig. 5 Theoretical and actual mass loss at different applied current densities after 7, 14 and 28 days of casting and curing for 40 mm cover

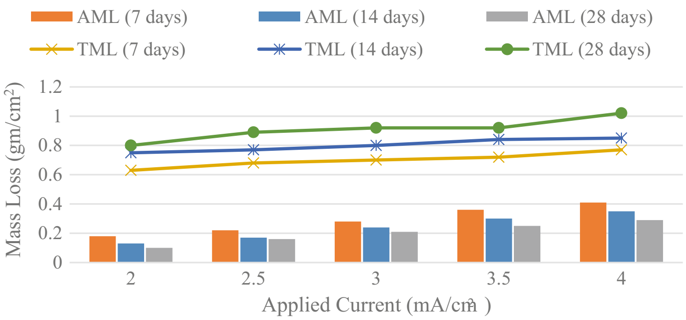

Fig. 6 Theoretical and actual mass loss at different applied current densities after 7, 14 and 28 days of casting and curing for 50 mm cover

3.3 Degree of Corrosion

The degree of corrosion induced due to the constant applied current can be evaluated in terms of the actual percentage mass loss of steel rebar.

3.4 Induced Corrosion Current

The induced corrosion current density can be evaluated mathematically by equating that the theoretical and actual mass loss of steel rebar. It is directly proportional to the actual mass of rust measured and inversely proportional to the time for development of the first surface crack.

Figures 7 and 8 represent a combined plot between the applied current density and induced corrosion current and degree of corrosion after 7, 14 and 28 of casting and curing of specimens for 40 mm and 50 mm cover, respectively. The plot shows

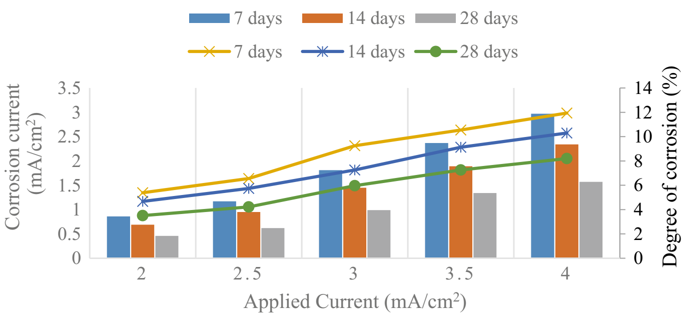

Fig. 7 Induced corrosion current and degree of corrosion at different applied current densities after 7, 14 and 28 days of casting and curing for 40 mm cover

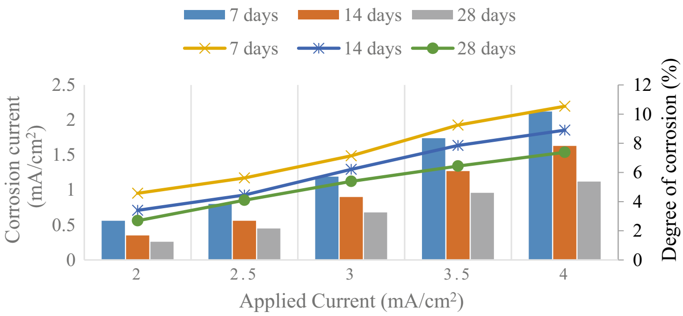

Fig. 8 Induced corrosion current and degree of corrosion at different applied current densities after 7, 14 and 28 days of casting and curing for 50 mm cover

that though there is an increment in the degree of corrosion induced as the applied current density increases, it is not linear. Similarly, there is an increment in corrosion current density induced, but it is not linear and after the applied current density of 3.5 mA/cm^2 is very less.

4 Conclusion

ICT has not been used so often to accelerate corrosion in steel reinforced embedded in concrete and to reduce the time for development of the first surface crack. In this study, it is used experimentally to evaluate the time needed for the first surface crack development in RC specimens at a different applied current and corresponding mass loss of steel rebar due to accelerated corrosion. Based on the analysis, the following conclusions can be made:

1. Time required for the initiation of the first noticeable surface crack of the test specimen decreases with the increase in applied current and increases with the increase in experiment days after casting and curing for a constant applied current. It increases as the cover increases.
2. There is not a good correlation between the actual experimental and theoretical mass-loss rates.
3. Degree of corrosion increases as the applied current increases. But the increment is not linear, and there is no correlation between the degree of corrosion and applied current.
4. Degree of corrosion decreases with an increase in experiment days after casting and curing for a constant applied current. It decreases as the cover increases.
5. Corrosion current increases as the applied current increases. But the corrosion current decreases with the increase in experiment days after casting and curing for a constant applied current. It decreases as the cover increases.

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