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CHARACTERIZATION OF IMPRESSED CURRENT TECHNIQUE TO MODEL CORROSION OF REINFORCEMENT IN CONCRETE

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ABSTRACT

Corrosion of reinforcement is an important durability concern for the structures exposed to coastal regions. Since corrosion of reinforcement involves long periods of time, impressed current technique is usually used to accelerate the corrosion of reinforcement in laboratories. Characterization of impressed current technique was the main focus of this research,which involved determination of optimum chloride content and minimum immersion time of specimens for which the application of Faraday's law could be efficient. To obtain optimum chloride content, the electrolytes in the corrosion cell were prepared similar to that of concrete pore solutions. Concrete prisms of 200 mm by 200 mm by 300 mm were used to determine the minimum immersion time for saturation. It was found that the optimum chloride content was 35 gm/L and the minimum immersion time for saturation was 140 hours. Accounting the results, a modified expression based on Faraday's law was proposed to calculate weight loss due to corrosion.

Keywords: *Corrosion; Impressed Current Technique; Minimum Immersion Time; Optimum Chloride Content.*

1. INTRODUCTION

The focus of this research was to study the impressed current technique to model the accelerated corrosion test in laboratory. Though the impressed current technique has been extensively used by several researchers (Allan and Cherry, 1992; Andrade *et al*., 1993; Andrade *et al*., 1990; Austin *et al*., 2004; Caré *et al*., 2008; Maaddawy and Soudki, 2003; He *et al.*, 2016; Kassir and Ghosn, 2002; Nossoni and Harichandran, 2012; Tran *et al*., 2011; Val *et al*., 2009; Shakib and Morshed, 2016, 2018), literatures describing its appropriateness are very scarce. In particular, suitability of Faraday's law for computing the loss of reinforcement due to corrosion in different test conditions, e.g. immersing water with variable chloride concentrations, immersion time before starting the test to saturate the concrete pores, current density applied during test, techniques applied to ensure sufficient water and oxygen in concrete and etc., were not investigated in detail in the past. In this research, two test conditions were investigated - a) different chloride concentrations in synthesized solution similar to that of concrete pore solution, b) time to saturate the concrete. Generally, a DC power supply with constant voltage is used to accelerate the corrosion process. The corrosion current amount flowing through the circuit is very much dependent on the chloride content in the electrolytes. It increases with the chloride content till the optimum is attained. So that the time required to obtain chloride saturation in the concrete is important to attain a steady current flow. Moreover, in chloride-induced corrosion, prediction of mass loss is also dependent on the chloride content present in the electrolytes (Nossoni and Harichandran, 2012; Tran *et al*., 2011; Shakib and Morshed, 2016, 2018). However, so far, there are no specific guidelines regarding the amount of chloride content and immersion time before starting the test to attain saturated chloride content (in terms of time to attain a steady current flow) for reinforced concrete specimen in any codes of standard.Thus, application of Faraday's Law in different testing environments may end up with different test results. Focusing on this issue, a favorable testing environment for applying the Faraday's Law was investigated in this research. Testing environment was evaluated in terms of efficiency of currenton the basis of gravimetric loss method.

1.1 Electrochemical Concepts and Principle of Faraday's Law

Reinforcing steel remains in stable passive state at very high pH as shown in Figure 1. Since the pH of concrete pore solutions is very high (Austin *et al.*, 2004; Nossoni and Harichandran, 2012; Shakib and Morshed, 2020, Shakib and Morshed, 2018), concretes give a good protection against corrosion (Bazant, 1979; Broomfield, 2006; Maaddawy and Soudki, 2003). On the other hand, a passive layer is formed due to hydration of cement on the steel surface, which also protects it from corrosion. But if any corrosive agent, like chloride ions, incorporate into the concrete, passive layer is destroyed and corrosion progresses (Bazant, 1979). The passive zone of the steel becomes a pitting zone as shown in Figure 2 and the zone expands to high pH with the increase in chloride concentrations.

To model this chloride induced corrosion in the laboratory, impressed current technique is used, where the steel corrodes electrochemically. In accelerated corrosion test, a constant DC power supply is used to apply current through the steel rebar as shown in Figure 3. In this methodology, presence of chloride ions, water and oxygen

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are obligatory. Considering this obligation, the concrete samples need to be immersed into the water containing chlorides. Faraday's Law is employed to evaluate the overall weight loss of the anodic bar which is directly related to current and time.

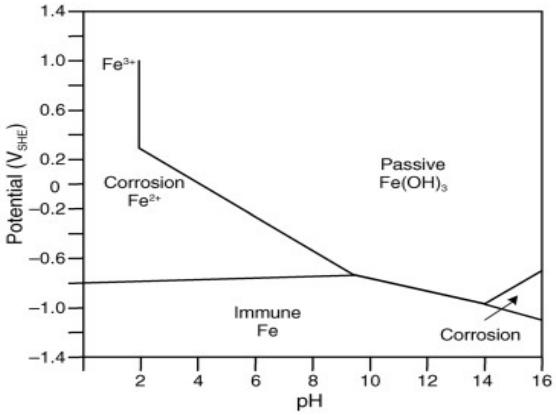

Figure 1: Pourbiax diagram of steel (Nossoni and Harichandran, 2012)

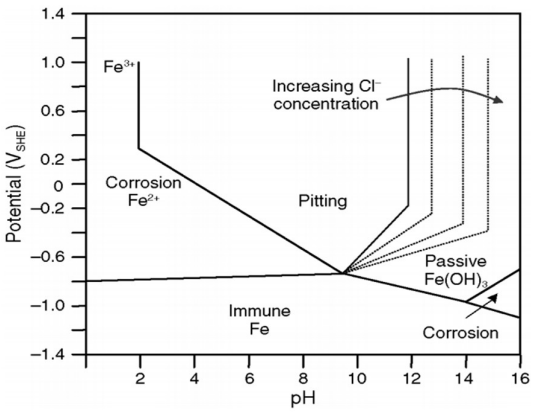

Figure 2: Pourbiax diagram of steel in the presence of chloride ions (Nossoni and Harichandran, 2012)

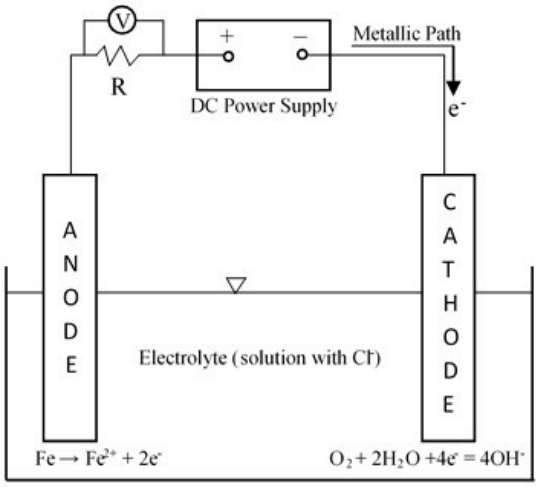

Figure 3: Schematic Diagram of Accelerated Corrosion Test Setup

The estimated corrosion-induced loss of steel using Faraday's law

$$M_F = \frac{MIt}{zF} = \frac{Mi_{corr}tA}{zF} \quad (1)$$

Where, M_F = the weight loss of steel bars (gm), M = atomic weight of metal (For Fe, M = 56 gm/mole), I = current (amperes), $i_{corr} = \frac{I}{A}$ = current density, A = corroding surface area of the rebar, t = time (seconds), z = ionic charge (for Fe, z = 2), F = Faraday's constant = 96,500 coulombs/mole.

The ratio of the estimated loss of steel to the actual loss found by gravimetric loss method is defined as current efficiency,

$$\eta = \frac{M_A}{M_F} \quad (2)$$

Where, M_A = actual weight loss (gm).

2. EXPERIMENTAL PROCESS

2.1 Materials and Specimens

Corrosion of reinforcement progresses through consecutive oxidation reduction reaction. The anodic and cathodic reactions are difficult to examine when the electrodes are embedded into the concrete. So, the experimentation was first performed in synthesized solutions. Bertolini *et al.* (2013) studied on the chemical composition and properties of concrete pore solutions. From which three different chemical compositions were considered in this study for simulatinga concrete environment. Pallets of NaOH, $Ca(OH)_2$, and KOH were used to prepare the synthesized solutions as shown in Table 1. The pH of prepared solutions was 13.7, 13.9, and 13.5

respectively. The high pH solutions were similar to that of concrete pore solution (Bertolini *et al.*, 2013; Nossoni and Harichandran, 2012). Two 10mm-Ø deformed mild steel bars were used as both anode and cathode for the test in synthesized solutions. The length of each bar was 76 mm. The bars were cleaned by steel wire brush. The effect of chloride ions was investigated through this experimentation. The optimum chloride concentration obtained from this investigation was used to simulate the corrosion in concrete prisms.

Table 1: Solution Properties (Bertolini *et al.*, 2013)

	$[OH^-]$ (mMol/L)	$[Na^+]$ (mMol/L)	$[K^+]$ (mMol/L)	$[Ca^{2+}]$ (mMol/L)	Calculated pH
Solution-1	470	130	380	1.0	13.7
Solution-2	834	271	629	1.0	13.9
Solution-3	288	85	228	0	13.5

The concrete used in the prisms was made with ordinary Portland cement with w/c of 0.45. The mix was designed according to the ACI 211.1 for a C30 grade concrete considering the requirements for corrosion protection of reinforcements in concrete exposed to corrosive environment. 19 mm downgrade stone chips was used as coarse aggregate and river sand with fineness modulus of 2.8 was used as fine aggregate in concrete. The mix proportion is shown in Table 2.Two different thicknesses of clear cover were used in this study- 19 mm and 40 mm. A 12 mm-Ø plain mild steel bar was embedded in the concrete prisms and a 4 mm-Ø mild steel wire used to act as an anode and cathode, respectively. A detail of specimens is shown in Figure 4.

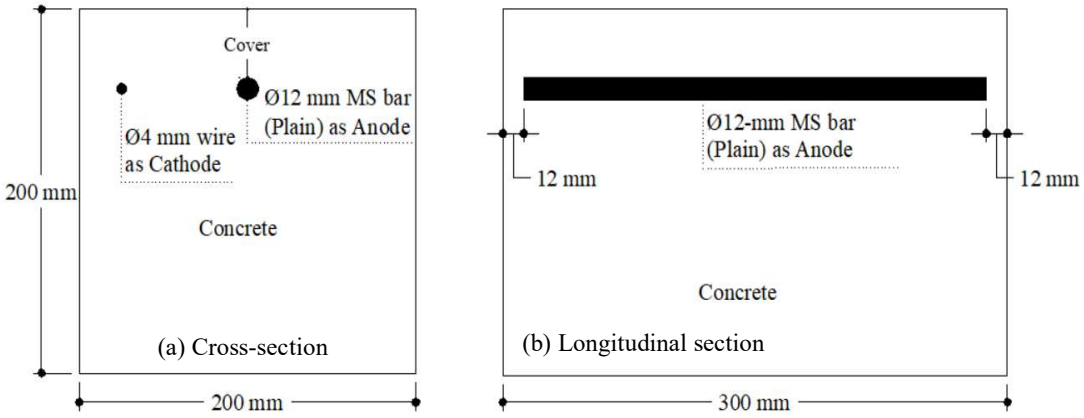

Figure 4: Details of prismatic specimens

A DC (converted from AC current) power supply was used to supply current through the circuit. The input AC voltage was 200-220V 50/60Hz switchable. Output DC voltage was variable (3-30 V). A resistor of 4.7Ω was used in the circuit and a multimeter was used to measure the voltage drop across the resistor, from which the current flowing through the circuit was calculated by Ohm's Law (I=V/R), where I is the current (A), V is the Voltage drop (V) across a fixed resistor, R (Ω). The schematic diagram of test setup is shown in Figure 5.

Table 2: Mix Proportions for the Concrete

Materials (kg/m^3)					w/c
Water	Cement	Fine Aggregate	Coarse Aggregate	Fresh density	ratio
190	422	677	1056	2345	0.45

2.2 Test in Synthesized Solution

In an impressed current technique, there are two electrodes- an anode and a cathode. The anode is connected to the positive pole of the power supply and the cathode is connected to the negative pole. The electrodes are placed in an electrolyte through which the ions transfer from one electrode to another. For the tests performed in synthesized solutions, three different solutions were prepared and used, as shown in Table 1. The amount of chloride was varied from 0 gm/L to 58 gm/L. The anode bar was cleaned by steel wire brush before and after the test. A new solution and anode bar were used for each trial. A constant 12V current was applied across the circuit. The test setup is shown in Figure 5(a). The distance between the anode and cathode was kept constant (20 mm) throughout the test. Each test was continued for 18 hours. The actual weight loss was measured from the difference between the weights recorded before and after the test. The actual weight loss was then compared with the theoretical weight loss following Faraday's law and the current efficiency was calculated as well.

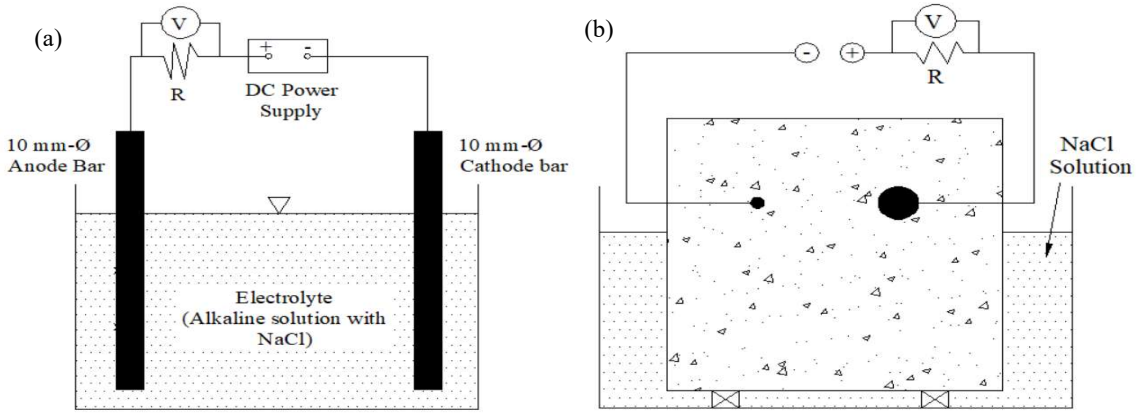

Figure 5: Schematic diagram of test setup (a) Synthesized Solution and (b) Concrete Prisms

2.3 Test in Concrete Prisms

A 200 mm by 200 mm by 300 mm concrete prism was used to perform the accelerated corrosion test in concrete environment. The corrosion setup is shown in Figure 5(b). In impressed current technique, an artificial supply of chloride ions is needed to increase the conductivity of concrete. On the other hand, a certain amount of chlorides (optimum chloride content) are required at the rebar surfacefor efficient use of the supplied current.The optimum chloride content adjacent to the steel concrete interface can be obtained by saturating the concrete with chlorides.For this reason,the specimens areneeded to immerse in chloride solutionsfor a certain period of time before starting the tests. There are no certain guidelines regarding this. In this context, the optimum chloride content obtained from the tests in synthesized solutions was used to immersethe specimens. The specimens were immersed in salt solutions with optimum chloride content for different period of time (0 day, 1 day and 7 day) before conducting the test to determine the optimum time for which a steady current flow was attained, consequent to a maximum current efficiency. A constant voltage of 12V was applied across the circuit. The actual weight loss and theoretical weight loss was measured as stated before and the current efficiency was also calculated.

3. RESULTS AND DISCUSSION

3.1 Tests in Solutions

The current efficiency for different chloride concentrations is plotted in Figure 6 for Solution-1. The graph shows that the efficiency of current is highly dependent on the amount of chloride present in solution. The oxidation of anode was almost zero in chloride free solution, but it gradually increased with the increase of chloride ion concentration. From Figure 6it is found that the current efficiency reached to 100% at a high chloride concentration of 30 gm/L. The chloride content required to reach 100% current efficiency was dependent on the pH of the solution and current density (Nossoni and Harichandran, 2012). This phenomenon can also be described by the pourbiax diagram for steel. According to pourbiax diagram, when no chloride ispresent there aretwo possible active zones for corrosion: one for pH lower than 9 and another for pH higher than 14 (Figure 1). Negligible corrosion of rebars occurred in the solution (pH = 13.7) without having chlorides (Figure 6). But due to addition of chloride content, a pitting zone was found and it became more active with increased chloride content (Figure 2). At a certain level of chloride (30 gm/L), total supplied current was fully efficacious in oxidizing the rebar. Before which, the current was partially used in oxidation process and rest to break the water molecules emmitting different types of gases. They were not chemically identified in this study but the probable reaction might be as follows (Nossoni and Harichandran, 2012),

Anode: $2OH^- = 1/2O_2 + 2H_2O + 2e^-$ 3

Cathode: $2H_2O + 2e^- = H_2 + 2OH^-$

When voltage-controlled power supply is used (as was the case in present study), the amount of current (I) increases with reactivity of the anode, which increases with the increase in chloride content. At a certain level of chloride content (optimum chloride content) a steady current flow was obtained. However, below that level, as the current flow icreased, the demand of chlorides also increased. That, in turn, increased the possibility of occurance of reactions other than the oxidation of steel. This might be the possible reason for the differences between the results of the present study and that of the previous works (Figure 6).

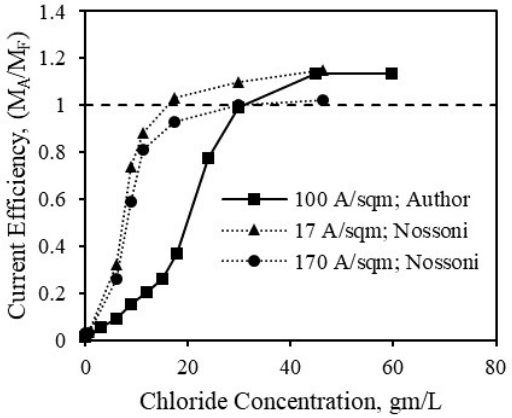

Figure 6: Variation of current efficiency with respect to different chloride concentration in "Solution 1"

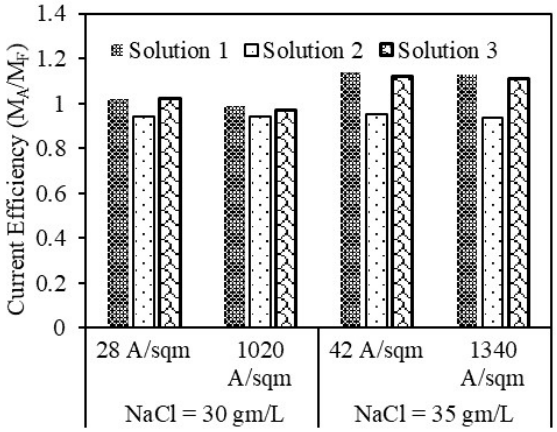

Figure 7: Current efficiency for different solutions

In chloride free solution all the current was used to break the water molecule and produced oxygen gas at anode and hydrogen gas at cathode. In presence of chlorides lower than a certain amount, partial current was used to oxidize the steel and rest of it was utilized for breaking water molecule. So, for a fixed pH there was a certain chloride content for which a full oxidation of anode occurred. For a solution having pH 13.7, it was found that a 30 gm/L of NaCl was needed for 100% efficiency of current. Since a 100% current efficiency was found for a NaCl concentration of greater than 30 gm/L, tests on the other solutions were conducted only for two different chloride concentration; 30 gm/L and 35 gm/L. The results are shown in Figure 7. It is seen that in Solution-1 and Solution-3, over 100% current efficiency was attained for 35 gm/L of NaCl solution irrespective of current density. Whereas for Solution-2 it was about 95% at 35 gm/L of NaCl. The reason for the current efficiency below 100% for Solution-2 might be the difference in solution properties (a relatively higher pH of 13.9). The optimum chloride content might also depend on the current density applied through the circuit and pH of the solution (Nossoni and Harichandran, 2012). It was reported that a higher chloride concentration was required to efficacious corrosion at higher pH. It was found that a NaCl of 16.5 to 30 gm/L was required for 100% efficiency depending on the current density and pH of solutions (Nossoni and Harichandran, 2012). For a higher current density, a higher optimum chloride content was also reported. To investigate the effect of current density, two types of current density were used in this study: one was low (<50 A/sqm) and the other was high (>1000 A/sqm). It is seen from Figure 7 that for a higher chloride content (35gm/L), over 100% efficiency was found in both cases; however, for chloride content of 30 gm/L, a lower current efficiency (97%) was found in case of higher current density. So it can be concluded that, 35 gm/L might be the optimum chloride concentration irrespective of current density.

3.2 Tests in Prisms

The high alkaline environment, attained due to hydration of cement in concrete, forms a passive film on the surface of the embedded steel which normally prevents the steel from corrosion. However, under chloride penetration, the passive film is disrupted or destroyed, and the steel is exposed to the harmful attackers and corroded spontaneously. From the investigation in synthesized solutions similar to the concrete pore solutions, it was found that a 35 gm/L of NaCl concentration caused a 100% current efficiency. This finding was applied to prepare the electrolytes for concrete specimens [Figure 5(b)]. After 28 days water curing, at an average compressive strength of 30.2 MPa, the prism specimens were immersed in the electrolyte solution, so prepared, for three different periods of time- 0 day, 1 day and 7 day in a steady state condition before starting the test. The results of the tests in concrete prism are presented in Figure 8.

Availability of water and chloride adjacent to the reinforcement is dependent on the concrete property (Neville, 2011). So a certain time is needed for the specimens to be immersed in chloride solutions for sufficient availability of water and chloride. It is seen from Figure 8 that the current supplied to the anode gradually increased up to a certain period of time and then became stable. The observed time period was 108 to 136 hr for cover = 19 mm [Figure 8(a)] and 110 to 140 hr for cover = 40 mm [Figure 8(b)]. That was due to the gradual increase in chlorides inside the concrete. The rate of increase of chloride inside the concrete depends mostly on the density and porosity of concrete. Since a single type (grade) of concrete was used throughout the experiments, the effect of density and porosity was assumed to be similar for all cases and hence their effect was neglected in this study. After attaining the chloride saturation, the current maintained a steady flow.

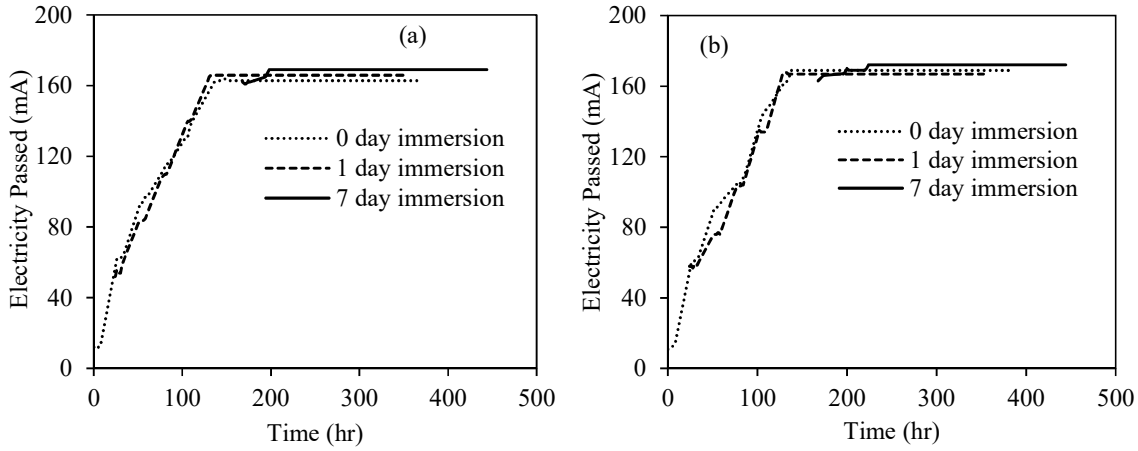

Figure 8: Effect of immersion time before starting tests for (a) 19 mm and (b) 40 mm clear cover

The effect of immersion period on the current efficiency is summarized in Figure 9. The efficiency of current was 72% when no immersion before starting test. It increased to 74% and 87% when the time of immersion was 1 days and 7 days, respectively for cover thickness is equal to 19 mm. In case of cover of 40 mm, the efficiencies were 69, 72 and 85% respectively.It was seen that the current efficiency was very much dependent on the chloride content adjacent to the reinforcent and the efficiency increased with the increase in chloride content (Figure 6). The unsteady flow of current meant that chloride content present adjacent to the reinforement was lower than the optimum, which in turn affected the current efficiency for any period of immersion time. On the other hand, the dependency of clear cover was found to be insignificant as shown in Figure 8 and Figure 9. This might be due to the fact that the penetration of chloride solution was allowed not only through the clear cover but through the two sides and bottom of the prisms as well in the test setup [Figure 5(b)]. In case of penetration through a 44 mm thick cover, a lower immersion time (one hour) was reported by Shao (2016). The lower (average 86%) value of the current efficiency was attained might be because of the hidrance of chloride ions from reaching to the rebar surface by the layer of accumulated corrsion products around the rebar. Whereas, in a test condition without chlorides inside the concrete, the efficiency wasreported as 34-45% (Nossoni and Harichandran, 2012; Shao, 2016). So, the Faraday's law needs to be calibrated by multiplying with the current efficiency factor (η) with at least 140 hr immersion of specimens in 35 gm/L of NaCl solution as follows

$$M_F = \eta \frac{MIt}{zF} \qquad 4$$

Where η = an average of 86% with at least 140 hrs immersion in 35 mg/L salt solution. This proposed value can be reexamined for other test conditions.

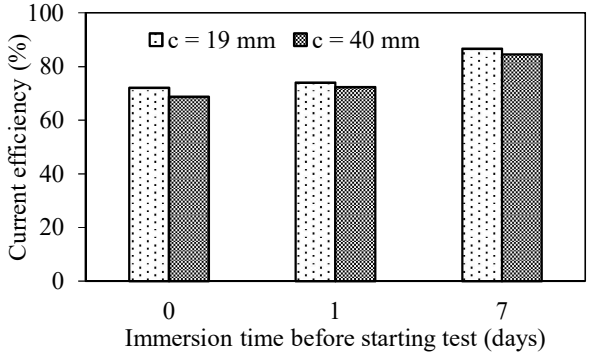

Figure 9: Current efficiency in concrete prisms for different immersion time

4. CONCLUSIONS

In impressed current technique, amount of chloride ions is an important factor affecting the corrosion of steel. In solutions similar to that of concrete pore solution, an experimental investigation was carried out to find the optimum chloride content. It was found that at a high chloride concentration of 35 gm/L of mixing water, the actual weight loss met the theoretical one. In concrete, the chloride ions are to be transported through the pore space need to be saturated with the chlorides adjacent to the steel-concrete interface for optimum current efficiency. An investigation was carried out regarding this point. The prismatic specimens were immersed in 35 gm/L chloride solution for different period of time and it was found that an immersion period of at least 140

hours before starting the tests was needed to saturate the specimen. A calibration factor (η) equals to 0.86 was introduced to calibrate the equation of Faraday's law to calculate the actual weight loss of steel bar, embedded in concrete, due to corrosion.

REFERENCES

Allan, M. L., and Cherry B. W., 1992. Factors Controlling the amount of corrosion for cracking in reinforced concrete, Concrete, (May), 426–430.

Andrade, C., Alonso C., and Molina F. J., 1993. Cover cracking as a function of bar corrosion: Part I-Experimental test, Materials and Structures, **26**(8), 453–464. https://doi.org/10.1007/BF02472805

Andrade, C., Alonso M., and Gonzalez J., 1990. An initial effort to use the corrosion rate measurements for estimating rebar durability. In Corrosion Rates of Steel in Concrete (pp. 29-29–9), ASTM International. https://doi.org/10.1520/STP25013S

Austin, S. A., Lyons R., and Ing M. J., 2004. Electrochemical behavior of steel-reinforced concrete during accelerated corrosion testing, Corrosion, **60**(2), 203–212.

Bazant, Z. P., 1979. Physical model for steel corrosion in concrete sea structures – theory, Journal of the Structural Division-ASCE, **105**(6), 1137–1153.

Bertolini, L., Elsener B., Pedeferri P., Redaelli E., and Polder R. B., 2013. Corrosion of steel in concrete, Weinheim, Germany: Wiley-VCH Verlag GmbH and Co. KGaA. https://doi.org/10.1002/9783527651696

Broomfield, J. P., 2006. Corrosion of steel in concrete: understanding, investigation and repair,Second Edition. https://doi.org/10.4324/9780203414606

Caré, S., Nguyen Q. T., L'Hostis V., and Berthaud Y., 2008. Mechanical properties of the rust layer induced by impressed current method in reinforced mortar, Cement and Concrete Research, **38**(8–9), 1079–1091. https://doi.org/10.1016/J.CEMCONRES.2008.03.016

El Maaddawy, T. A., and Soudki K. A., 2003. Effectiveness of impressed current technique to simulate corrosion of steel reinforcement in concrete, Journal of Materials in Civil Engineering, **15**(1), 41–47. https://doi.org/10.1061/(ASCE)0899-1561(2003)15:1(41)

He, J., Zhou Y., Guan X., Zhang W., Wang Y., and Zhang W., 2016. An integrated health monitoring method for structural fatigue life evaluation using limited sensor data, Materials (Basel, Switzerland), **9**(11). https://doi.org/10.3390/ma9110894

Kassir, M. K., and Ghosn M., 2002. Chloride-induced corrosion of reinforced concrete bridge decks, Cement and Concrete Research, **32**(1), 139–143. https://doi.org/10.1016/S0008-8846(01)00644-5

Neville, A. M., 2011. Properties of concrete 5th Edition, Pearson Education Limited.

Nossoni, G., and Harichandran R., 2012. Current efficiency in accelerated corrosion testing of concrete, Corrosion, **68**(9), 801–809.

Shakib, S., and Morshed A. Z., 2018. Modeling of cover concrete cracking due to uniform corrsion, Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development, KUET, (February), 1–12.

Shakib, S., and Morshed A. Z., 2020. Experimental and numerical simulation of corrosion induced expansive pressure on concrete cover, Engineering Solid Mechanics, 8, https://doi.org/10.5267/j.esm.2019.9.001

Shakib, S. and Morshed A. Z., 2016. Study on prevention of rebar corrosion through cathodic protection by using sacrificial anode, Proceedings of the 3rd International Conference on Civil Engineering for Sustainable Development, KUET, (February), 978–984.

Shakib, S., and Morshed A. Z., 2018. Initiation and propagation of crack due to corrosion of reinforcement - an experimental investigation, IOSR-JMCE ,15(4), 12–16, https://doi.org/10.9790/1684-1504041216

Shao, K., 2016. Experimental investigation of non-uniform corrosion of the steel bars in concrete, M. Phil thesis, Hong Kong University of Science and Technology

Tran, K. K., Nakamura H., Kawamura K., and Kunieda M., 2011. Analysis of crack propagation due to rebar corrosion using RBSM, Cement and Concrete Composites, **33**(9), 906–917. https://doi.org/10.1016/j.cemconcomp.2011.06.001

Val, D. V., Chernin L., and Stewart M. G., 2009. Experimental and numerical investigation of corrosion-induced cover cracking in reinforced concrete structures, Journal of Structural Engineering, **135**(4), 376–385. https://doi.org/10.1061/(ASCE)0733-9445(2009)135:4(376)