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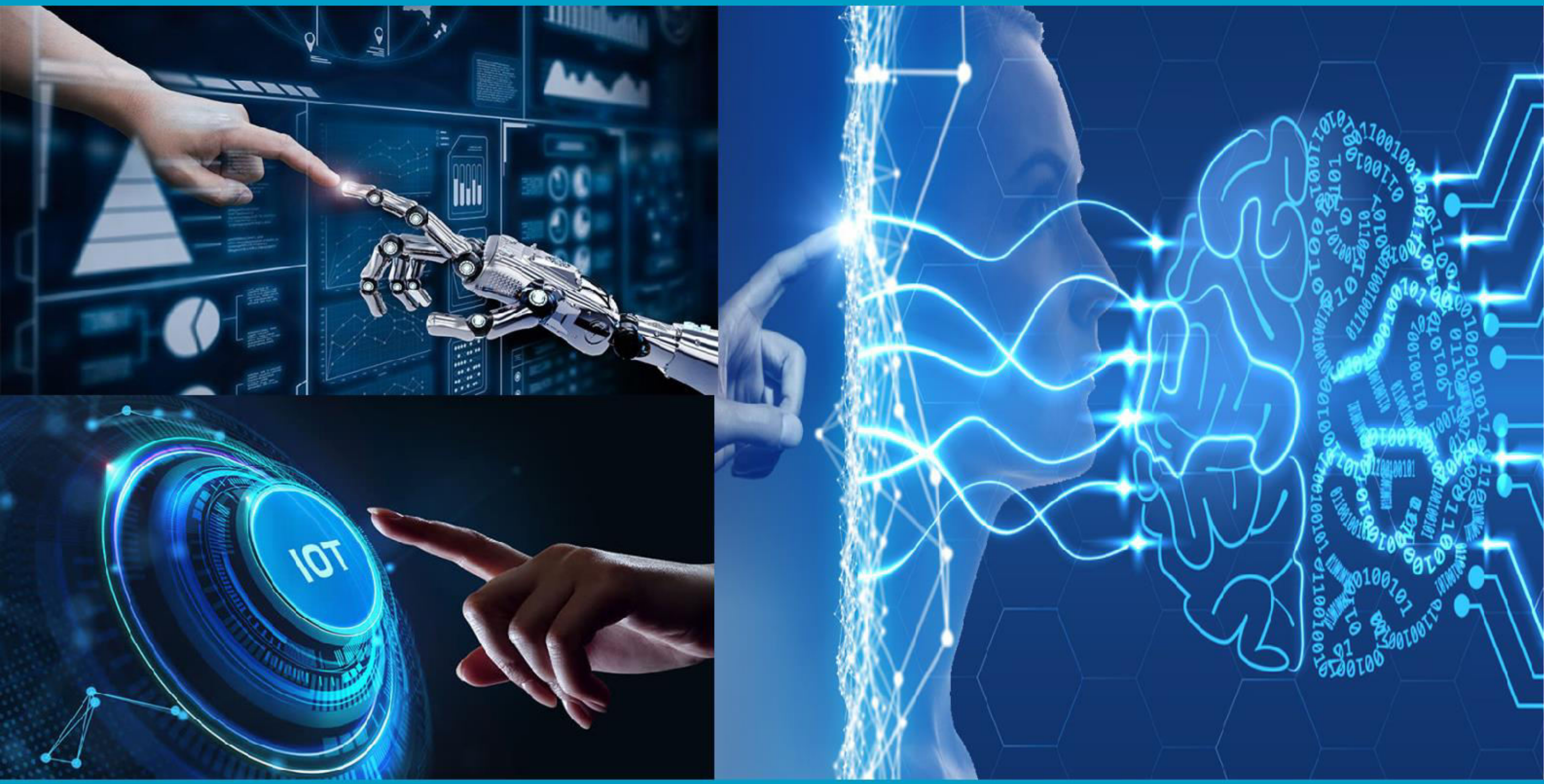

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Chloride Induced Rebar Corrosion in Concrete under Accelerated Condition

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ABSTRACT: Experimental study and numerical analysis of the corrosion-induced pressure that causes the concrete cover crack to begin and continue to expand was the major topic of this thesis. The research and analysis were carried out by the author. On the basis of the results of the complete investigation, one may draw the following deductions and conclusions. The impressed current method, which plays a large part in the corrosion of steel, requires a substantial number of chloride ions as an important component. In order to ascertain the optimum level of chloride in the concrete pore solution, a series of experiments were carried out in solutions with properties that were analogous to those of the concrete pore solution. When there was a high percentage of chloride in the mixing water, which was 3.5 percent by mass, it was found that the actual mass loss agreed with the predicted one. This was a very interesting discovery. In order to achieve a current efficiency of one hundred percent, the chloride ions that are going to be transported through the pore space of the concrete must first be saturated with the chlorides that are close to the steel-concrete interface. Only then will it be possible to achieve current efficiency of one hundred percent. A search and an investigation were carried out with regard to this specific place. It was discovered that the cubical specimens needed to be submerged for at least one day prior to the beginning of the tests in order to get saturated with the chloride solution that contained 3.5 percent chloride. The amounts of time that the specimens were submerged in the chloride solution varied, but the total time spent submerged in the solution was consistent.

KEYWORDS: corrosion-induced pressure, steel-concrete, chloride solution, chloride induced rebar corrosion

I. INTRODUCTION

India is classified as a deltaic country and encompasses a total area of 147,570 square kilometers. The coastal area encompasses close to 29,000 square kilometers, which is approximately 20 percent of the total land area of the country. One of the most important and difficult maintenance problems that Bangladesh faces, particularly in its coastal areas, is corrosion of the reinforcing steel (also known as "rebars") in concrete structures. Concrete, with its highly alkaline pore solution, has its own built-in mechanism for protecting itself against corrosion. This mechanism involves the formation of a layer of passivation, which is a surface film of iron oxide. Chlorination and carbonation, on the other hand, both cause a disruption in this passive layer (Bazant, 1979).

If the concentration of chloride ions in the environment is high enough, the passive layer will be destroyed, and the steel will corrode on its own. On the other hand, corrosion can be caused by carbonation, which is the reaction of carbon dioxide (CO_2) with the cement in concrete. This is also known as the carbonation process (Nossoni & Harichandran, 2012). A significant amount of damage can be caused to marine structures by the high concentration of chlorides that is found in the salty water that is found in coastal areas. The rate of corrosion can be affected by a variety of factors, including the concentration of chloride, temperature, relative humidity, cover thickness, and quality of the concrete. When the reinforcement corrodes, the transformation of metallic iron into oxides can result in a volume increase of up to 600 percent, depending on the final oxide form (Liu & Weyers, 1998).This expansion causes concrete to crack and spall, which in turn reduces the strength and durability of the concrete, which in turn compromises the serviceability of structures made of reinforced concrete.

The management and upkeep of a structure is a challenging endeavour, particularly in the case of marine structures such as bridges, culverts, and buildings located in coastal areas. The term "Structural Health Monitoring," or SHM for short, has developed into a practical instrument for assessing the state of a structure's health and predicting the likelihood of its collapse (He et al., 2016; Kulkarni & Achenbach, 2008). Crack propagation as a result of reinforcement corrosion is one of the primary failure mechanisms for the majority of environmental hazards. Corrosion damage is proportional to the amount of mass loss in steel, so this is a significant concern.In point of fact, it can be quite challenging to precisely calculate the amount of mass that is lost due to corrosion in steel that is embedded in concrete. As a consequence of this, the indirect prediction of corrosion is the strategy that is more practicable for SHM. The width of the cracks on the surface of the concrete could be considered one of the important parameters.

in order to determine the level of corrosion This prediction might be very helpful in figuring out how likely it is that corrosion will cause failure.In addition to the prediction of corrosion through the monitoring of crack width, a protection system is required to extend the life of marine structures. Alternatively, a prevention system is necessary when the structures have already been compromised before the issue escalates into a major concern. These days, one of the most common strategies for warding off corrosion is known as cathodic protection. Two methods of cathodic protection that have been investigated in the past are the sacrificial anode system and the impressed current system (Vrable & B., 1977). In sacrificial anode cathodic protection methods, a metal in the electrochemical series with a higher electromotive force than steel is utilized.

II. ACCELERATED CORROSION TEST

The experimental investigation of steel bar corrosion in concrete and alkaline solution, with the use of impressed current to speed up the corrosion process, is the focus of this chapter. Because the fluid in the pore space of concrete is highly alkaline, the experiment was set up in an alkaline solution. In addition, the mass loss in the accelerated corrosion tests was calculated using Faraday's Law.

Steel corrosion in reinforced concrete is a long-term process that occurs over the serviceable life of the structure. It could take years for reinforced concrete specimens to corrode, and studying the effects of corroded rebar on structural members might require decades. An accelerated corrosion test using impressed current was used in this study to enhance the corrosion rate and study the effect of corrosion damage on concrete members in a short period of time in order to understand better the corrosion process.

Simultaneously, accelerated corrosion tests were used (Andrade et al., 1993; Alonso et al., 1998b; Val et al., 2009; Tran et al., 2011), but no uniform test procedure was established. The true mass loss of the bars was measured using the gravimetric method, and the results were compared to the theoretical value derived using Faraday's Law. This chapter includes the findings of a comprehensive examination of accelerated corrosion testing of steel bars under various environmental conditions in order to determine the conditions under which Faraday's Law would provide the most accurate results. The growth of corrosion products, pressure induced by corrosion products, and cracking of cover concrete due to pressure were all investigated in this environment.

1.1 Electrochemical Concepts and Principle of Faraday'sLaw

Corrosion is an electrochemical process that results in the formation of a microcell. An oxidation-reduction reaction happens when a potential difference is created, with the metal acting as an anode. A constant DC power supply is used to apply current to the steel rebar in an accelerated corrosion test. The steel bar acts as an anode in the presence of chloride and water. In this investigation,During the test, a constant current from the DC power supply was used to keep the applied voltage across each specimen under control. The entire mass loss of the anodic steel bar, which was directly proportional to current and time, was calculated using Faraday's Law. Figure 3.1 depicts a typical schematic diagram of an accelerated corrosion test setup.

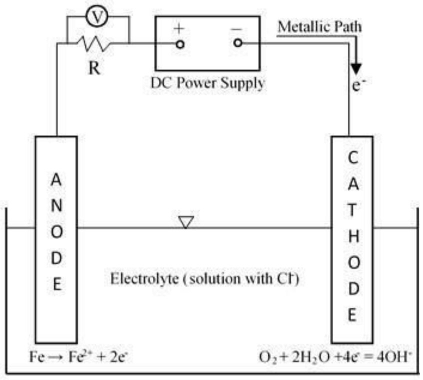


Figure2.1: Schematic Diagram of Accelerated Corrosion Test Setup

AsshowninFigure3.1,theanodicreactionistheoxidationofirontoferrousionsaccordingto:
$Fe=Fe^{2+}+2e$ (3.1)
Thecathodic reactionis thereductionofoxygentohydroxide ionsaccordingto:
$O_2+2H_2O +4e^-=4OH$ (3.2)
An electrochemical potential is applied between the reinforcing steel anode and cathode to cause corrosion. The current and a constant voltage was applied by the controlled DC supply to calculate an estimated corrosion-induced steel loss using Faraday's law.
Where mF is the mass loss of steel bars (gm), M is the atomic weight of the metal (for Fe, M = 56), I is the current (amperes), t is the time (seconds), Z is the ionic charge (for Fe, Z = 2), and F is the Faraday constant = 96,500 amperes/second.

1.2 Current Density

Different current densities and test settings were used by different studies. The effectiveness of the impressed current technique in inducing corrosion of steel reinforcement in concrete was summarised by El Maaddawy et al., (2015), as shown in Table A1. The accelerated corrosion by impressed current technique was effective in inducing steel corrosion in reinforced concrete, according to prior experimental data. Faraday's law was used to compute theoretical mass loss in this technique.However, the measured corroded mass loss of steel rebar based on gravimetric mass loss did not always match the theoretical mass loss calculated using Faraday's law. Regardless of current density, this fluctuation was determined by the amount of chloride ions present in the vicinity of the reinforcement. The presence of chloride ions in concrete can be divided into 2 types: chloride addition during casting and chloride ingression through concrete pores. Current density was defined as the current provided through the circuit per unit active corroding surface area to assess the rate of corrosion in impressed current systems (Alonso et al., 1998a; Austin et al., 2004; Molina et al., 1993; Nossoni & Harichandran, 2014).

1.3 Materials Used

In this study, two 10 mm diameter grade 500W deformed mild steel bars were used as both anode and cathode. Each bar was 76 mm in length. A steel wire brush was used to clean the bars. The high pH solution was made with NaOH, $Ca(OH)_2$, and KOH pallets. Prepared solutions had pH values of 13.7, 13.9, and 13.5, respectively. The high pH solutions were similar to the concrete pore solution in terms of pH. (Nossoni & Harichandran, 2012). In this experiment, ordinary Portland cement with a w/c of 0.45 was used to make the concrete.The mix was designed for a C30 grade concrete in accordance with ACI 211.1, taking into account the requirements for corrosion protection of reinforcements in concrete exposed to corrosive environments. In concrete, coarse aggregate was 19 mm downgrade stone chips, and fine aggregate was river sand with a fineness modulus of 2.8. Table 3.1 shows the mix proportion.Current was supplied through the circuit that used a DC (converted from AC current) power supply. The switchable input AC voltage was 200-220V 50/60Hz. The DC voltage at the output was variable (3- 30 V). A 4.7 resistor was used in the circuit, and the voltage drop across the resistor was measured with a multimeter, from which the current flowing through the circuit was calculated.

Ohm's Law (I=V/R) is used to compute the resistance (R), where I is the current (A), V is the voltage measurable difference (V), and R is the resistance (R).

Table2.1:MixProportionsfortheConcrete

Materials (kg/m3)					w/c ratio
Water	Cement	Fine Aggregate	Coarse Aggregate	Fresh density	
190	422	677	1056	2345	0.45

1.4 Methodology

Both environments were used in the accelerated corrosion test. I in a high-pH solution resembling concrete pore solution, and ii) in concrete. In both environments, the anode's corroding surface area (A=16.0 cm2) and the gap between the electrodes were kept constant. During the test, the chloride ion concentration in the solutions was varied from 0 to 1000 mMol/L. Steel corrosion is influenced by the number of chlorides in the electrolyte. The concentration of chlorides in electrolytes at which the actual mass loss equals the theoretical mass loss is known as the optimum chloride content. The optimal chloride content was investigated in this study.

1.5 Accelerated Corrosion Test in Solution

The pH of the concrete pore solution (pH > 13.0) is extremely high due to the presence of NaOH, Ca(OH)2, and KOH (Bertolini et al., 2013). Table A2 shows the concentration of different ingredients. The solutions were prepared in the same way as the concrete pore solutions. Table 3.2 shows the species concentrations in different concrete pore solutions, which was also used by Nossoni and Hari chandran (2012).

Table 2.2: Solution Properties

	$[OH^-]$ (mMol/L)	$[Na^+]$ (mMol/L)	$[K^+]$ (mMol/L)	$[Ca^{2+}]$ (mMol/L)	Calculated pH
Solution1	470	130	380	1.0	13.7
Solution2	834	271	629	1.0	13.9
Solution3	288	85	228	0	13.5

The test was carried out with a constant voltage supply and the voltage drop across the fixed resistor was measured. For both, distorted reinforcing bars with a diameter of 10 mm were used.
Anode and cathode are two different types of electrodes. Table 3.3 shows the various proportions of sodium chloride added to the solution.

Table2.3:DifferentCombinationofSaltSolution

Sl	[Cl-]/[OH-]	NaCl(mMol)	NaCl(%)
1	0	0	0.0
2	0.05	25.5	0.2
3	0.1	51	0.3
4	0.2	102	0.6
5	0.3	153	0.9
6	0.4	204	1.2
7	0.5	255	1.5
8	0.6	306	1.8
9	0.8	408	2.4
10	1	510	3.0
11	1.5	765	4.5
12	2	1020	6.0

The setup for the test in solution is shown in Figure 3.2. Before and after the test, the anode bar was cleaned with a steel wire brush. For each trial, a new solution and anode bar was used. The difference between the weights recorded before and after the test was used to calculate the actual mass loss. A constant current of 12v was applied to the circuit. Throughout the test, the distance between the anode and cathode was kept constant (20 mm). Each test was carried out for a total of 18 hours.

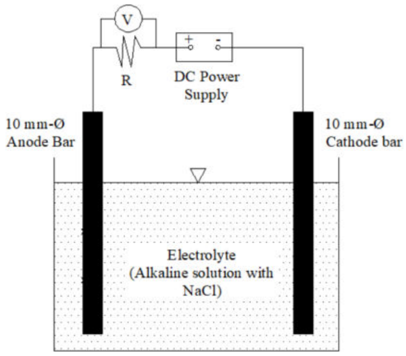


Figure2.2:Accelerated CorrosionTestSet-UpinSolution

1.6 Accelerated Corrosion Test in Concrete

The circuit was given a constant current of 12v. The distance between the anode and the cathode was kept constant throughout the test (20 mm). Each test took a total of 18 hours to complete. The circuit was given a constant current of 12v. The distance between the anode and the cathode was kept constant throughout the test (20 mm). Each test took a total of 18 hours to complete. The circuit was given a constant current of 12v. The distance between the anode and the cathode was kept constant throughout the test (20 mm). Each test took a total of 18 hours to complete.Before conducting the test, the specimens were immersed in salt solutions with optimum chloride content for various periods of time (0 day, 1 day, and 7 days) to determine the optimum time for which efficiency was 100%. As anode and cathode, two 10 mm deformed rebars were used. To maintain similarity with the test in solution, a constant distance (20 mm) was kept between two electrodes. Across the circuit, a steady voltage of 12V was applied. As previously stated, the actual and theoretical mass losses were measured, and the current efficiency was calculated.

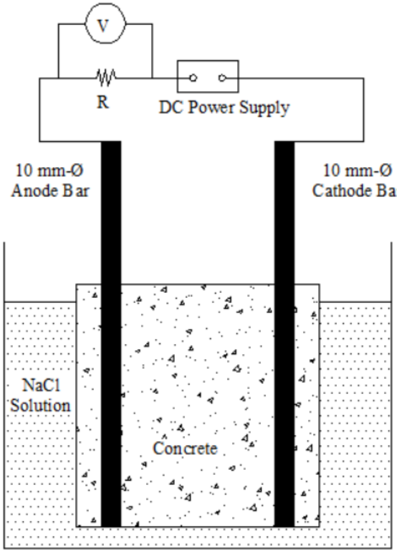


Figure2.3:AcceleratedCorrosionTestSet-UpinConcrete

III. RESULTSANDDISCUSSION

In the current efficiency was plotted against the [Cl-]/[OH-] for different chloride concentrations. Each data point's current efficiency was calculated using an average of three sets of tests. The graph shows that current efficiency is highly influenced by the amount of chloride in solution. The oxidation of the anode was almost nil in chloride-free solution and gradually increased as the amount of chloride ions increased. Accordingthe current efficiency reached % at a high chloride concentration [Cl-]/[OH-]= 1.0, which represents % salt in solution.The amount of chloride required to achieve 100% current efficiency was determined by the pH of the solution and the current density (Nossoni &

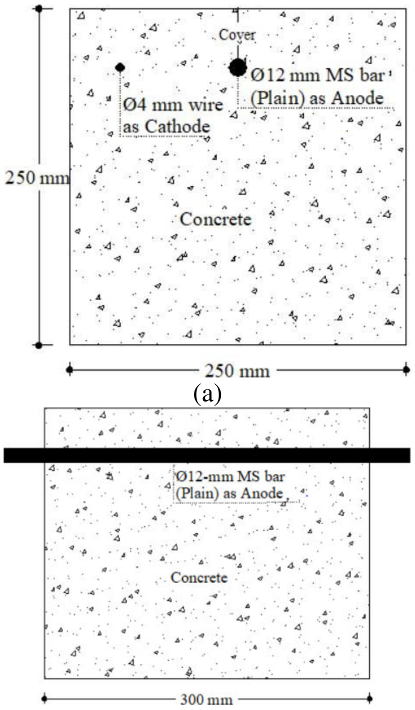
Harichandran, 2012). The pourbiax diagram can also be used to explain this phenomenon.How to make steel. When no chloride was present, the pourbiax diagram showed two active zones for corrosion: one for pH less than 9 and another for pH greater than 14. When the pH of the solution was 13.7, there's no corrosion. However, a pitting zone was discovered as a result of the addition of chloride, and it became more active as the chloride level increased. When the pH was higher, however, more chloride content was needed for oxidation.Because, in addition to steel oxidation, a variety of many other reactions may have occurred. The reaction produced some gases which irritated the eyes. They haven't been chemically identified, but the likely reaction is as follows: (Nossoni & Harichandran, 2012),Anode: $2OH^-$ = 1/2O2 + 2H2O + $2e^-$Cathode:2H2O+$2e^-$=H2+$2OH^-$In a chloride-free solution, all of the current was used to break the water molecule, resulting in oxygen and hydrogen gas at the anode and cathode, respectively. In the presence of less than a certain number of chlorides, partial current was used to oxid the steel, while the remains were employed to break water. So, for a given pH, there existed a specific chloride level at which the anode was fully oxidised. It was discovered that for a pH 13.7 solution, 3.0 % NaCl by weight was needed for 100 % current efficiency.It was also influenced by the amount of current flowing through the circuit. Previous studies show that depending on the current density, 1.65 % to % NaCl was required for % efficiency (Nossoni & Harichandran, 2012). When a current density of 100 A/m2 was used, Figure 3.4 showed that a higher ([Cl-]/[OH-] 1.0) was required for a % efficiency, which was also observed by (Nossoni & Harichandran, 2012) when a current density of 170 A/m2 was used.

1.7 Investigation On PhysicalChangesOf CorrosionProducts

For this experiment, C30 concrete was also used. Table 3.1 shows the mix proportion calculated according to ACI 211.1. Due to the concrete's exposure condition in a saline environment, a w/c of 0.45 was selected to implement the codal restriction. The binding material was ASTM Type-I (Ordinary Portland Cement), the coarse aggregate was 19 mm downgrade stone chips, and the fine aggregate was river sand with a fineness modulus of 2.8. The water used in this study had a chloride ion concentration of 1200 mg/L and was tap water. Concrete's compressive and tensile strength were determined using ASTM C39 and ASTM C426, respectively. Concrete's average compressive and tensile strength were found to be 30 MPa and 2.9 MPa, respectively. In this research, two forms of steel reinforcement were used. An anode was made of a 12 mm diameter Grade 60 MS plain bar, while a cathode was made of a 4 mm diameter wire. For beam specimens, the length of each bar was 380 mm, and for plates, it was 75 mm. In this study, two types of specimens were used: beam specimens and circular cross-section plate. Plates verified the crack start phenomenon observed in the beam specimen. The beams were 200 mm x 200 mm x 300 mm in size. Cylindrical plates had a diameter of 100 mm and a thickness of 50 mm. Four beam specimens with clear covers of 20 mm, 37.5 mm, 50 mm, and 75 mm were used to embed plain bar. Figure 3.1 depicts a schematic diagram of the test specimen. To avoid pitting, the uncovered portion of bar in beam specimens was coated with cement paste for a length of 25 mm. The 12 mm diameter bar (anode) was placed in the centre of cylindrical plates, and three 4 mm diameter wires (cathode) were arranged equidistant from each other and from the central anode bar. Figure 3.2 depicts the test specimens. The specimens were given a 28-day cure.

Table3.1: MixProportionsfortheConcrete

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



(a)

(b)

Figure3.1:DetailsofBeam specimen(a)CrossSection(b)LongitudinalSection

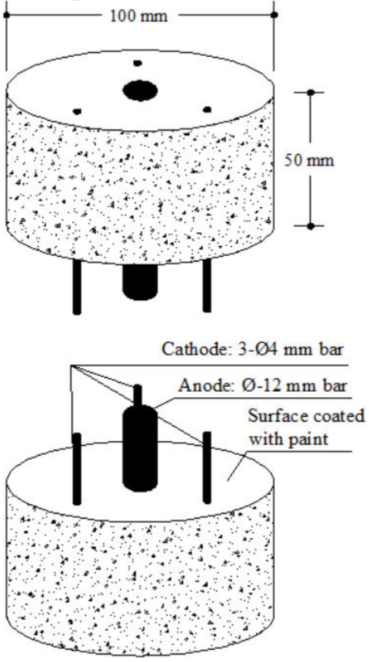


Figure3.2:DetailsofCylindrical Plates (a)TopView(b)BottomView

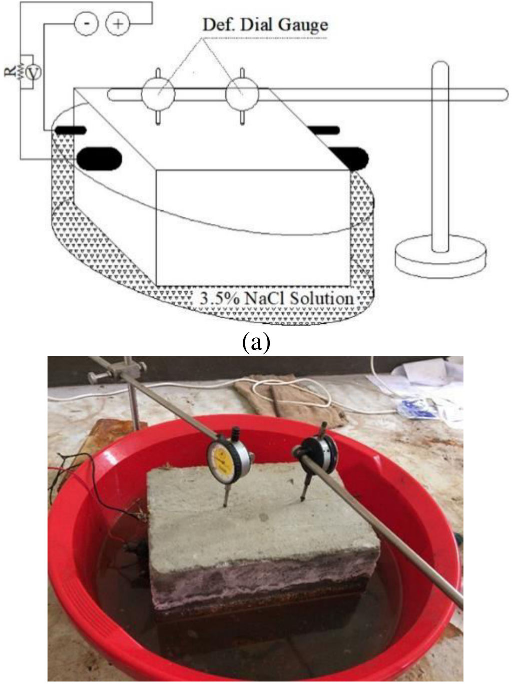
TestSetup

After the steel has depassivated, a microcell forms, creating a potential difference between the corroding bar and the surrounding corrosion products, and the corroding bar continues to corrode. An external DC power supply was used to supply a direct current between the anode (steel reinforcement) and cathode in order to replicate this phenomenon in a short period of time. The power supply had a 30 V, 6 A capacity. The voltage drop across a fixed resistor was measured while a constant voltage of 30 V was applied to the circuit. Ohm's law ($I = V/R$) was used to calculate the current supply.So, because current efficiency in accelerated corrosion tests was % when the specimens were ponded in 3.5 %

NaCl solution for one day in the preceding chapter, the specimens were partially ponded in 3.5 % NaCl solution for at least one day before starting the test.

Beam Specimen

To measure the heaving due to corrosion, two deformation dial gauges were placed on the top surface of the beam specimen along the longitudinal reinforcement. The set-up was shown in Figure 3.3. A magnifying USB digital Microscope (Manufacturer: TQC, Model: LD6184, Resolution: 1 microne) was used to measure crack width.



(a)

(b)

Figure3.3: DetailsofTest Setup forBeamSpecimen (a) SchematicDiagram(b)OnsideView

IV. CONCLUSIONS

The primary focus of this thesis was an experimental investigation and numerical analysis of the corrosion-induced pressure that causes the concrete cover crack to begin and continue to spread. The following inferences and conclusions can be made on the basis of the findings of the comprehensive study. When using the impressed current technique, the quantity of chloride ions is a significant factor in determining the degree to which steel corrodes. An experimental investigation was carried out in solutions that were comparable to that of the concrete pore solution in order to determine the ideal concentration of chloride. It was discovered that the actual mass loss coincided with the theoretical one when there was a high concentration of chloride in the mixing water, which was 3.5 percent by mass. In order to achieve a current efficiency of one hundred percent, the chloride ions that are to be transported through the pore space of the concrete must first be saturated with the chlorides that are adjacent to the steel-concrete interface. Regarding this particular point, a search and investigation were carried out. The cubical specimens were submerged in a chloride solution containing 3.5 percent for varying amounts of time, and it was discovered that the specimens needed to be submerged for at least one day prior to the beginning of the tests in order to become saturated.

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