Pitting corrosion analysis of steel rebars in concrete corrosive environment using COMSOL Multiphysics simulation

A Thesis

Submitted to the Graduate Faculty of Indian Institute of Technology Indore in Partial Fulfilment of the Requirement for the degree

MASTER OF TECHNOLOGY IN METALLURGY ENGINEERING AND MATERIALS SCIENCE

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JUNE 2022



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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "Analysis of pitting corrosion of steel rebar in the concrete corrosive environment using Comsol Multiphysics simulation" in the partial fulfillment of the requirements for the award of the degree of MASTER OF TECHNOLOGY and submitted in the DEPARTMENT OF METALLURGY ENGINEERING AND MATERIALS SCIENCE, Indian Institute of Technology Indore, is an authentic record of my work carried out during the time period from August 2021 to June 2022 under the supervision of Dr. Mrigendra Dubey (Associate Professor), the discipline of Metallurgy Engineering and Material Science (MEMS) Indian Institute of Technology (IIT) Indore. I have not submitted the matter presented in this thesis for the award degree to anotherinstitute for any students.

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ACKNOWLEDGMENT

It is my great pleasure to thank the people who made this project work possible. First and foremost, I would like to thank the IIT Indore faculty and staff for their commitment to educating their students. I would especially like to thank my supervisor, Dr. Mrigendra Dubey, for believing in me to carry out this work under his supervision. His constant encouragement, friendly interaction and valuable support have made this work to its present form.

I would like to thank my PSPC members, Dr. Vinod Kumar and Dr. Srimanta Pakhira for their valuable time in looking and assessing my work during my mid-term and end-term presentation and for giving me valuable suggestions to boost my work.

I am thankful to Dr. Vinod Kumar, Head of the department –MEMS for providing facilities that I needed throughout the M.Tech project work. I am also thankful to the faculty of this department for their constant valuable support and effort in teaching the concept to improve my knowledge in Material science and engineering.

Finally, I would like to thank my senior Yeeshu Kumar, Moupia Mukherjee, Manish Kumar Dixit for their valuable suggestion in presentation and writing my thesis work. I thank my friends and my parents for their constant support.

DEDICATION

Dedicated to my Guide

My Parents

My Teachers

My Seniors

My Friends

ABSTRACT

Corrosion of reinforcement steels, induced by chloride ions penetrating into the concrete, is the main cause of early damage, loss of serviceability and safety of reinforced concrete structures, which can be even more severe. Among the different forms of corrosion pitting corrosion is an insidious localized form of corrosion. In this work, we have created a 3-D finite element model of reinforcement bar made of 316 stainless steel and plain carbon steel subjected to a corrosive concrete environment and investigated pitting corrosion behavior inside the rebars with the help of COMSOL Multiphysics software. In this work we have used two types of studies stationary and time dependent for the rebar material. The effect of pitting corrosion was investigated by examining the electrochemical parameters such as electrolyte potential and electrolyte current density and the variation in total electrode thickness change with time for both SS316L and plain carbon steel. The values of electrolyte potential distribution and electrolyte current density for plain carbon steel are higher than that of SS316L rebar. For 144h in case of plain carbon steel the value is $-3.59 \times 10^{-4} \,\mu$ m while for SS316L it is $-1.08 \times 10^{-8} \,\mu$ m. Total electrode thickness change increases as the time passes. Hence plain carbon steel is more susceptible to corrosion than SS316L which is more corrosive resistant material for rebars.

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LIST OF SYMBOLS

arphi	Electric potential (V)
V_n	The normal velocity of moving flux (m/s)
$i(\varphi)$	Dissolution current density (A/m ²)
Ζ	Number of electron involved (unit less)
F	Faraday's constant (96485.34 C/mol)
C _{solid}	Concentration of metal (mol m ⁻³)
i,	Electrolyte current density (A/m ²)
<i>is</i>	Electrode current density (A/m ²)
arphiı	Electric potential at electrolyte (V)
$arphi_s$	Electric potential at electrode (V)
Q	Current source (A/m ³)
η_o	Activation over potential (V)
N_i	Molar flux for species $i \pmod{m^2 s^{-1}}$
D	Diffusion constant (m ² s ⁻¹)
с	Concentration (mol m ⁻³)
u	Bulk velocity (m/s)
μ	Mobility $(m^2 V^{-1} s^{-1})$
E _{eq}	Equilibrium potential (V)
Cr	Corrosion rate (mm/y)
A _{eq}	Equivalent weight (kg/equivalent)
ρ	Density (kg/m ³)

ACRONYMS

SEM	Scanning electron microscope
NACE	National Association of Corrosion Engineers
TEM	Transmission electron microscope
SCC	Stress corrosion cracking
SEP	Standard electrode potential
SS	Stainless steel
СРТ	Critical pitting potential
ALE	Arbitrary Langrangian Eulerian
GDP	Gross domestic product
AISI	American Iron and Steel Institute
FEA	Finite element analysis
FEM	Finite element method

CHAPTER 1: INTRODUCTION

1.1 Overview

The thesis is presenting pitting corrosion analysis using computational method by COMSOL Multiphysics has been studied. Considering the drawbacks of experimental restriction. A 3-D pit model method has been created for the investigation of pitting corrosion in 316 stainless steel and plain carbon steel reinforcement bars exposed to corrosive concrete. For both SS316L and plain carbon steel, a stationary and time-dependent investigation on a pit model system was conducted, as well as a comparison of variation in total electrode thickness change and corrosion rate with a single pit.

1.2 Corrosion and its economic aspect

Corrosion is basically the environment's destructive attack (chemical breakdown) on a material. Any substance's partial or complete wearing away, dissolving, or softening as a result of a chemical or electrochemical reaction with its surroundings is included in this description. Corrosion processes not just affects chemical properties of metals and metal alloys, but also physical properties & mechanical behaviors [1]. Corrosion is the natural transformation of a refined metal into a more chemically stable state like oxide hydroxide or sulphide. Corrosion is a opposite extractive metallurgy, which relies upon stress, environment, erosion and temperature. Corrosion affects directly on the economy as it leads to the replacement of equipment which adds the cost of replacing in corroded structures. It reasons foremost monetary losses degrees from 1% to 5% of GNP consistent with year for any nations. NACE IMPACT study had reported the cost of corrosion considering the different economic sectors such as agriculture, industry, and services of different countries, which has been shown in figure 1.1.

When the NACE reports were analyzed, the corrosion cost globally is around 3.4 percent of global GDP. Corrosion costs India approximately 4.2 percent of GDP [2]. Corrosion may have negative consequences for human health, the environment, and environmental security that are difficult to quantify in terms of lost GDP. It cost someone their life in addition to the financial losses. The Genoa, Italy Bridge Collapse (2018), the Aloha accident (1988), the Bhopal accident (1984), the Silver bridge failure (1997), the sinking of the Erika (1999), pitting corrosion accidents, helicopter and aircraft incidents, and the Guadalajara sewer explosion (1992) are just a few examples of major accidents caused by corrosion. These mishaps serve

as a stark reminder of the dangers of corrosion, which must not be overlooked.

Economic Regions	Agriculture CoC US\$ billion	Industry CoC US\$ billion	Services CoC US\$ billion	Total CoC US\$ billion	Total GDP US\$ billion	CoC % GDP
United States	2.0	303.2	146.0	451.3	16,720	2.7%
India	17.7	20.3	32.3	70.3	1,670	4.2%
European Region	3.5	401	297	701.5	18,331	3.8%
Arab World	13.3	34.2	92.6	140.1	2,789	5.0%
China	56.2	192.5	146.2	394.9	9,330	4.2%
Russia	5.4	37.2	41.9	84.5	2,113	4.0%
Japan	0.6	45.9	5.1	51.6	5,002	1.0%
Four Asian Tigers + Macau	1.5	29.9	27.3	58.6	2,302	2.5%
Rest of the World	52.4	382.5	117.6	552.5	16,057	3.4%
Global	152.7	1446.7	906.0	2505.4	74,314	3.4%

Fig. 1.1 The global cost of corrosion by different sectors by regions (NACE STUDY 2013)

1.3 Electrochemical corrosion consideration

Metals degrade electrochemically as a result of interactions with their surroundings. The corrosion behavior of metallic materials is explained by particular reactions with their surroundings, such as oxidation and reduction reactions [2]. The following is a quick description of such a reaction.

1.3.1 Oxidation reaction

Metal atoms lose one or more electrons and become positively charged ions, or the metal ion moves from a lower to a higher valence state. This is referred to as an oxidation process, and the electrode at which it happens is referred to as an anode. If a metal M undergoes oxidation, the general formula for such a process is as follows:

 $M \longrightarrow M^{n+} + ne^{-}$

M metal becomes n+ positively charged ion (Mn+) and losing its n valence electron. The oxidation process of iron (Fe) and Al are shown below.



1.3.2 Reduction reaction-

When the oxidation process occurs the at anode the electrons are released, as a result the reaction is consumed in a chemical reaction termed a reduction reaction, and the point where

this reaction occurs is known as a cathode. The reduction reaction's generic chemical equation is shown below.

 $R^{n+} + ne^- \longrightarrow R$

By consuming the ne- produced by anodic reactions, Rn+ species are transformed to R. Reduction can take place in two ways: the species at a higher oxidation state is changed into a lower oxidation state, such as; or the species from a lower oxidation state is transformed to a higher.

 $R^{n+} + e^{-} \longrightarrow R^{(n-1)+}$

Alternatively, the species from a neutral state is converted into negatively charged species such as;

$$R + e^- \longrightarrow R^-$$

Additional reduction processes are also possible, depending on the medium or electrolyte's composition.

(a) If an acid solution contains dissolved oxygen, the reaction on the cathode will be as follows:

 $O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O$

(b) If the solution is neutral or basic and contains dissolved oxygen, the reaction is as follows.

 $O_2 + 2H_2O + 4e^- \rightarrow 4(OH^-)$

1.4 Forms of corrosion

Before Fontana and Greene coauthored their famous book in 1967, many people had used the idea of explaining the numerous ways corrosion may harm metals based on their appearance. In their 1936 book on corrosion, McKay and Worthington discussed numerous types of corrosion. after Alan Pollitt's book, which was published thirteen years earlier, in 1923. However, with slight changes amongst authors, the classification that follows appears to have received the most widespread approval. Each form may be distinguished just by looking at it. The bare eye is usually enough however to magnify is sometimes useful. Careful examination of damaged test specimens or failed equipment can often yield crucial details for corrosion problem solutions. It is very important to inspect before cleaning. Types of some common corrosion

1. Uniform Corrosion

- 2. Galvanic Corrosion
- 3. Pitting Corrosion
- 4 Crevice Corrosion
- 5. Intergranular Corrosion

1.4.1 Uniform corrosion

When the electrochemical or chemical reactions occur consistently on the entire surface which is exposed to the environment or over a vast surface area of a metal it is usually the defining feature. The metal thins and eventually breaks down. A metal piece made up of zinc or steel, when these metal pieces are immersed in a sulfuric acid taken in dilute form dissolves at constant pace across whole surface [5]. To limit the effect of uniform corrosion these methods are really helpful, 1. Cathodic protection, 2. Using the appropriate materials including coatings, 3. Inhibitors. It occurs on a tonnage basis also known as general overall corrosion. The exposed surface undergoes homogeneous oxidation and reduction reactions at the microscopic level. In the environment, primary reason for uniform corrosion is oxygen in steels etc. and its alloys. For ex. gate valve used to transport the chemicals uniform corrosion can be observed as shown in figure 1.2. Corrosion reduced thickness of pin which holds gate valve due to which gate falls and pin fails.



Fig. 1.2 Uniform corrosion in gate valve used to transport chemicals [2,3]

1.4.2 Galvanic corrosion

Two dissimilar metals when submerged in corrosive or conducting fluid, they usually have a potential difference. This potential difference causes electron movement between these metals if they are placed in contact (or otherwise electrically linked). This type of corrosion is termed as Galvanic corrosion because here electric current and dissimilar metals are considered [6]. Steel screws, for example, rust when exposed to brass in a marine environment. The steel will corrode along the steel & copper junction tubing in a household water heater (galvanic couple formation). The difference in electrode potential of two metals is the most important aspect.

The greater the difference, the greater the galvanic corrosion driving force. Figure 1.3 shows the huge metal door is the cathode and bolts are anode in the presence of electrolyte bolts corrodes galvanically.



Fig 1.3 Iron bolts corroding galvanically [3]

1.4.3 Crevice corrosion

Crevice corrosion occurs when a stagnant solution in crevices, such as around the edges of nuts and rivet heads, attacks metal surfaces. When dust, grit, and other corrosive particles are accumulated on surfaces, they create an environment in which water collects and corrodes the component. It can happen when two metals contact or when a metal comes into contact with a nonmetal. This damages the metallic portion, which is induced by a chemical concentration gradient. Outside the crevice, oxygen causes an electrochemical concentration cell. The air contained in this differential aeration cell is oxygen. The oxygen content & pH rise in crevice (the cathode) chlorides, on the other hand, are at a lower level [7]. Crevice corrosion can be observed under Type 316 bolts holding a Type 316 structural beam as shown in figure 1.4.



Fig. 1.4 In Type 316 bolt crevice corrosion has developed [10]

1.4.4 Pitting corrosion

It is a corrosion that attacks a specific area of a metal and eventually causes holes to form. The collapse of the Silver Bridge in West Virginia, USA, in 1967 is an example of pitting corrosion leading to SCC. When a small area is exposed to the environment and becomes anodic, this type of corrosion happens. Meanwhile, a cathode is formed in another part of the metal [10]. This causes a sort of galvanic corrosion that starts on the metal's surface but can progress downwards, eventually causing structural failure. Pitting is harmful than uniform corrosion because it is harder to detect. Products from the corrosion frequently hide the pit. A very narrow pit having little total metal loss might cause an entire engineering system to fail. Stainless steel or the passivating material are more susceptible to this type of corrosion. Pit formation in AISI 304 rolled steel is shown in figure 1.5.



Fig. 1.5. Pitting corrosion of AISI 304 rolled steel [4]

Pitting corrosion follows the same basic mechanism as crevice corrosion the oxidation reaction is concentrated in the pit and the complementary reduction occurring on the remaining surfaces. The pits are said to expand because of gravity [8]. It propagates and then terminates when the pit is started, culminating in the construction of a hole and the failure of pipelines occurs. Pipelines corrosion in oil and gas pipelines as shown in figure 1.6 caused by chemicals found in oil and gas.



Fig. 1.6. Showing the failure of the pipeline by pitting corrosion [6]

1.4.5 Intergranular corrosion

Intergranular corrosion occurs majorly along grain boundaries in alloys and in specific conditions. Individual grains are known to have varied orientations and boundaries, which are referred to as grain boundaries [4]. Grain boundaries are not as reactive as grain itself, although impurities can affect grain boundaries under certain conditions. Metal structure can be altered by heat treatment and welding, which can lead to intergranular corrosion. Intergranular corrosion can cause a severe loss of mechanical characteristics and, in extreme cases, can turn the metal into a pile of individual grains. Intergranular corrosion can be observed usually in stainless steel. Alloys become more prone to such corrosion when they are heated upto 550-800 °C for a long period of time. Intergranular corrosion in SS tank on both side of weld in figure 1.7.



Fig. 1.7. On a stainless steel tank, corrosion occurred on both sides of the weld in the illustration above [8]

1.5 Literature review

1.5.1 Mechanism of pitting corrosion and its stages

Pitting corrosion is the most damaging of the various types of corrosion. There are various publications available on the suggested pitting mechanism, phases, and factors related to putting corrosion. The mechanism of pitting, stages of pitting, and factors impacting pitting corrosion, as well as a strategy to prevent such corrosion, were examined and proposed by Akpanyung K.V et al. [9]. Steel, aluminum and some other metals form a passive film and there is higher chances of pitting corrosion in such metals. The loss of the passive film is the primary cause of pitting corrosion. The method is explained with the help of the diagram given above.



Fig. 1.8 Schematic diagram of Pitting corrosion [7]

At earliest stage of pitting the passive film breaks down, according to Akpanyung K.V et al. On the passive film surface anions of strong acids are absorbed as corrosive ions such as chloride ions, causing mutual repulsion and tension on the material's interfacial surface lowers down. When repulsion is strong enough, the passive film breaks down. Pit initiation (nucleation) occurs where the passive films break, making it susceptible to pitting corrosion. Pitting initiation and propagation are influenced by a number of factors mentioned as following [11]. Low pH, high chloride concentrations, and low dissolved oxygen concentrations are all environmental factors that can induce film breakdown.

- Improper use of protective coating or damage.
- The adding non-metallic components causes irregularities in the metallic structure.
- Chemical or mechanical action damages the protecting film (passive film).

When the material in figure 1.8 is exposed to a harsh corrosive environment, chemical species attack uniformly and the material corrodes uniformly. However, in some areas (pits), the rate of material degradation is extremely high. Pit initiation mechanisms can be divided into three categories: penetration of an aggressive environment, ion adsorption, and film breakdown [11]. The propagation of pits follows the initiation of pits. The following are the reactions that occurred (anodic and cathodic, respectively).



These reactions take place everywhere across the material's surface. More stagnant conditions cause oxygen depletion in the pit portion when the protective film is damaged. This means

there is less oxygen in the pit area and more oxygen on the material's remaining surface. Because of the scarcity of oxygen, the anodic reaction (oxidation) is concentrated in the defective pit region, or anodic reaction rate is higher than the cathodic reaction rate, and the material is removed from the pit section while the remaining surface is protected by the cathodic reaction. Due to the unfavorable ratio, there will be more metal dissolution in the pit area, and the pit will begin to grow in size. Pit propagation is the term for this occurrence. The self-propagating nature of the process results in the accumulation of charge in the pit section due to constant metal dissolution producing positive ions (Mn+). Negative ions, such as chloride ions, that arrive from corrosive media like saltwater balance the positive accumulating ions near the pit region. The positive ions are also kept neutralized by OH⁻ ions by the process called hydrolysis.

The presence of hydrogen and chloride ions in the corrosive media prevents repassivation in the pit, resulting in the generation of free acid and a drop in PH. Finally, due to the autocatalytic process, the pit grows and metal perforation occurs, resulting in the process termination.

1.5.2 Common pit shapes

Pitting corrosion results in pits of varying forms and sizes [9]. Trough pits and sideways pits are the two types of pits shown in Figure 1.9. The pit might be cup-shaped or hemispherical in shape, conical in shape (most frequent), or flat sided and irregular in shape. The frequent shapes displayed in figure 1.9 include elliptical, narrow deep, vertical grain attack, shallow broad pit, horizontal grain attack, subsurface, undercutting & vertical grain attack, among others.



Fig 1.9 Common shapes of pit [12]

1.5.3 Factors responsible for pitting corrosion

Pitting corrosion can be influenced from various elements, and study is still ongoing. Environmental factors, metal composition, pitting potential, corroding medium pH, chloride concentration, fluid velocity, and the nature of the metal's surface are all factors to consider. Temperature and its state are two factors that can influence pitting corrosion [11-13].

- The environmental parameter is the most essential among these various aspects. The concentration of charged ions, the pH of the corrosive medium, and the concentration of the inhibitor utilised are all factors to consider. [13].
- The microstructure and content of an alloy have a significant impact on pitting resistance [13]. The tendency of such an alloy can be compensated for or lessened by adding a component to the alloy's microstructure. For example, adding Cr to stainless steel improves its passivation properties, whereas adding nitrogen and tungsten in small amounts improves the pitting resistance of stainless steel.
- Temperature is another important aspect in pitting corrosion. As the temperature rises, the pitting potential values drop. The pitting potential is the limit beyond which pitting can occur [13]

1.5.4 Electrochemical Parameters for Pitting

1.5.4.1 Pitting potential

The minimum potential (E_P) below which no pit was found regardless of how long the metal was exposed to corrosive environment. Above this potential pitting would start on the spot. There are several factors, which affect pitting potential such as environment composition, temperature, and the composition of alloy or metal, etc.[14]. Figure 1.10 shows the anodic polarization curve of pitting potential of Al in sodium chloride corrosive medium is represented [15]. When the pitting potential is achieved, the current begins to rise and pits appear on metallic surface. This method is known as potentiostatic method of calculating pitting potential (E_p).



Fig. 1.10 Pitting potential of Al in NaCl solution [15]

1.5.4.2 Repassivation potential

The potential below which pit growth stops, also known as protection potential, is called repassivation potential (Er). Pits that begin to grow at or above their pitting potential will continue to grow even if the potential is dropped to Ep [16], according to Pourbaix. Figure 1.11 shows the polarization curve for the repassivation potential of stainless steel (SS).



Fig. 1.11 Polarization curve for the repassivation potential for stainless steel (SS) [16]

1.5.4.3 Critical pitting temperature (CPT)

It is one of the most essential parameters or tools to determine SS resistance by pitting corrosion & it is defined as the minimum temperature at which stable pit forms. When the temperature falls below the CPT, no stable pit forms, and transpassive corrosion takes over, as shown in figure 1.12. When the temperature is higher than the CPT, stable pitting will form. CPT measurements have piqued the interest of many academics since they are commonly used for ranking austenitic SS resistance against pitting corrosion. If CPT is more, the resistant is more for the stainless steel or alloy for pitting [15].



Fig. 1.12 CPT (critical pitting temperature) [17]

1.5.5 Pitting corrosion of reinforcing steel bars in chloride contaminated concrete

Corrosion caused by chloride is a primary cause of reinforced concrete structure degradation in the marine environment. Corrosion will begin and progress at a rate determined by the local environmental conditions and also concrete quality. Because the corrosion product expands and the concrete's low tensile strength, just a little corrosion is needed to spall the concrete cover off the reinforcement and corrosion can further occur [19]. In this study accelerated corrosion tests are used to investigate the corrosion of reinforcing steel bars in chloride-contaminated concrete. After that 3-D laser scanner is used to scan steel bars which are corroded. The geometrical parameters of the corroded bars are investigated using statistical analysis methods based on the acquired 3-D pictures of the corroded bars.

Ten reinforced concrete examples, ranging in size from 350×80×400mm³ were cast. Figure 1.13 shows each specimen has five reinforcing bars with a 33 mm concrete overlay. At 28 days, the concrete mix was supposed to have a cubic compressive strength of 40 MPa. The concrete mix proportion is shown in figure 1.14. In this study 50 HPB300 steel plain bars having diameter of 14 mm were employed as reinforcement. The HPB300 bars have a yield strength of around 300 MPa. Figure 1.14 shows the chemical composition of the steel bars. 400 mm long reinforcing bar before casting was sandblasted to remove rust coatings. Epoxy resin was used to coat the terminal ends of the bar 75 mm long on each side before insolating tape was applied. Corrosion affected the central part of the pipe, which was around 250 mm long [20].



Fig 1.13. Specimen design. Adapted with permission from ref. [19].Copyright 2018, Elsevier Ltd.

Table 1 Mix proportion	of concrete												
Components	5	Portlan	d cement (P	42.5)	Fir	ne aggregate		Coarse	aggregate		Water		Additives
Wt.%		14.6			29.8			48.7			6.7		0.2
Table 2 Chemical comp	position of st	eel bars.											
Element	С	Si	Mn	Р	S	Cr	Мо	Ni	Со	Cu	V	Sn	Fe
Wt.%	0.24	0.42	1.10	0.03	0.03	0.20	0.07	0.20	0.01	0.20	0.02	0.03	97.45

Figure 1.14 Mixture properties of concrete and chemical composition of rebar. Adapted with permission from ref [19]. Copyright 2018, Elsevier Ltd

Anodic corrosion testing is used to estimate pit depth, cover cracking, and strength loss of reinforcing bars in concrete. Reinforcing bars act as an anode in the anodic corrosion test, while metal serves as the cathode. Between the anode and the cathode, an external power source with a steady electric current or voltage is used to drive chloride ions from the external solution into the concrete causing reinforcing bar corrosion. Concrete specimens were cured for 28 days in air at a room temperature of about 25° C. The copper cathode was immersed in a 5% NaCl solution during the accelerated corrosion test, and a constant current density of 2.27 mA/cm2 was applied between the reinforcing bars and the copper as shown figure 1.15 [21].



Fig 1.15 Acceleration corrosion test. Adapted with permission from ref [25]. Copyright 2018, Elsevier Ltd

Following the accelerated corrosion test the rusted steel bars were carefully removed from the specimens by breaking the concrete, washed with tap water, dried naturally, and weighted. The process of cleaning, washing, and weighing was repeated until the final weight change was less than 0.1 g. The following formula was used to compute the mass loss of corroded bars:

$$\Delta m = \frac{m_o - m_c}{m_o} \times 100\%$$

where Dm is % mass loss, mo is the original steel bar's per-unit-length mass, and mc is the steel bar's per-unit-length mass after the corrosion products were removed. A micrometre gauge with a 0.01 mm accuracy was used to measure the pit depth in the corroded bars.

The surface morphology of the corroded steel bars was measured using a 3D light scanner with a 0.05 mm precision after cleaning. The scanning procedure generated 3D coordinates for each location on the steel bar's surface. They were examined with the Matlab program to generate various geometrical features such as pit depth. Fig.1.16 represents a 3D image of a corroded steel bar produced using the 3D light scanner. Equation to find the pit depth is shown below.

$$P(x) = \max_{k \in (1,2,...,n)} (R - \sqrt{y_k^2 + z_k^2})$$

where P(x) is largest pit depth on the cross section along the circumference, R is the radius of the original steel bar.



Fig 1.16 3D scanned image of rebar. Adapted with permission from ref [25]. Copyright 2018,

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The pit depth was calculated to identify the maximum pit depth along the perimeter of each cross section of the corroded bar. The longitudinal distribution of pit depth of four typical corroded bars with varied corrosion levels measured by percent mass loss is shown in figure. 1.17. The pit appeared randomly along the length of the corroded bar, but the depth of the pit was not evenly distributed. The maximum pit depth is discovered to be varied for steel bars with various levels of corrosion. The pit depth on the other hand was shown to increase as corrosion level increased [22]. The maximum pit depth was determined to be 2.05, 2.80, 2.93, and 3.79 mm in steel bars with mass losses of 3.6%, 12.1%, 19.7%, and 31.9 % for x=232.5, 141.5, 13.5 & 155.5 mm.



Fig 1.17 Pit depth distribution along length of rebar. Adapted with permission from ref [25]. Copyright 2018, Elsevier Ltd.

Using accelerated corrosion experiments corrosion of reinforcing steel bars in chloridecontaminated concrete was explored experimentally in this work. A 3-D laser scanner was used to create 3-D images of 50 corroded steel bars. Corrosion bar's pit depth is unevenly distributed. The maximum pit depth increases as the corrosion level rises [23].

Chapter 2: SIMULATION WORK

2.1 About COMSOL Multiphysics

COMSOL Multiphysics is a simulation software that uses finite element based computational fluid dynamics (CFD). It is important for both academic and research purposes. It covers a vast range of scientific domains, from fundamental chemical and mechanical issues to extremely advanced electronics, nanotechnology, optics, and other branches of research and applied sciences. The term 'multiphysics' should be highlighted [30]. Because multi means more than one and physics is a branch of science, multiphysics comprises multiple physics that are engaged in a given phenomena. COMSOL is widely used by researchers all over the world because of its flexibility in selecting physics and the ease with which they can be coupled together. To use COMSOL, you must have a basic understanding of mathematical modelling.

Engineers and scientists in various disciplines of engineering, manufacturing, and scientific research utilize the COMSOL Multiphysics program to model designs, devices, and processes. COMSOL Multiphysics is a simulation platform that allows you to model fully coupled multiphysics and single-physics systems [24]. All of the phases in the modeling workflow are included in the Model Builder, from specifying geometry, material attributes, and the physics that characterize specific phenomena to solving and postprocessing models for precise results.

Modeling, in combination with tests, is effective for optimizing processes and devices faster and more accurately than using experimental methods or testing prototypes alone. We can obtain a deeper understanding of the design or process by developing experimentally validated models for our studies since we can study it in a more convenient manner than in the lab. Multiphysics models take into account a wide range of possible operating conditions and physical impacts. This allows models to be used to better analyse, design, and optimise processes and devices for real-world applications.

Model Builder in COMSOL Multiphysics offers us with a complete simulation environment and a consistent modelling workflow from start to finish shown in figure 2.1. The modelling process includes :

- Geometry
- Physics based modeling
- Equations based modeling

- Meshing
- Optimization and research
- Solvers
- Post-processing and visualization



Fig 2.1. Modeling workflow

First of all, simulation was performed on a simple geometrical 2D shape and validation of computational result with the literature or the experimental results available.

2.2 Pitting corrosion study on rebars under concrete environment

Corrosion is an important factor that affects the lifespan and durability of reinforced structues made of concrete. Furthermore, it significantly maintenance costs for rebars increases over time [28]. Corrosion is induced by the accumulation of chlorides on the rebar, which leads to the formation of rust, which causes the rebar's volume to expand. Internal stresses are created where there is contact between the rebar & concrete, causing cracks to form in concrete.

2.2.1 Model description

A rebar placed at the center of reinforced beam having square cross-section made up of concrete is considered for geometry. The study focuses on the pitting corrosion of rebar and its impact. Modeling and simulation were carried out with the help of COMSOL Multiphysics for corrosion analysis, using data from the literature or experimental work. It helped me save a lot of time and money [26-30]. Diameter of rebar D, dimension of cross-section L and the thickness of concrete cover C are three basic characteristics taken into account. Schematic



Fig 2.2 Pitting corrosion in RC structures [31]

A computational model of the steel rebar consisting of pit in a concrete environment was built by using COMSOL version 5.6 as shown in figure 2.3. Pitting corrosion was analyzed in the steel rebar. The model for concrete environment was built of dimensions: height (L) 600 mm and width (w) 100 mm and depth 100 mm. The steel rebar was built with dimensions as: height (L) 400 mm, major radius 10 mm, minor radius 2 mm, axial pitch 12 mm. Steel rebar is surrounded by concrete which acted as electrolyte medium having an electrical conductivity of 1 e⁻² S/m. A conical pit was created of size of radius 3mm.



Fig. 2.3 Geometric representation of 3D model of steel rebar under concrete medium

2.2.2 Material selection

A 3-Dimensional model of $600 \times 100 \times 100$ cm³ cubic concrete specimen with electrical conductivity $1e^{-2}$ S/m is used for this study was prepared with the help of COMSOL Multiphysics version 5.6. The concrete specimen bore an embedded with 10 mm major radius and minor radius of 2 mm made up of two types of materials first is stainless steel 316L and another is low carbon steel, samples for the study are steel rods being use in a building

construction. It is referred to as low carbon steel bar with a very low carbon composition of \leq 0.24% and other components plain carbon for rebar [28-29]. The composition of SS 316L and plain carbon steel are given in table-2.1 (a) and 2.1 (b).

Element	% present
Carbon(C)	0.03
Silicon (Si)	1.00
Manganese (Mn)	2.00
Phosphorous (P)	0.045
Sulfur (S)	0.015
Chromium (Cr)	16.50-18.50
Nickel (Ni)	10.00-13.00
Nitrogen (N)	0.10
Molybdenum (Mo)	2.00-2.50
Iron (Fe)	Balance

Table 2.1 (a) Chemical composition of SS316L

Element	% present
Carbon	0.14 - 0.20
Iron	98.81 - 99.26
Manganese	0.60-0.90
Phosphorous	0.040
Sulphur	≤ 0.050

Table 2.1 (b) Chemical composition of plain carbon steel

2.2.3 Meshing

Meshing is an integral part of the analysis because the COMSOL Multiphysics software uses the finite element method. Some electrochemical parameters such as current density & electrolyte potential, are required for analysis, and these parameters are calculated using mathematical equations. Partial differential equations are used to solve these equations. The real problem has many/infinite degrees of freedom, making manual calculation difficult to solve [31]. To tackle such a problem, Finite Element Analysis (FEA) is utilized, in which a mesh is generated that divides the entire model domain into the number of elements for which a solution can be found. To produce the result, the data is interpolated [35] throughout the entire domain. Simple physics-controlled meshing was employed in this case, as seen in figure 2.4.

Description of mesh	Values
Maximum element size	21
Minimum element size	0.9
Curvature factor	0.3
Resolution of narrow (small) regions	0.85
Maximum element growth rate	1.35
Predefined size	Extra Fine

Table 2.2 (a). Mesh size for extra fine

Description of mesh	Values
Maximum element size	12
Minimum element size	0.12
Curvature factor	0.2
Maximum element growth rate	1.3
Predefined size	Extremely fine

Table. 2.2 (b) Mesh size for extremely fine

3-D model viz. created, a physics-controlled mesh with extra finer and extremely finer element sizes are used [30-39]. Figure-2.4 depicts the meshing of a model with a single conical pit on the steel reinforcement bar's outer surface. Description of mesh for the model can be seen from table 2.2 (a) and table 2.2 (b). The model can be separated into non-overlapping components called as elements as a result of meshing. The answer of each component is represented by the unknown function & response of the entire mathematical model is deduced via making approximation & component's assembly element set. As a result, discretization of the domain is required for finite element [40-44]. Our model makes use of a tetrahedral mesh as it covers geometry completely.



Fig.2.4. Meshing of single conical pit in rebar model



Fig 2.5. Magnified image of meshing

2.2.4. The governing equations

We already know that COMSOL is based on FEA, we use meshing for discretization of the model. Then break down entire model in the elements which corresponds to a PDA (partial differential equation) then we solve these equations to find the solution. Based on simulations done with the COMSOL Multiphysics 5.6 program and model predicted the growth of pit successfully. [45-47].

For calculating electrode charge transfer, the 'secondary current distribution' is used it follows Ohm's law & Tafel, Butler–Volmer equation.

$$\nabla - \rho^{-1} (\nabla \emptyset) = Q$$

where ' ϕ ' is potential field, ' ρ ' is the resistivity, 'Q' is external current. Current density, i, in the following equation:

$$\mathbf{i} = -\rho^{-1} (\nabla \emptyset)$$

The ' η ' denotes activation overpotential in the following equation:

$$\eta = \emptyset - \text{Eeq}$$

where 'Eeq' is the equilibrium potential.

The cathodic & anodic Tafel equation is shown in the following equation :

$$i = -i0 \ 10^{h} /A$$

'A' is Tafel slope &'i0' denotes exchange current density

To make a pitting corrosion model in steel rebars, we have solved for current density & potential in the electrode selected and the region of electrolyte considering concerned species contributing concentrations and involves electrochemical reactions[47]. As in our developed model, the rebars made of 316 steel and plain carbon steel viz. a metal conductor and the model proposed will obey Ohm's law in the following equation (4).

$$il = -\sigma l \nabla \varphi l$$
 (4)

Further, the current conservation in the electrolyte

$$\nabla \cdot il = Ql(5)$$

Where φl is electric potential in V, *il* is current density vector in A/m² in the electrolyte, in the electrolyte σl is the electrolyte conductivity and *Ql* is general electrolyte current source in A/m³. Following equations are for the electrode:

$$\nabla \cdot is = Qs \ (6)$$
$$is = -\sigma s \nabla \varphi s \ (7)$$

Where φl = electric potential at electrolyte, φs = Electric potential at the electrode surface.

The electrochemical reactions rate is expressed by the relation of reaction rate to the activation over potential. For an electrode reaction the activation over potential is represented by noby following equation.

$$\eta o = \varphi s, ext - \varphi l - Eeq \ (8)$$

2.2.5 Boundary condition

Pit acts as anode and steel rebar acts as cathode in the 3-D pit model system created. The electrolyte is outside the steel rebar and is an equivalent electrolyte medium with a 1e-2 S/m electrical conductivity [49]. The boundary condition at secondary current distribution and primary current distribution interfaces is comparable to insulation condition, and it may be represented using equation 10.

$$i_l \cdot n = 0 \tag{10}$$

Where 'n' is the normal vector & ' $i_{l'}$ is electrolyte current density vector.

2.2.6. Computational input model parameter

We have used concrete as a medium in our case and its resistivity (ρ) value was measured through the experiments. The cathodic reaction is defined by the cathode equilibrium potential (Eeq,c), cathode exchange current density (i0,c) and the cathode Tafel slope (Ac). Likewise, the anodic reaction has been defined through the anode equilibrium potential (Eeq,a), anode exchange current density (i0,a), anode Tafel slope (Aa) and anode limiting current density (ilim,a) [48-50]. The values used in these models were abstracted from previous investigations

in which stainless steel and plain carbon steel were compared [50-51]. Materials used for modelling SS316L and plain carbon steel and their electrochemical parameters are shown in the following tables 2.3 (a) and 2.3(b).

Material for rebar	SS316L
βa	60 mv/dec
βc	-110 mV/dec
Eoa	780 mV
Eoc	-160 mV
ioa	1.80×10 ⁻⁴ A cm ⁻²
ioc	5.80 ×10 ⁻⁹ A cm ⁻²
iL	1.16×10 ⁻⁴ Acm ⁻²
Do ₂	1.00×10m ² s ⁻ 1
Co	0.3 mol.m ⁻ 3

Table 2.3 (a)The parameter for SS316L for the developed model is taken

Material for rebar	Plain Carbon Steel
βa	60 mv/dec
βc	-160 mV/dec
Eoa	780 mV
Eoc	-160 mV
ioa	1.80×10 ⁻⁴ A cm ⁻²
ioc	6.00 ×10 ⁻⁹ A cm ⁻²
iL	1.16×10 ⁻⁴ Acm ⁻²
Do ₂	1.00×10m ² s ⁻ 1
Co	0.3 mol.m ⁻ 3

Table 2.3 (b). The parameter for plain carbon steel for the developed model is taken

2.2.7. Result and discussion

Using the COMSOL Multiphysics we determine the effect of pitting corrosion in 316 stainless steel and plain carbon steel. Two key electrochemical parameters were investigated. Electrolyte potential was the first, and electrolyte current density was the second. The potential formed by the ions within the electrolyte on the rebar surface is known as electrolyte potential. Higher electrolyte potential values suggest that the metal has reduced corrosion resistance in any region. The current generated due to motion of ions inside the electrolyte is called electrolyte current density. The amount of ions transported over anodic (circular pit) surface determines electrolyte current density [42].

Stationary study

A stationary solver can be used in a stationary or steady-state environment. The Stationary study is used when field variables do not change over time. This study type is also utilized for optimization problems with a stationary PDE constraint. A Stationary study stage is added. A parametric continuation solver can also be created. The results of stationary study on SS316L and plain carbon steel simulation have been provided.

2.2.7.1 Electrolyte potential

Table 3.3 (a) & (b) contains information of the material input parameter values for the 3d model created. In the created 3D model of the rebar, Figures 3.6 illustrate electrolyte potential distribution at the contact of electrolyte. metal surface made up of SS 316L rebar. Figure 3.6 shows distribution of electrolyte potential at the conical pit interface and

electrolyte for a pit, respectively. The anode is the surface of the conical pit, while the cathode is the remaining inside surface of the rebar.

The electrolyte current density vector or put, the path of electron flow from pit i.e. anode through the electrolyte to the cathode, is illustrated in the distribution in the pictures as arrows emerging from pit surface. Laplace equation as mentioned in eq 1., governs the distribution of electrolyte potential for model created of rebar at the interface. The electrolyte potential distribution is -0.2V in all situations of the developed single pit model and at pits electrolyte potential is higher shown through a scale on the right-hand side having different colors shown in figure 2.6 .The electrolyte potential is -0.2 V in the red area, which corresponds to the pit section. When we move farther away from defective area, the value decreases, as indicated

by the blue color. Near the anode increased electrolyte potential implies that the concentration of electrolyte's ion is higher there, and our metal (316 L stainless steel) is more sensitive to pitting corrosion there [51]. The electrolyte potential magnitude is lower on the cathode side, i.e. the steel rebar's remaining interior surface. The lower the electrolyte potential, the more corrosion resistant the material (316L stainless steel). Figure 2.7 (enlarged view of single pit model) shows the defective region in the rebar due to pitting corrosion in the form of a 3-D conical pit, as well as the distribution of electrolyte potential at the interface of electrolyte and pit. The electrolyte potential (go to default view) in the developed rebar single pit model is represented in Figure 2.6, and the values of electrolyte potential are represented with the help of a vertical scale on the right-hand side using different colors, along with the current density vector. This view clearly shows the defective area, i.e. pit, as well as the electrolyte potential values.



Fig. 2.6 Distribution of electrolyte potential for SS316L in 3D pit model. (go to default view)



Fig. 2.7 Distribution of electrolyte potential for SS316L in 3D pit model. (XY view and YZ view)

Similarly the electrolyte potential distribution is -0.38V in all situations of the pit model created for plain carbon steel rebar, and the electrolyte potential has higher value at pit, as shown through a scale on the right-hand side having color coding shown in figure 2.8 for 3D pit model. The electrolyte potential is -0.38 V in the red area, which corresponds to the pit section. When we move farther away from defective area, the value decreases, as indicated by the blue color. The increased electrolyte potential near the pit i.e. anode implies that electrolyte's ion concentration is higher there, and our metal (plain carbon steel) is more sensitive to pitting corrosion there [52]. The electrolyte potential magnitude is lower on the cathode side, i.e. the steel rebar's remaining interior surface. The electrolyte potential for plain carbon is more so less corrosion resistant the material.



Fig 2.8 Electrolyte potential distribution for plain carbon steel in single pit 3D model. (go to default view)

2.2.7.2 Electrolyte current density

It is another important electrochemical parameter that is used for the calculation of CR with Faraday's law. Corrosion rate is directly proportional to electrolyte current density [45]. Figure 2.9 shows density distribution for electrolyte current. The electrolyte current density is known to play an important impact in corrosion rate study [52].

The higher the electrolyte current density at a certain site, the faster the material disintegrates in that section compared to other sections [39]. The anode is the pit, while the cathode is the rebar surface. At any conical pit and electrolyte interface , both cathodic processes and anodic processes occur

simultaneously, and the current density in the interface is a product of electron exchanges for both processes [50].

The distribution of electrolyte current of SS316L rebar model is demonstrated in figures 2.9. a pit. Electrolyte current density is addition of ion flu of ions present in electrolyte and it is considered as one of the most crucial electrochemical parameter used to calculate CR. [46-48].



Fig 2.9 Distribution of Electrolyte current (A/m^2) for SS316L in a pit model

We can see the distribution at the conical pit in the single pit model of SS316L rebar from figure 2.9, which is the enlarged view of the corroded portion, and observed that at the vertex of the pit and on the periphery of the pit, the value of electrolyte current density which can be seen in scale. The region is depicted here by red color and the value comes out to be 1.87×10^{-9} A/m² in the 3D pit model of rebar. However the minimum value of electrolyte current density comes out to be 2.86×10^{-13} A/m². The value decreases as we go away from the interface so the oxidation process is prominent in the region of pit, and the rate of anodic reaction in the pit is significantly faster than in the surrounding regions. The electrode potential w.r.t a standard reference electrode is shown in Figure 2.10. The electrode potential is 0.2 volts.



Fig 2.10 Electrode potential vs adjacent reference electrode for SS316L

Similarly we can see the distribution at the conical pit in the single pit model of plain carbon steel rebar from figure 2.11, which is the enlarged view of the corroded portion, and observed that at the vertex of the pit and on the periphery of the pit, the value of electrolyte current density which can be seen in scale.



Fig. 2.11 Electrolyte current distribution (A/m^2) for plain carbon steel in single pit model.

The region is depicted here by red color and the value comes out to be 1.64×10^{-6} A/m² for the case of 3D pit model of the rebar. However the minimum value of electrolyte current density comes out to be 2.5×10^{-10} A/m². The value decreases as we go away from the interface and the oxidation process is prominent in the region of pit, and the rate of anodic reaction in the pit is significantly faster than in the surrounding regions. The electrode potential w.r.t a standard reference electrode is shown in Figure 2.12. The electrode potential



Fig.2.12 Electrode potential vs adjacent reference electrode for plain carbon steel

Time dependent study

Three-dimensional modelling and simulations were carried out on SS316L and plain carbon steel rebars in a corroding environment, such as concrete. The Time Dependent study is used when field variables change over time.

2.2.7.3 Electrolyte potential

Figure 3.13 illustrates electrolyte potential distribution at the contact of the metal surface of SS316L rebar & the electrolyte. Anode is the surface of the conical pit, while the cathode is the remaining inside surface of the rebar. The electrolyte current density vector simply put the path of electron flow from anode i.e. pit from electrolyte to cathode, is illustrated in the distribution in the pictures as arrows emerging from pit surface. Equation, expresses the Laplace equation, governs the distribution of electrolyte potential in rebar model created at the interface.

The electrolyte potential distribution is -0.21V in all situations of the developed single pit model, and at pits the electrolyte potential is higher as shown in figure 2.13 through a scale on the right-hand side having different colour coding for a pit model. The electrolyte potential is -0.21 V in the red area, which corresponds to the pit section. When we go farther away

from defective area, the value decreases, as indicated by the blue colour. The increased electrolyte potential near the anode i.e. pit implies that the electrolyte's ion concentration is higher there, and our metal (316 L stainless steel) is more sensitive to pitting corrosion there [49]. The electrolyte potential magnitude is lower on the cathode side, i.e. the steel rebar's remaining interior surface. The lower the electrolyte potential, the more corrosion resistant the material (316L stainless steel). Figure 2.14 (enlarged view of single pit model) shows the defective region in the rebar due to pitting corrosion in the form of a 3-D conical pit, as well as the distribution of electrolyte potential at the interface electrolyte & pit. Electrolyte potential (go to default view) in the developed rebar single pit model is represented in Figure 2.13, and the values of electrolyte potential are represented with the help of a vertical scale on the right-hand side using different colors, along with the current density vector. This view clearly shows the defective area, i.e. pit, as well as the electrolyte potential values.



Fig. 2.13 Distribution of Electrolyte potential (V) for SS316L in a pit model for 24h



Fig.2.14 Distribution electrolyte potential for SS316L pit 3D model. (XY view and YZ view)

Similarly the electrolyte potential distribution is -0.48V in all situations for the pit model of plain carbon steel rebar, and at the pit higher is the electrolyte potential shown in figure 2.15 through a scale on the right-hand side having different color coding for a pit model. The electrolyte potential is -0.48 V in the red area, which corresponds to the pit section. As we move farther away from the defective area, the value decreases, as indicated by the blue colour. The increased electrolyte potential near the anode i.e. pit implies that electrolyte's ion concentration is higher there, and our metal (plain carbon steel) is more sensitive to pitting corrosion there [50]. The electrolyte potential magnitude is lower on the cathode side, i.e. the steel rebar's remaining interior surface. The electrolyte potential for plain carbon is more than SS316L so less corrosion resistant the material.



Fig.2.15 Electrolyte potential distribution for plain carbon steel in single pit 3D model for 24h

2.2.7.4 Electrolyte current density

It is another important electrochemical parameter that is used for the calculation of C.R. by using Faraday's law. Corrosion rate is directly proportional to electrolyte current density [35]. The is shown in figure 2.16 shows electrolyte current density distribution. Electrolyte current density is known to play an important impact in corrosion rate study [51].

The higher the electrolyte current density at a certain site, the faster the material disintegrates in that section compared to other sections [39]. The anode is the pit, while the cathode is the rebar surface. At any conical pit and electrolyte interface both the cathodic processes and anodic occur simultaneously, and product of the electronic exchanges in both processes is current density [52].

The distribution of electrolyte current in SS316L rebar model has been illustrated in figures 2.16. for single pit respectively. We know already that addition of all the flux of ions present in the electrolyte is electrolyte current density is which can be considered as a crucial electrochemical parameters to calculate CR [45-50].



Fig. 2.16 Electrolyte current distribution (A/m²) for SS316L in single pit model for 24h

We can see the distribution at the conical pit in the single pit model of SS316L rebar from figure 2.16, which is the enlarged view of the corroded portion, and observed that at the vertex of the pit and on the periphery of the pit, the value of electrolyte current density which can be seen in scale. The region is depicted here by red color and the value comes out to be 2.68×10^{-9} A/m² in the case of single 3D pit in the rebar. However the minimum value of electrolyte current density comes out to be 1.92×10^{-13} A/m². The value decreases as we go away from the interface so the oxidation process is prominent in pit region, and the rate of anodic reaction in the pit is significantly faster than in the surrounding regions. The electrode potential w.r.t to a standard reference electrode can be shown in Figure 2.17. The electrode potential is 0.21 volts.



Fig. 2.17 Electrode potential vs adjacent reference electrode for SS316L for 24h

Similarly we can see the distribution at the conical pit in the single pit model of plain carbon steel rebar from figure 2.18, which is the enlarged view of the corroded portion, and observed that at the vertex of the pit and on the periphery of the pit, the value of electrolyte current density which can be seen in scale.

The region is depicted here by red color and the value comes out to be 9.16×10^{-5} A/m² in the case of single 3D pit in the rebar. However the minimum value of electrolyte current density comes out to be 2.38×10^{-10} A/m². The value decreases as we go away from the interface so the oxidation process is prominent in pit region, and the rate of anodic reaction in the pit is significantly faster than in the surrounding regions. The electrode potential w.r.t a standard reference electrode is shown in Figure 2.19. The electrode potential is 0.48 volts.



Fig.2.18 Electrolyte current distribution (A/m²) for plain carbon steel in single pit model for 24h



Fig.2.19 Electrode potential vs adjacent reference electrode for plain carbon steel for 24h

2.2.7.5 Total electrode thickness change

Total change in electrode thickness for both the rebars materials was also calculated with the help of Comsol Multiphysics. Total change in electrode thickness for the time for example 24h, 48h, 72h, 96h,120h and 144h was observed for both SS316L and plain carbon steel rebars and it has been observed that as the time increases the change in total electrode thickness also increases linearly which can be seen following graphs 2.1 (a) & (b).



Fig.2.20 Total electrode thickness change (μm) for SS316L in 24h



Fig.2.21 Total electrode thickness change (μm) of an enlarged view of conical single pit model

Time taken	Total electrode thickness
	change
24h	-1.82× 10 ^{- 9} μm
48h	-3.65× 10 ^{- 9} μm
72h	-5.46× 10 ^{- 9} μm
96h	-7.30× 10 ⁻ 9 μm
120h	-9.12× 10 ⁻ ⁹ μm
144h	-1.08× 10 ^{- 8} μm

Table 2.4 (a) Total electrode thickness change (µm) with time taken for SS316L



Graph.2.1(a) Total electrode thickness change (μm) vs time (h) for SS316L

In SS316L the change in total electrode thickness for 24 hours comes out to be -1.82×10^{-9} µm. Similarly in plain carbon steel the total change in electrode thickness comes out to be -5.97×10^{-5} µm for 24h.



Fig. 2.22 Total electrode thickness change (μm) for plain carbon steel in 24h

Time taken	Total electrode thickness
	change
24h	-5.98× 10 ⁻⁵ μm
48h	-1.20× 10 ⁻⁴ μm
72h	-1.79× 10 ⁻⁴ μm
96h	-2.39× 10 ⁻⁴ μm
120h	-2.99× 10 ⁻⁴ μm
144h	-3.59× 10 ⁻⁴ μm

Table 2.4 (b) Total electrode thickness change (µm) with time taken for plain carbon steel



Graph.2.1(b) Total electrode thickness change (µm) vs time (h) for plain carbon steel

Chapter 3: SUMMARY

3.1 Conclusion

In conclusion a finite element 3 dimensional rebar models of SS316L and plain carbon steel has been designed successfully pitting corrosion behavior occurs in rebars embedded under concrete electrolyte having a conductivity of 1 e⁻² S/m. Also, we have validated the experimental work on pitting corrosion from the software COMSOL Multiphysics and have a good agreement. Pitting corrosion is observed and analyzed by some electrochemical parameters like electrolyte current density and electrolyte potential from COMSOL Multiphysics simulation for stationary study. Values of electrolyte potential obtained is showing negligible variation along surface of pit and highest value is i.e., -0.2 V on the interface of pit and electrolyte for SS316L and for plain carbon steel is -0.38V. More the electrolyte potential, suggests that the pit is more prone to the corrosion here plain carbon steel is more susceptible to corrosion as compared to SS316L rebar. Highest value of electrolyte current density is at the pit viz. 1.64×10^{-6} A/m² in the case of plain carbon steel and for SS316L is less 1.87×10^{-9} A/m² in a 3 D pit implies that the surface of pit was corroded heavily. For time dependent study the value for electrode potential in case of SS316L is less i.e. -0.21V and for plain carbon steel is -0.48V. At pit Electrolyte current density value is observed highest viz. 9.16×10^{-5} A/m² for plain carbon steel shows it is more susceptible to corrosion and for SS316L is 2.68×10^{-9} A/m². If we talk about total electrode thickness change then results shows that values for plain carbon steel are much on the higher side than that of SS316L for ex. For 144h in case of plain carbon steel the value is -3.59×10^{-4} µm while for SS316L it is -1.08×10^{-8} µm. Total electrode thickness change increases as the time passes. Hence plain carbon steel is more susceptible to corrosion than SS316L which is more corrosive resistant material for rebars.

3.2. Scope for future work

COMSOL, among the different computational methods, produces good results that are consistent with experimental findings. As a result, we anticipate that this modelling for rebars described in our paper will definitely be very useful in analyzing practical pitting corrosion problems, saving both money and time.

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