



# “Assessment of Corrosion and Retrofitting of Columns of Partially Completed Structures in Highway Projects”

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## ABSTRACT

Concrete is the second most common building material in the world, behind water. Concrete may be regarded as the greatest building material, yet it is susceptible to deterioration due to a variety of causes. A major problem in Civil Engineering is the corrosion of steel in reinforced concrete.

Many Highway Projects have been stalled due to various issues leading to termination of Contracts. This results in partially completed structures which leads to corrosion of reinforcement exposed to atmosphere. Concrete's strength, expansion, and mass can all be affected by corrosion. As a result of the several tactics developed to reduce or eliminate steel corrosion in concrete, corrosion inhibitors appear to be the most promising of all corrosion preventative measures.

Commercially available corrosion inhibitors are quite expensive and have an impact on the overall cost of the construction because they only guard against one kind of corrosion, either carbonation or chlorides. This necessitates the need for a less expensive substitute that can prevent corrosion caused by carbonation and the presence of chlorides. In this investigation, corrosion inhibitors such as Picolinic Acid, 4-Aminobenzoic acid, Salicylaldehyde, and 2-Aminopyridine with a 1% addition were examined and fitted.

**Keywords:** Concrete, Corrosion, Reinforcement, Civil, Highway, Inhibitors, Structures.

# CHAPTER 1

## INTRODUCTION

### 1.1 General

When compared to industrialised countries, the percentage of people living in cities and urban areas of India almost doubled to 27.78 percent in 2001. However, the 28.53Crore urban population in 27 metros, 396 cities, and 4738 towns is larger than the entire population of emerging and developed countries. Parliament formed the National Highways Authority of India (NHAI) in 1988 through the NHAI Act (NHAI).The NHAI Act, 1988 states that, “An Act to provide for the constitution of an Authority for the development, maintenance and management of national highways and for matter connected therewith or incidental thereto”. The National Roadways Creation Project comprises the building, maintenance, and administration of 50329 kilometres of national highways, among other duties.[1]

The National Highways Development Project (NHDP), India's largest ever highways project, will be completed in stages by the National Highways Authority of India (NHAI). The nation's arterial highway system, the 1,32,499 km of National Highways, connects every region of the country. Only 2% of the country's overall road network is designated as a national highway, yet that 2% carries 40% of the nation's total traffic. Increases in passenger and freight traffic necessitate fast upgrading of the country's road system. As a result, the Indian government launched large projects to upgrade and enhance national highways through several phases of the National Highways Development Project (NHDP) and Bharatmala Pariyojana. Many Highway Projects have been stalled due to various issues leading to termination of Contracts. This results in partially completed structures which leads to corrosion of reinforcement exposed to atmosphere. Examples of partially constructed structures of the NH-6 Fagne-Maharashtra/Gujrat border section four-laning project, shown in Fig. 1.1, show reinforcing bars being exposed to the environment.





Figure 1.1: Partially completed column structure of NH-6

Construction materials such as reinforced concrete, which has been proven to be long-lasting and durable, are commonly used.

Over the last few decades, structural engineers, infrastructure owners, and customers have become increasingly concerned about the long-term performance and durability of concrete structures. At a minimum, reinforced concrete constructions should survive 75 years or more. However, issues may arise in as little as a few years due to a durability issue rather than a structural one. Many mechanisms, acting singly or in concert, can cause concrete structures to degrade. Processes such as alkali aggregate reactivity and corrosion of reinforcement inside the concrete can lead to material degradation.

## 1.2 Corrosion

Corrosion is a serious and costly issue in material science. In the context of corrosion, metals are considered to be damaged when they are subjected to chemical, electrochemical and biological processes. Consequently, it's the exact opposite of mining for metals from ores. "Generally, metals are not stable and tend to return to more stable compounds, a process known as corrosion, in the vast majority of settings. When corrosion occurs, a material's intrinsic qualities are negatively affected by its interactions with its environment. Metals are oxidised when they come into contact with water or oxygen, resulting in the formation of oxides. Latin "Corrosus" means "gnawed at," and the term "corrosion" is derived from this Latin word.

In the field of materials science, corrosion is a major problem. In the context of corrosion, metals are considered to be damaged when they are subjected to chemical, electrochemical and biological reactions. Hence, it's a far cry from the extraction of metals from their ores. Generally, metals are not stable and tend to return to more stable compounds, a process known as corrosion, in the vast majority of settings. In addition to the degradation of intrinsic qualities, corrosion may also be described as the deterioration of a material's reactivity to its environment. Metals are oxidised by water or oxygen when they come into contact with them.

A concrete structure's service life and maintenance budget are severely impacted by corrosion of reinforcing bar (rebar) embedded in the concrete, one of the most significant phenomena. Concrete reinforcement is eroded by electrochemical processes.. There is virtually no room in concrete for corrosion products that have a volume bigger than the parent metal (about 5-7 times), so they collect between the rebar and concrete, resulting in cracking and spalling of the concrete cover. Structural issues may arise if the reduction of rebar cross section is significant.

### **1.3 Classification of Corrosion**

Corrosion does not have a standard classification, although the following classification is used:

#### **1.3.1 Uniform or general corrosion**

The term “widespread corrosion” refers to the uniform penetration (or thinning) of the exposed metal surface as a result of widespread corrosion. Anodes and cathodes on the metal surface concurrently cause the general attack, which is caused by local corrosion cell action. This uniform corrosion of the material is caused by the movement of the anodic and cathodic regions on the surface. Corrosion occurs in an environment that is either liquid, gaseous, or hybrid, depending on the type of metal/alloy that is being exposed to the environment (solid, water, biological organisms, etc.). Fig. 1.2 depicts a rusted steel storage tank with an evenly corroded exterior.



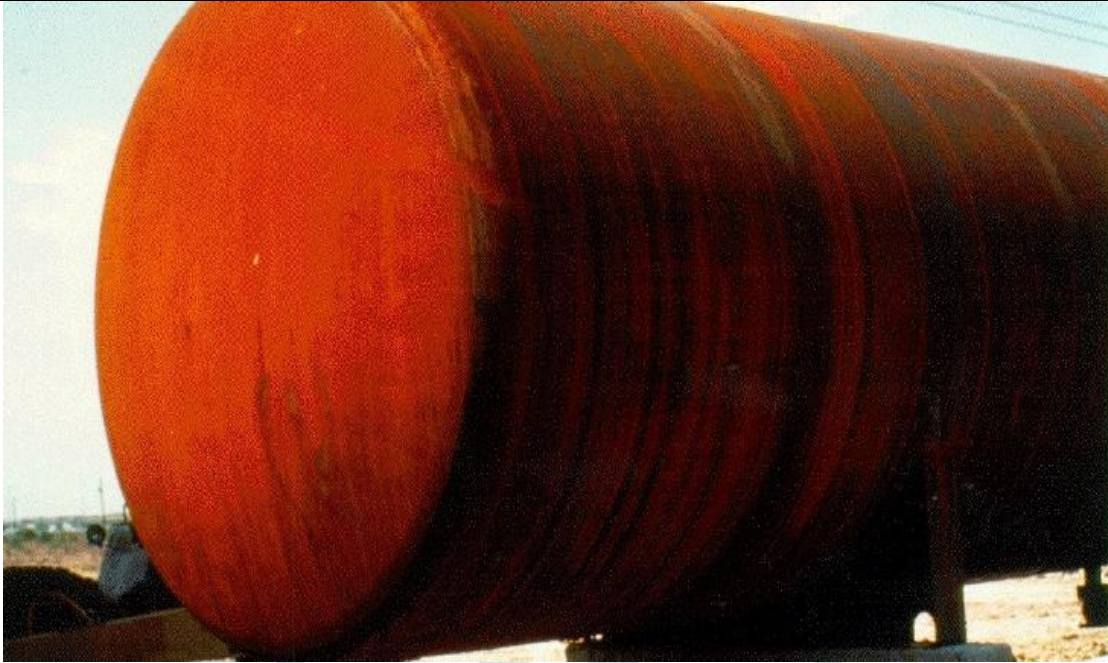


Figure 1.2: Uniform corrosion on a storage tank

### 1.3.2 Galvanic corrosion

In the presence of an electrolyte and an electron conductive channel, galvanic corrosion is the end result of an electrochemical reaction between two dissimilar metals. When corrosion occurs due to galvanic action, the metal at the anode of the cell is more negatively charged (active) and thus corrodes at a faster rate. If the cathode is a more positive (noble) metal, then corrosion will occur less frequently, as evidenced by the presence of corrosion at the intersection of the two metals. Galvanic corrosion can develop and speed up the corrosion of aluminium or magnesium alloys when they come into contact with steel. Fig. 1.3 depicts galvanic corrosion in operation.



Figure 1.3: Galvanic corrosion

### 1.3.3 Localized corrosion

Electrolyte corrosion refers to the deterioration of a specific portion of an object's exposed surface. More difficult to manage than normal corrosion is this type of corrosion. The following are the types of localised corrosion:

#### 1.3.3.1 Crevice corrosion

After the onset of pitting corrosion in a stationary electrolyte, it is quite similar to this. There are a number of factors that contribute to this corrosion, including changes in local chemistry, such as a decrease in oxygen, an increase in pH, and an increase in hydrogen ion concentration. It is because of the oxygen shortage that metal dissolution occurs as a result of cathodic reaction for oxygen reduction in the crevice area. Crevice corrosion can occur on any metal in a corrosive environment. Aluminium and stainless steel metals, which rely on their oxide coating for corrosion protection, are particularly vulnerable to crevice corrosion, especially in seawater with chloride ions. Corrosion in crevices does not have to be caused by metal. Crevice corrosion may be caused by a wide range of materials, according to reports. Chloride surroundings tend to have a higher concentration of it. Crevice corrosion is caused by an electrochemical process. Metal oxidation is a process that takes time to begin, although it can be accelerated later on. An example of crevice corrosion is shown in Fig. 1.4.



Figure 1.4: Crevice corrosion on a stainless steel flange



### 1.3.3.2 Filiform corrosion

Corrosion that occurs “under film” is a particular type of crevice corrosion. corrosion occurs under painted or plated surfaces when moisture penetrates through cover to substrate. Lacquers and “quick-dry” paints are the most susceptible to this problem. Until field testing shows that these substances have no negative effects, they will not be used. Filiform corrosion is seen in Fig. 1.5.

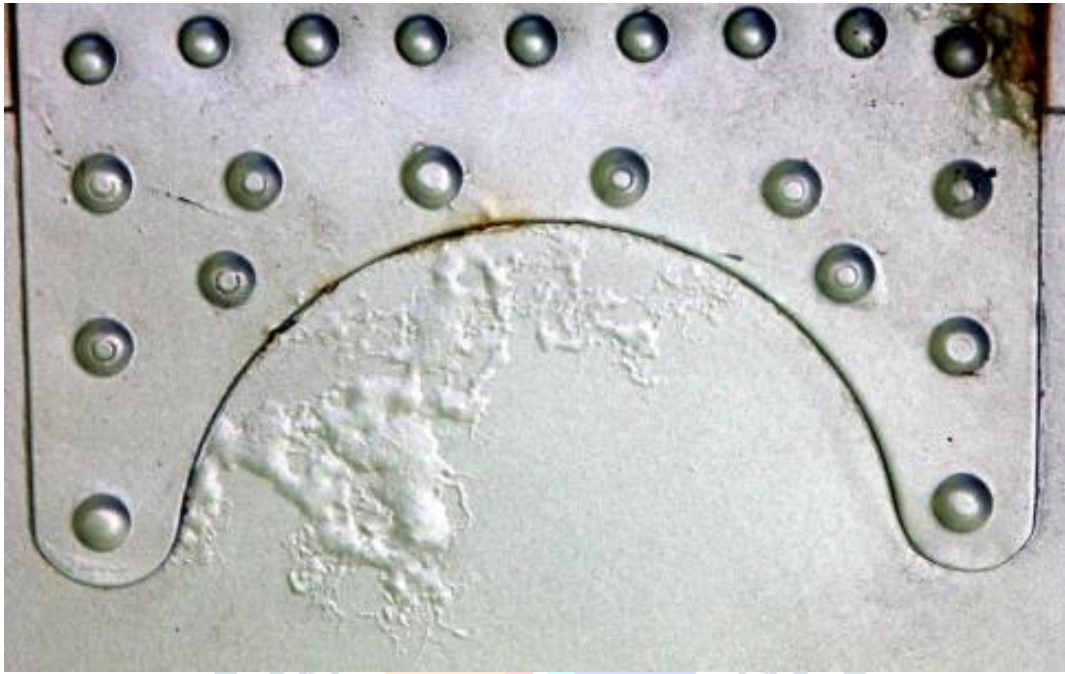


Figure 1.5: Filiform corrosion spreading beneath painted surface

### 1.3.3.3 Pitting corrosion

Pitting corrosion occurs when cells become blocked. A “chimney” may be founded by corrosion products that cover pits. Detecting, anticipating, and trying to prevent pitting corrosion damage is considered a more serious threat than uniform corrosion damage. The breakdown of a comprehensive engineering system can be accompanied by a small, shallow pit with minor metal loss. In both crevice and pitting corrosion, differential concentration cells may be used to explain cathodic processes, such as the reduction of oxygen or the evolution of hydrogen. Large portions of the surface will become cathodic, whereas pits and fissures will become anodic and corrode. Corrosion that occurs uniformly throughout a metal surface will be significantly slower because metal disintegration will be focused in small areas. To avoid corrosion, large fissures are less likely to be corroded by water flow because it mixes and replenishes oxygen and other elements that are depleted in large crack systems. Figure 1.6 depicts a case of pitting corrosion in activity.



Figure 1.6: Pitting corrosion on sink surface

#### 1.3.3.4 Intergranular corrosion

Corrosion that occurs only in a small area is known as intergranular corrosion. Assault mode is preferred when aiming for grain boundary phases or zones close to them.. The major body is not subjected to much assault. This leads in a decrease in the material's strength and ductility. Often, the assault is swift, piercing the metal and resulting in failure. An illustration of intergranular corrosion is shown in Figure 1.7.

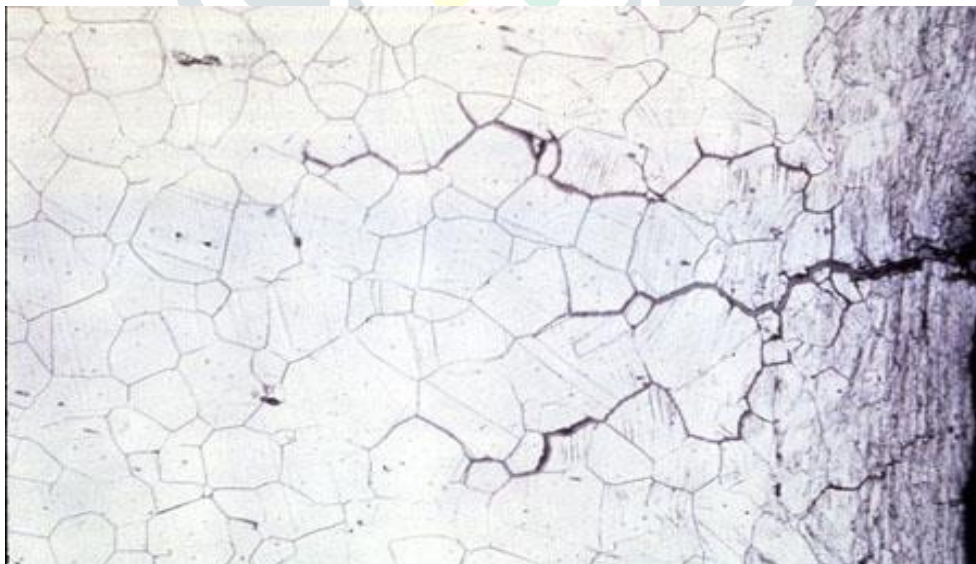


Figure 1.7: Intergranular corrosion of stainless steel



### 1.3.4 Microbiologically Influenced Corrosion (MIC)

Corrosion caused by microorganisms (bacteria, fungus, etc.) and/or their metabolites is known as MIC. This extremely corrosive kind is produced by aerobic bacteria as part of their metabolic process. This method can destroy metals, polymers, glass, and ceramics. Minerals, organic acids, ammonia, sulphide, and a wide range of microorganisms are all examples of corrosive species which work in concert to attack metals, with the interactions between them often being incredibly complicated. Fig. 1.8 depicts a MIC corrosion case.



Figure 1.8: MIC corrosion inside a fire sprinkler systems

### 1.3.5 Erosion corrosion

Mechanical degradation is known termed as “erosion” in this context. The term “erosion corrosion” refers to a metal's corrosion being accelerated by circumstances that contribute to erosion. High fluid surface velocities combined with an aggressive chemical environment cause this phenomena. Some examples of this are an oilfield check valve's fluid flow past a stationary item, or a ship's propeller churning a stationary body of water with its swift movements. Erosion-corroded surfaces, in contrast to the corroded surfaces caused by many other types of corrosion, are generally rather clean. There are pinholes in the pipe wall shown by the red arrow in Fig. 1.9. Notice how thin the crushed pipe wall is compared to the rest of the pipe (blue arrow). A portion of the failed pipe is seen in this image, with the inside surfaces clearly visible. An abnormally thin wall section where pinhole leaks had occurred is shown by a red arrow in Figure, whereas the blue arrow indicates to the usual wall thickness. The erosion-corrosion phenomena causes the copper pipe wall to become thinner in new installations. The passive corrosion protective coating has been lost in some sections due to turbulence and high water velocity, resulting in increased corrosion of the pipe wall, thinning of the pipe wall, and eventually water leakage.

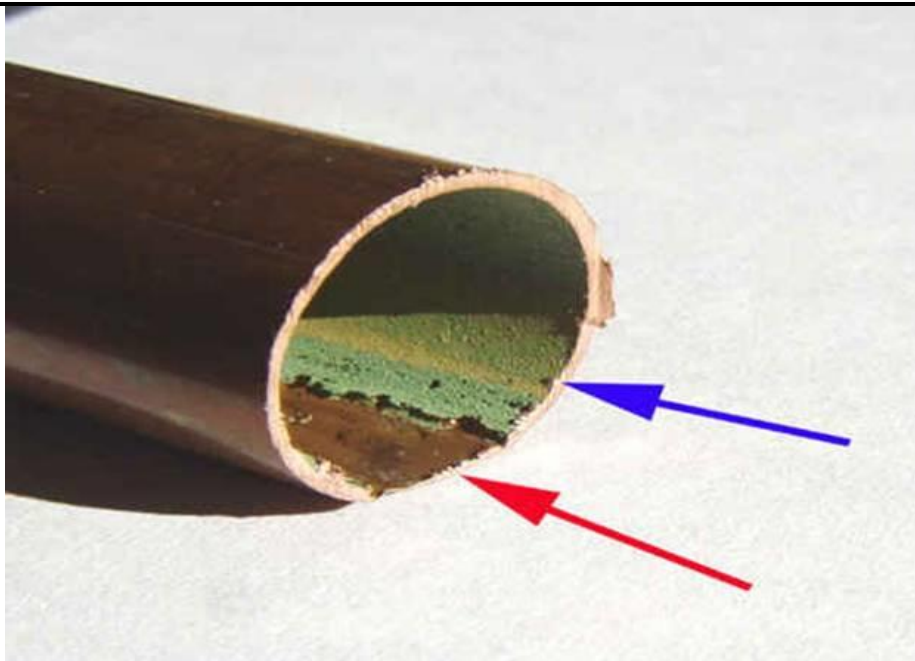


Figure 1.9: Erosion corrosion inside a pipe

## 1.4 Corrosion Inhibitors

Chemical inhibitors can be used in a variety of ways to slow down corrosion processes. When it comes to fighting corrosion, oil extraction and processing companies have always relied on inhibitors as their first line of defence. Corrosion inhibitors have been the subject of several scientific studies. Most of what we know now was developed via a series of failed trials in the lab and on the ground. Adding corrosion inhibitors to a solution at low concentrations slows it down corrosion by a significant margin. As a result of these constraints, it is extremely difficult to develop or use inhibitors within the defined guidelines of equations and theories. This improvement can be used as a gauge of an inhibitor's competency:

$$\text{Inhibitor efficiency (\%)} = 100 \frac{[\text{CR}(\text{uninhibited}) - \text{CR}(\text{inhibited})]}{\text{CR}(\text{uninhibited})}$$

where CR(uninhibited)=corrosion rate of the uninhibited system,  
CR(inhibited)=corrosion rate of the inhibited system.

## 1.5 Classification of Inhibitors

Corrosion inhibitors are classified based on the physical technique of protection and the mechanism of protection they utilize.:

### 1.5.1 Admixed inhibitors

Inhibitors that are mixed into fresh concrete during the mixing process for new constructions are known as admixed inhibitors. Immediately following the addition of water, these chemicals are incorporated into the cement mixture. Cement's hydration processes can be affected by the use of admixed inhibitor. Retarder was

added to the concrete mix in order to counteract the acceleration of inhibitors and to provide a little additional retardation to the process. As admixed inhibitors, calcium nitrite, sodium nitrite, sodium benzoate, and sodium chromate-based inorganic compounds are utilised. There have also been organic molecules proposed as mixed inhibitors that use combinations of alkanol- and amine-containing compounds or amino- and carboxylic acid-based esters of aliphatic carboxylic acids and saturated fatty acids as emulsification.

### 1.5.2 Migrating inhibitors

When these chemicals are applied to the hardened concrete surface, anodic and cathodic corrosion processes are inhibited at the steel-concrete interface. They can then diffuse through the concrete to the underlying reinforcing rods. Surface applied corrosion inhibitors and penetrating corrosion inhibitors are two other names for these inhibitors, both of which refer to their physical form of application. In the last 15 to 20 years, the use of corrosion inhibitors that migrate has enhanced. Inorganic compounds based on Monofluorophosphate or combinations of alkanolamines and amines often serve as the basis for these inhibitors.

Concrete can also be penetrated by aqueous solutions if they are sprayed or paddled onto the surface. Under ambient circumstances, the vapour pressure of alkanolamines and amines is rather high, facilitating the diffusion and migration of these chemicals into concrete. Adsorption on the steel surface allows amino alcohols like ethanolamide and dimethylethanolamide, which operate at the cathode and block oxygen reduction to the hydroxyl ionic species, to function.

### 1.5.3 Anodic Inhibitors

Anodic inhibitors cause a significant anodic shift in the corrosion potential by forming a protective oxide film on the metal's surface. As a result, the passivation area shifts the metallic surface. From time to time, they are referred to as passivators. Anodic inhibitors include substances such as chromates, nitrates, and tungstate.

### 1.5.4 Cathodic Inhibitors

Cathodic inhibitors either slow down the cathodic process or precipitate preferentially on cathodic sites, preventing reducing species from diffusing to the surface. It is also possible to use cathodic toxins to slow down cathodic reactions. Hydrogen may also be absorbed by metals by cathodic charging or aqueous corrosion. This raises the metal's sensitivity to hydrogen-induced cracking. Oxygen scavengers, which react with dissolved oxygen, can also be used to lower corrosion rates to a certain degree. Examples of scavengers for oxygen are sulfite and bisulfite ions, both of which react with oxygen to generate sulphate.



### 1.5.5 Mixed Inhibitors

The cathodic and anodic responses of mixed inhibitors are both reduced by their use. Indirectly, precipitates block anodic and cathodic sites on the surface by virtue of their role as film-forming compounds. Metal surfaces are protected from corrosion by calcium and magnesium salts found in hard water. Metals can be protected from corrosion by this film. Silicates and phosphates are two of the most common perpetrators. Softeners that use sodium silicate to prevent the formation of corrosive water are available for use in the home. Aerated hot water systems use sodium silicate to keep steel, copper, and brass safe. Protection, on the other hand, isn't always reliable and is strongly reliant on pH. Oxygen is also required for the effective suppression of phosphates. In contrast to chromates and nitrites which offer superior protection, silicates and phosphates are beneficial in applications requiring non-toxic additives despite their lack of protection.

### 1.5.6 Volatile inhibitors

Vapour phase inhibitors (VPIs) are also known as volatile corrosion inhibitors (VCIs). Volatilization from a source moves the compounds to the area of corrosion in a sealed environment. By neutralising carbon dioxide's acidity or changing the surface's pH toward a less acidic range, the volatile basic compound morpholin prevents corrosion in boiler condenser tubes. As soon as the corrosion product is formed, it is vaporised, leaving the metal surface vulnerable to further assault. Corrosion occurs quickly respond as a result, and eventually there is too much corrosion. When molybdenum is exposed to oxygen and oxygen-containing atmospheres, the oxidation corrosion product molybdenum oxide becomes volatile. In closed-vapor processes, volatile corrosion inhibitors such as salts of dicyclohexylamine and cyclohexylamine are used (shipping containers).

## 1.6 Objectives of the study

The objectives of the work are as follows:

- To understand the corrosion behaviour in partially completed structures of highway project,
- To study different standard methods of retrofitting of columns using corrosion inhibitors,
- To identify the most effective corrosion inhibitor for use in partially finished structures to increase corrosion resistance.

## 1.7 Outline of the Report

The report consists of the following six chapters:

**Chapter 1:** Under the title *'Introduction'*, the chapter deals with the brief introduction of topic, brief details on corrosion, objectives and outline of the report. It illustrates the brief description of corrosion inhibitors.

**Chapter 2:** Under the title '*Literature Review*', the brief details in respect of previous studies conducted by the different researchers has been mentioned.

**Chapter 3:** Under the title '*Study Area Details*', it emphasizes the details of the study area and project road. The brief of project road has been mentioned with various maps.

**Chapter 4:** Under the title '*Methodology*', an attempt has been made to elaborate the methods and technologies used to study corrosion behaviour of the partially completed structures. The thorough details in respect of methodology have been mentioned.

**Chapter 5:** '*Results and Discussions*', is the section where the results of the tests are reviewed.

**Chapter 6:** This chapter titled '*Conclusions and Future Scope*', presents the most significant findings of the study.



## CHAPTER 2

### LITERATURE REVIEW

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#### 2.1 General

Even after 20 years of research, the corrosion of steel in concrete is still a major issue. Numerous investigations are needed to better understand and avoid this form of corrosion due to the large number of variables. This chapter includes the details of studies and data collected by different Researchers on experimentations conducted for the study of Corrosion resistance.

#### 2.2 Reviews of Researchers on Corrosion Resistance

Jang et al. corroded rebar samples in concrete saturated solutions containing corrosion-inhibitor-added de-icing salts and salt replacements, as well as ordinary sodium chloride solutions (1995). Galvanic cells were used to examine the impact of corrosion-inhibitor-added salt de-icers on rebar corrosion. The galvanised reinforcing steel samples were collected after 240 days. The depth and area percent of corrosion on the reinforcing steels were measured using an optical microscope. The addition of de-icing salts and salt substitutes to the corrosion inhibitor was shown to be helpful in reducing rebar corrosion. The pH values of concrete-saturated solutions with corrosion-inhibitor added de-icing salts and salt substitutes varied dramatically. Precipitates are created by chemical interactions between a concrete-soaked solution and corrosion-inhibitor-added de-icing salts and salt alternatives, according to research. Furthermore, there seems to be an ideal concentration of corrosion inhibitor for efficient rebar corrosion reduction, and it has been found that rebar corrosion induced by these salts and replacements accounts for less than half of overall rebar corrosion.

In an alkaline chloride solution containing 0.1 M chloride ions, Monticelli et al. (2000) studied the anticorrosive characteristics of many organic and inorganic substances. Only 0.005 M 5-hexylbenzotriazole, 0.05 M sodium  $\beta$ -glycerophosphate, and saturated dicyclohexylammonium nitrite (DCHAMN) were able to resist pitting corrosion after 30-day exposures to the severe electrolyte.

Malik et al. (2004) studied the performance of several surface-applied corrosion inhibitors, including dimethyl ethanolamine-based, tri-ethanolamine-based, and vapour-based inhibitors. An electrochemical test and a physical inspection of the rebar were both used to determine the health of the exposed specimens. Open circuit potential and polarisation data were used in the electrochemical experiments. Studies on MCI's effectiveness in preserving concrete rebar have been reviewed and discussed.



M. Moreno et al. (2004). studied the critical chloride concentration of reinforcing steel received in the form of as-received reinforcing steel submerged in solutions imitating pore liquid of alkaline and carbonated concrete. Potentiodynamic polarisation curves were used to study the electrochemical mechanisms that effect rebar corrosion in concrete. Polarization resistance measurements were used to track the pace of steel deterioration over time. Various combinations of bicarbonate and carbonate concentrations in the simulated pore fluid were also investigated.

Carbonation-induced corrosion was examined in solutions imitating the pore chemistry of carbonated concrete by Trabanelli et al. (2005) using benzoic acid and its derivatives. As a corrosion inhibitor for concrete reinforcements, sodium monofluorophosphate (MFP) has been investigated as a possible penetration into concrete materials. Conventional Portland cement and a water-cement ratio of 0.5 were used to make the cylindrical mortar specimens with a diameter of 35 mm and a length of 40 mm. To minimise moisture loss, all specimens were first stored for a year at 20°C in an adhesive aluminium sheet. Carbonated and non-carbonated hardened cement pastes were analysed for monofluorophosphate penetration patterns. In this experiment, the MFP aqueous solution was applied to the exterior of cement paste specimens for 7 and 28 days. Cement paste specimens (3cm in diameter, 6cm height) were coated with either a carbonated or non-carbonated 5-mL amount of an aqueous MFP solution (20 percent by mass).

Heiyantuduwa et al. (2006) investigated the use of DMEA-based organic inhibitors to protect steel from corrosion. Corrosion potential, corrosion rate, and mass loss are only a few of the metrics used to assess the durability of cement mortar specimens. A saturated calomel reference electrode was used to record corrosion potentials for each test specimen at regular intervals (SCE). In the start, the measurements were taken every day until equilibrium conditions were reached, and then weekly after that point. Fibre optic microscopy was also used to capture images. A rise in the chloride content causes the corrosion potentials of cement mortar specimens to go from positive to negative. Corrosion potentials, on the other hand, change toward higher positive values when corrosion inhibitor is introduced. The mass loss of steel rebar is reduced by approximately 43 percent when DMEA inhibitor is added to the cement. Chloride concentration has a direct effect on the corrosion of steel reinforcement. However, when the concentration of the corrosion inhibitor increases, the corrosion rate of the rebars decreases.

Rebar corrosion was studied by researchers Saraswathy and colleagues (2007), who looked at the effectiveness of anodic and cathodic corrosion inhibitors (sodium nitrite and zinc oxide), as well as the combination of anodic and cathodic corrosion inhibitors. The kind and concentration of inhibitors used in the compression, tensile, chloride diffusion, and macro cell corrosion tests were varied. Additionally, the addition of inhibitors to concrete increased the concrete's compressive strength and corrosion resistance.

Jitu K et al. (2011) studied the effectiveness of corrosion inhibitors in acidified calcium hydroxide solutions. By using Anodic Polarization curve and Impedance test, it was found that sodium nitrite and sodium

molybdate were effective corrosion inhibitors in an acidic environment. The higher the concentration of both substances, the greater the inhibitory effect. At concentrations as low as 0.013 percent of the total solution mass, sodium molybdate was found to be more effective than sodium nitrite; however, at concentrations as high as 0.040 percent of the total solution mass, their inhibitory effects were found to be similar.

Monticelli et al. (2011) investigated two corrosion inhibitors, sodium 2-amino-benzoate and sodium glycerophosphate, in a synthetic solution mimicking the composition of the pore solution in a carbonated concrete containing chlorides. In order to see if the two compounds may be used together safely and if their combination can effectively limit corrosion attack in the presence of both chlorides and carbonation, tests have been done. In this experiment, he found that increasing the immersion time from 45 minutes to 72 hours had no significant effect on steel corrosion behaviour in carbonated chloride-containing solutions (from this point on, the blank solution). Corrosion products on the metal surface may not be shielding the metal from corrosion, as this shows.

According to Kulwinder et al. (2016), a great deal of study has previously been done on the use of corrosion inhibitors to prevent chloride-induced corrosion. Although research into the role of inhibitors in the prevention of rebar corrosion by carbonation was still in its early phases, the findings were encouraging. Previous study focused on the incorporation of inhibitors into concrete during the casting process. It was important to determine whether or not inhibitors put to concrete's surface would be effective. Commercially available amine group-based inhibitors (which are currently in use to prevent chloride-induced corrosion) and generic compounds containing the amine group were used to explore concrete carbonation-induced corrosion.

HilkeVerbruggen et al. (2016) investigated a number of inhibitors for the two types of corrosion that may occur in reinforced concrete: pitting corrosion (caused by chloride attack) and uniform corrosion (by a drop in pH). Anodic and cathodic inhibitors, which delay oxidation and lower the reduction process, are distinguished from mixed inhibitors, which influence both half-reactions. Corrosive conditions and metal surfaces, therefore, have a significant impact on the inhibitor's capacity to effectively prevent corrosion. Inhibitors were Cerium nitrate hexahydrate ( $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ ),  $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$ , 2,5-Dimercapto-1,3,4-thiadiazole (DT), 2-Mercaptobenzothiazole (MBT) with a purity of 97.0 percent, and 1H-benzotriazole (BTA) with a purity of 98.0 percent. The authors of this research indicated that an inhibitor should be utilised in three situations that may occur during the reinforced concrete production process.

According to Ibrahim et al. (2017), corrosion of reinforcing steel bars in concrete structures is a serious concern, particularly in oil and gas and maritime settings due to concrete's high corrosiveness. This challenge is particularly prevalent in oil and gas environments. In order to combat corrosion, a variety of techniques are applied, such as protective coatings, cathodic protection, and sealants. However, corrosion inhibitors are becoming increasingly popular among researchers owing to their affordability and convenience of usage.

Because MCIs may penetrate the pores of concrete, forming a monomolecular layer between the steel bar and the concrete, they are efficient in preventing corrosion of steel bars and thereby increasing concrete structures' service life by delaying corrosion initiation. The performances of selected migratory corrosion inhibitors either as admixture or apply on the surface of concrete has been studied and the evaluation of its effectiveness in the corrosion reduction of the steel bars is presented.

According to Zhijie Yuan et al., corroded bridge piers are often exposed to dynamic pressures, such as vertical pounding caused by earthquakes or railway trains (2017). Repeated axial stresses were used to imitate this vertical hammering action. Under axial and horizontal cyclic stresses, corrosion of reinforced concrete (RC) buildings poses a significant seismic risk. Experiments on eight RC column specimens were carried out in order to see how corrosion and repeated stress affected the seismic performance of a column post. According to the results, corrosion has a significant impact on the column's yield strength and load-bearing capacity. When longitudinal steel mass was lost by 7.16 percent in corrosion specimens compared to noncorroded specimens, load bearing capability reduced by 18.27 percent. Repeated axial loads had no significant effect on the mechanical properties of the deteriorated RC piers. By conducting cyclic testing, a finite-element model was utilised to assess the impact of corrosion level on the seismic performance of columns. Corrosion affected anything between 0% to 28% of the steel. According to the finite-element study, when corrosion increased, the yield strength (35%) and ultimate displacement (34%) decreased.

Shiping Yin et al. (2019) reviewed the investigation to find out how well textile-reinforced concrete (TRC), which is a restricted concrete, and a corroded steel bar adhere around each other. Based on the findings of electrochemical corrosion and pullout tests, the bond characteristics between concrete and a steel bar in unconfined and confined conditions were evaluated in terms of corrosion-induced cracking, failure mode, bond-slip curve, bond strength, and bond failure mechanism. Using data from the literature, the confinement effects of TRC and fiber-reinforced polymer (FRP) on the ultimate bond strength between an unconfined concrete block and a corroded steel bar were investigated. According to the findings, TRC confinement may effectively increase the binding characteristics between concrete and a corroded steel bar while also reducing the development of corrosion-induced fractures. In addition, as the steel bar was being pulled out of the hole, TRC was able to prevent any further crack expansion. After confinement with TRC, the failure mechanism was changed from splitting to splitting pullout to improve the brittle failure characteristic of the connection between concrete and corroded steel bar. TRC's confinement effect is equivalent to FRP's with a lower fiber-reinforcement ratio.



## CHAPTER 3

### STUDY AREA DETAILS

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#### 3.1 General

The main objective for road development is improvement in the economic conditions and social welfare of road users and nearby habitation area. Travel time and costs of vehicle use gets reduced due to increased road capacity and improved pavements. Road construction can also provide other benefits, such as enhanced access to markets, employment opportunities, education and health services, and reduced vehicle traffic.

If proper precautions are really not followed throughout the project's design and implementation, it's possible that improvements to the road will have severe detrimental effects on the nearby towns. A large number of persons and properties may be adversely affected by road construction when it occurs in such a close proximity to them. Disruption to livelihood, loss of accustomed travel routes and community links, increase in noise and pollution may also have an impact on people indirectly. People are drawn to roads, which in turn attract businesses. Roads act as catalysts for change, which can benefit or harm the delicate equilibrium that exists between humans and their natural landscape. Due to India's rapid economic growth, the number of traffic on Indian roadways, particularly highways, has multiplied many times over, making the present infrastructure unable to handle the growing demand. Government of India's Ministry of Road Transport and Highways has entrusted the National Highway Corridors with increasing their capacity to ensure the safe and efficient passage of traffic in order to meet this challenge. Some of the current two-lane roadways will be converted into four-lane highways by the government. The project would envisage widening of existing 2 lane highways into four lanes with additional features such as provision of underpass, service roads, flyovers, Railway over bridge (ROB) and bridges, etc. so as to enhance operational efficiency and safety.

The specifics of the project road and the condition of the construction have been examined in this study in an effort to determine how these factors may impact the structural strength and progress.

#### 3.2 Description of the Study Area

Maharashtra's Khandesh region includes the districts of Dhule and Nandurbar, as seen in fig. 3.1.

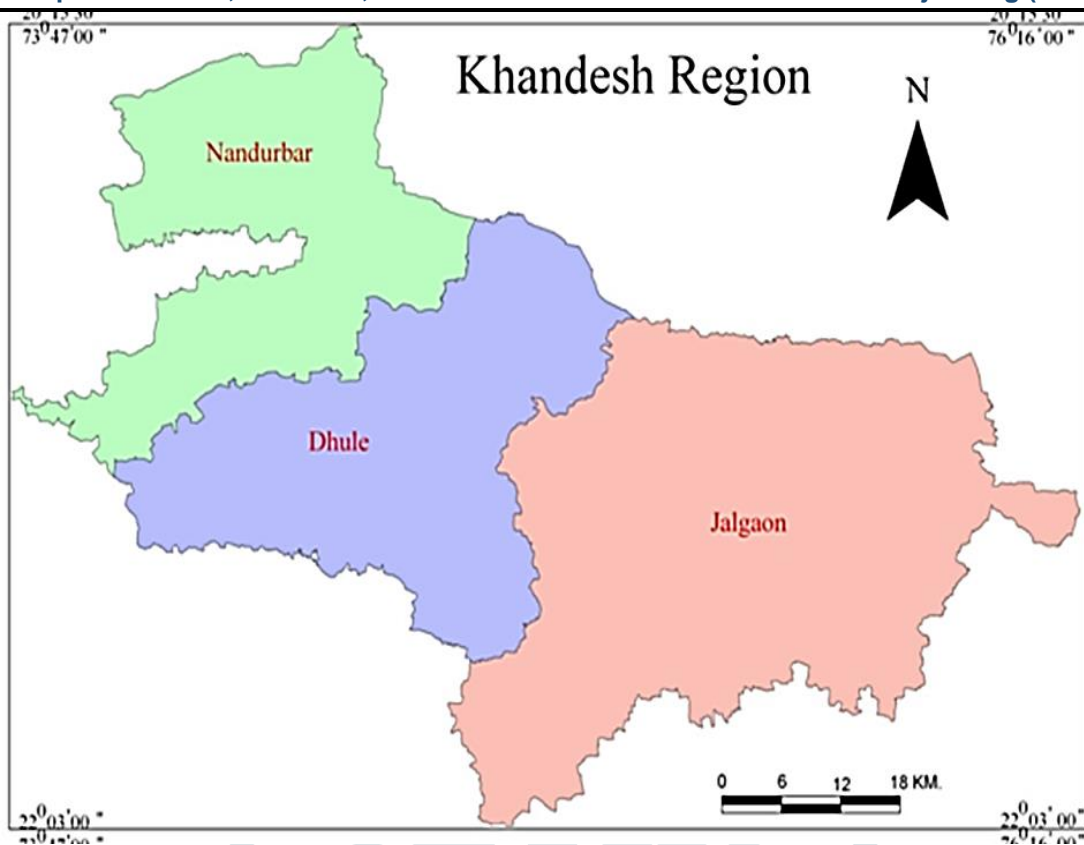


Figure 3.1:Khandesh region

Khandesh region covers an area of three district of North Maharashtra i.e. Nandurbar, Dhule and Jalgaon. The national highway No.6 (NH-6) passes from these three districts. The extension of the Khandesh region is between latitudes  $20^{\circ}00'00''\text{N}$  to  $22^{\circ}00'30''\text{N}$  latitude and longitudes  $73^{\circ}31'00''\text{E}$  to  $76^{\circ}28'00''\text{E}$ .

Jalgaon district is the northernmost part of the State of Maharashtra. It covers an area of  $11765\text{ km}^2$ . There are total 15 tehsils in the district. The average density of population of Jalgaon district is  $313\text{ persons/km}^2$ . Jalgaon district was formerly known as East Khandesh district. It is located in Maharashtra's north-west area. There are around 4 million people living in the district. Many religious and cultural institutions may be found here. Satpuda and Ajanta mountain ranges divide it from the rest of India.

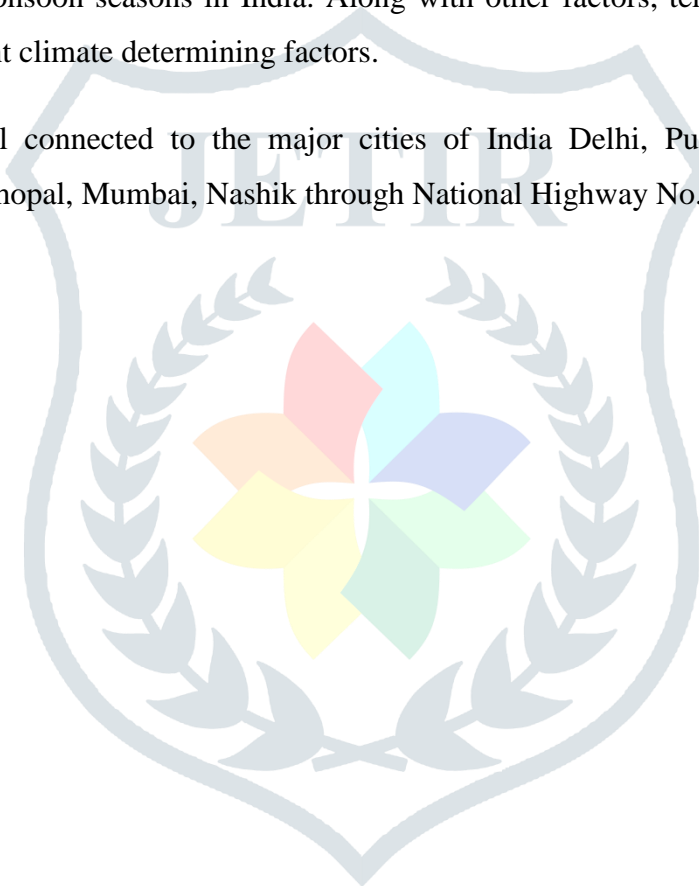
The Dhule district is located in northern Maharashtra with latitudes ranging from  $20^{\circ} 38'$  to  $21^{\circ} 61'$  N and longitudes ranging from  $73^{\circ}50'$  to  $75^{\circ}11'$  E.. It is situated at a crossroads where three national highways converge: the NH-6 (Surat-Nagpur), the NH-3 (Mumbai-Agra), and the NH-211 (Dhule-Solapur). The districts of Nandurbar to the north, Nashik to the south, and Jalgaon to the east encircle Dhule. Dhule is the district's administrative centre.

The Maharashtra state administrative district of Nandurbar is located in the north-west corner (Khandesh Region) of India. It was on July 1, 1998, when Dhule was split into two districts: Dhule and Nandurbar. Nandurbar city serves as the district's administrative centre. The district has a total land area of 5035 square kilometres. Nandurbar district is bordered by Dhule district to the south, by Gujarat to the west, and by

Madhya Pradesh to the north and north-east. The Narmada River serves as the northern boundary of the district.

Khandesh has a wide range of climates. Hot and dry summers are common in this area with temperatures peaking out around 44°C. The present study is carried out over Khandesh region of Maharashtra which includes districts Jalgaon, Dhule and Nandurbar. It is roughly estimated that almost 85% of the total rainfall occur during rainy season of four months and the remaining spread over other months of each year. IMD data shows that the Khandesh area receives an average of 90cm of rain per year. This is followed by a lovely winter temperature. Except for the monsoon season, Khandesh has a dry climate. There are four distinct seasons to the year. December to February is the beginning of the cold season, while March to May is the beginning of the hot season. As of June to September, the monsoon season is in effect. October and November are the post-monsoon seasons in India. Along with other factors, temperature, humidity and air pressure are most important climate determining factors.

Khandesh region is well connected to the major cities of India Delhi, Pune, Nagpur, Durg, Raipur, Sambalpur and Kolkata, Bhopal, Mumbai, Nashik through National Highway No. 6 as shown in fig. 3.2.





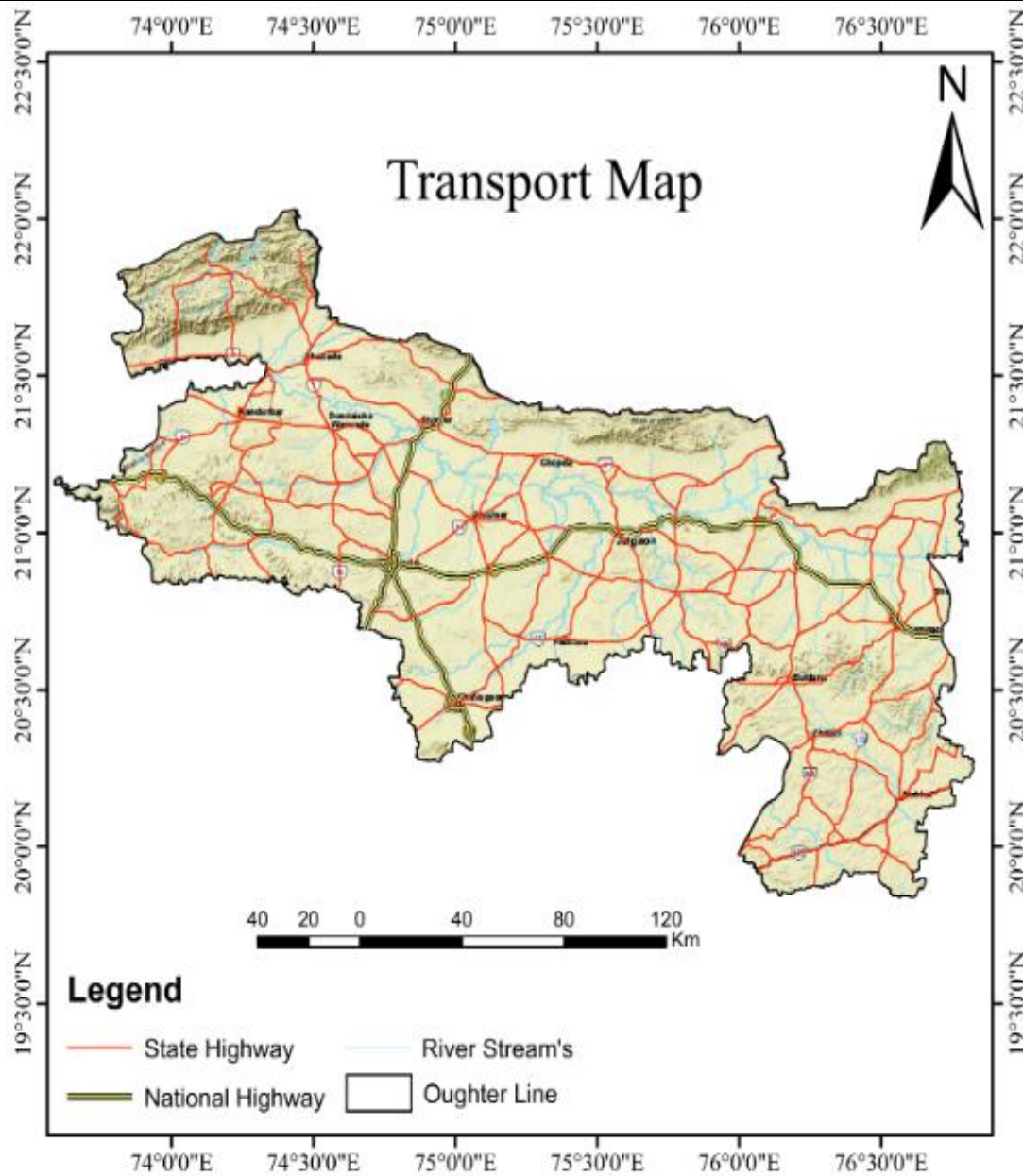


Figure 3.2: Transport map of Khandesh region

### 3.3 Description of the Project Road

The project road corridor starts from Fagne in Dhule district at km 510.00 of NH-6 and ends at Maharashtra-Gujarat Border at km 650.79 of NH-6. The present configuration of the project road is mostly 2-lane except some stretches are two lane with paved shoulders and 4-lane (divide / undivided) in urban/ semi urban areas. Service road is not seen in built-up areas. The pavement type in all along project corridor is flexible. The project road has one existing bypass i.e. Dhule (connecting NH-3 to NH-6) and two level crossings are there in which one is narrow gauge at km 632.92 of NH-6 near Chinchpada and other at km 647.10 of NH-6 near Nawapur town. The length distribution of the project road in different districts is tabulated in table 3.1:

Table 3.1: District wise length of Project road

S. N.	District	Chainage	Length (km)	(%)
1	Dhule	km 510.00- km 606.00	96.00	68.19
2	Nandurbar	km 606.00- km 650.79	44.79	31.81
Total			140.79	100%

The Right of Way (RoW) available with the NHAI for the entire length of corridor is about 24 m to 45 m for existing road alignment. The RoW is fairly clear except shops, houses and other structures on the both sides of the project road in the settlement areas. Presently, the project road is 2 lanes road and vehicle pressure on this road demands to widen existing two lane road into four lanes road. Project goals include widening highways to four lanes with paved shoulder in order to meet traffic load for the next 15-20 years at a minimum. On the basis of projected traffic growth, widening and strengthening of the project corridor to 4 lanes becomes essential. A concrete or earthen shoulder, appropriate drainage, a Railway Over Bridge (RoB), Bypasses slight realignments utilities and amenities are also included in the plan. As far as engineering design can go, it has been taken into consideration to limit the need for relocation, tree cutting, and cultural property shifting. Improved ride quality, route speed, and reduced travel time and cost are all expected outcomes of the proposed enlargement and strengthening of the project road. With the widening and improvements of the existing highway, the faster corridor will be established linking to east-west corridor of Khandesh region of north Maharashtra. The improvements will help local population of Khandesh region to have better access to facilities of education, health care, family welfare, trade, commerce, market, employment etc. also the people inhabiting areas along to facilities of education, health care, family welfare, etc.

### 3.4 Development of the Project Road

The National Highways Authority of India is responsible for the construction of the project route, which begins in Dhule district and ends at the Maharashtra-Gujarat Border at km 650.79 of NH-6. It is an important East-West highway which is also called Great Eastern Road and also referred as Asian Highway-46 (AH-46). NH-6 starts from Kolkata and goes upto Hazira port. The highway is important for interstate connectivity between West Bengal, Jharkhand, Orissa, Chhattisgarh, Maharashtra and Gujrat. It is a part of New NH-53 which is important for port to port connectivity between Paradeep at Orissa to Hazira at Gujrat. The work of 4 laning of this project stretch was awarded to M/s. ILFS on BOT basis in the year 2016. However, due to the financial crisis of the Contractor M/s. ILFS, the Contract Agreement has been terminated by NHAI in the

year 2019. At the time of termination of the Contract Agreement, about 65% of the physical progress had been achieved by the Contractor. This termination of the Contract has been resulted in partially completed structures at site. M/s. J. M. Mhatre Infrastructure Pvt. Ltd. will be the contractor for the remainder of the four-lane section of the NH-6 between Fagne and the Maharashtra/Gujrat border in 2020, according to the National Highways Authority of India (NHAI).The work is ongoing by the Contractor. The major challenge involved is retrofitting of the partially completed structures in the project highway. At the time of award of the work to the Contractor, about 90 structures were in partially completed state. The details of the structures to be constructed in the project road are as described in table 3.2 below:

Table 3.2: Details of Structure to be constructed in Project road

S. N.	Particular	Details
1	Interchange Dhule bypass	01 No.
2	Viaduct	01 No.
3	Major Bridges	10 Nos.
4	Minor Bridges	90 No.
5	Vehicular Underpasses	14 Nos.
6	Pedestrian Underpasses	10 Nos.
7	ROB	3 Nos.

The key plan of the project highway from Fagne to Maharashtra / Gujrat border section of NH-6 has been shown in fig. 3.3.

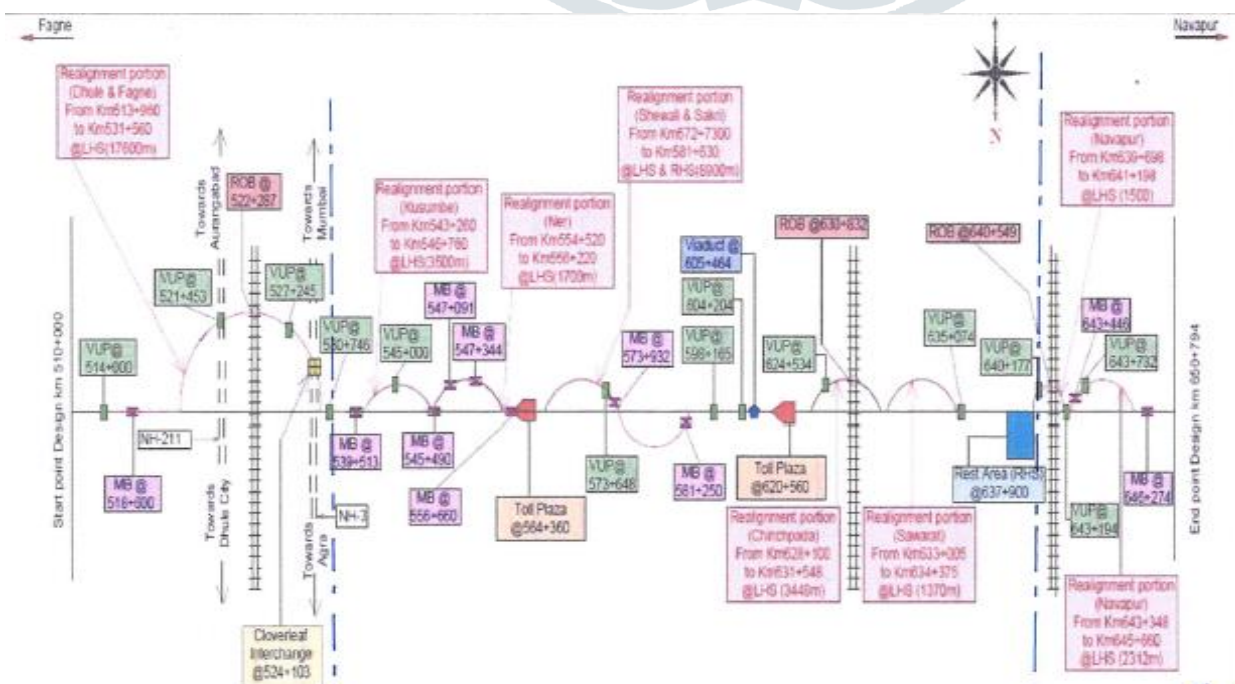


Figure 3.3: Key plan of the project road



## CHAPTER 4

### METHODOLOGY

#### 4.1 General

In this chapter, the methodology used for the research work has been elaborated. The details in respect of collection of samples, tests conducted, procedures of testing, etc. have been mentioned in this chapter.

#### 4.2 Collection of Samples

The Thermo Mechanically Treated (TMT) Steel bars of 1000mm in length and 32 mm in diameter have been taken from partially completed structures on the project route. The reinforcing bars have been cut using Gas cutter to obtain the test specimen of required dimensions. The samples have been taken from site as shown in fig. 4.1.



Figure 4.1: Collection of sample at site

#### 4.3 Testing of samples for Chemical and Mechanical Properties

For the investigation of chemical composition and mechanical qualities, TMT steel bars spanning 1000 mm in length and 32 mm in diameter, as well as TMT steel bars of the same dimensions taken from partially



constructed structures on the project route, were examined by means of test at the project lab of Contractor M/s. J. M. Mhatre Infra Pvt. Ltd. at Dhule camp office.

The chemical parameters of samples analyzed are as given below in table 4.1:

Table 4.1: Chemical Composition parameter

S. N.	Test Parameter
1	Carbon
2	Sulphur
3	Phosphorous
4	Sulphur + Phosphorous

The mechanical parameters of samples analyzed are as given below in table 4.2:

Table 4.2: Mechanical property testing parameter

S. N.	Test Parameter
1	Yield Stress
2	Ultimate Tensile strength
3	Ratio of TS/YS
4	Elongation
5	Mass
6	Bend Test
7	Rebend Test

#### 4.4 Methods of Testing of samples for Chemical and Mechanical Properties

The reference methods used for conducting various tests on samples and details of reference code used are given in table 4.3 below:

Table 4.3: Methods of testing and reference code

Test Parameter	Reference Test Method / code
Carbon	IS: 8811-1998, ASTM E 415
Sulphur	
Phosphorous	
Sulphur + Phosphorous	
Yield Stress	IS: 1608 (Part 01) - 2018
Ultimate Tensile strength	
Ratio of TS/YS	
Elongation	
Mass	IS: 1786-2008
Bend Test	IS: 1599-2019
Rebend Test	IS: 1786-2008

#### 4.5 Corrosion Inhibitors

Corrosion resistance of TMT steel bars was tested using several types of chemical corrosion inhibitors in this study. The compounds were chosen based on their ability to halt corrosion and their potential for use as corrosion protection. Table 4.4 lists the corrosion inhibitors that were used in the experiment.

Table 4.4: Chemical corrosion inhibitors used for experimental work

Chemical	Chemical Formula	Molar Mass (gm/mol.)	Appearance	Density (g/cm <sup>3</sup> )
2-Aminopyridine	C <sub>5</sub> H <sub>6</sub> N <sub>2</sub>	94.12	Colorless solid	1.21
Picolinic Acid	C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub>	123.11	White Solid	1.025
Salicylaldehyde	C <sub>7</sub> H <sub>6</sub> O <sub>2</sub>	122.12	Dark Green Oil	1.146
4-Aminobenzoic Acid	C <sub>7</sub> H <sub>7</sub> NO <sub>2</sub>	137.14	White Powder	1.374

Pure  $\text{Ca}(\text{OH})_2$  was used to imitate the media environment. For the aim of bubbling, 99 percent pure NaCl and carbon dioxide gas from a normal  $\text{CO}_2$  cylinder were utilised to create an environment that mimicked a concrete specimen under the impact of carbonation and chloride-induced corrosion. Multipurpose epoxy glue Fevitate Rapid is a two-component epoxy formula. Only seconds before usage, it is combined in a 1:1 ratio with resin and hardener to create the final product you see. It is used in these tests to avoid the chemical reaction of a section of the steel bar with the pore solution.

#### 4.6 Preparation of specimen for Testing for Corrosion

Machining 60-mm lengths of 32-mm steel bars is the first step in the fabrication process. The electro-chemical cell and different experiments necessitated drilling and threading these steel bars on one end. In order to guarantee adequate conductivity, the drill's diameter was fixed at 3 mm and its depth was kept at 10 mm.

Wire brushes and sandpaper were used to scrub each 60-millimeter-long piece of steel bar to eliminate any residual rust. After soaking in analytical reagent grade hexane, they were allowed to air dry before a thorough clean. It is necessary to wait at least one hour between the application of the first layer of epoxy to the specimens before applying the second, which is done after the specimens have been air dried for 24 hours. 24 hours after epoxy treatment, the specimens were stored. Figure 4.2 depicts a sample that has been treated and is ready for testing. It is then screwed into the hole that has been created, and an electrical wire is tightened between the two bolts in order to guarantee proper conductivity. Figure 4.3 depicts the finished steel specimen's line diagram.

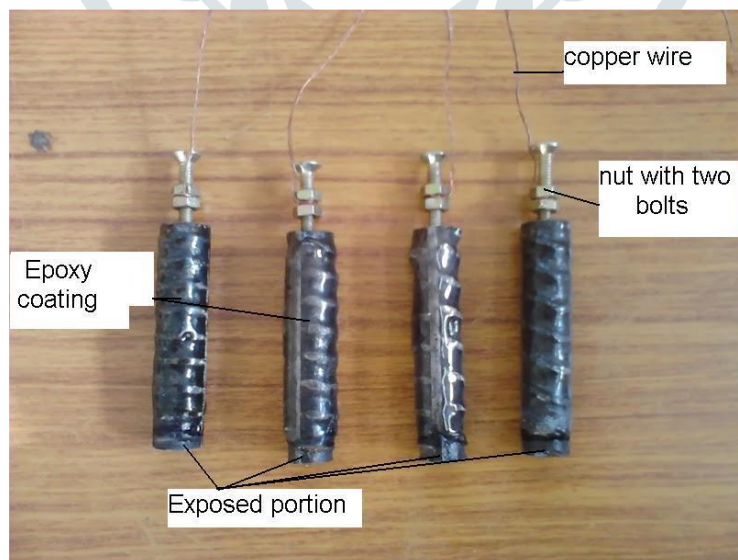


Figure 4.2: Details of prepared steel specimen used for experimental works

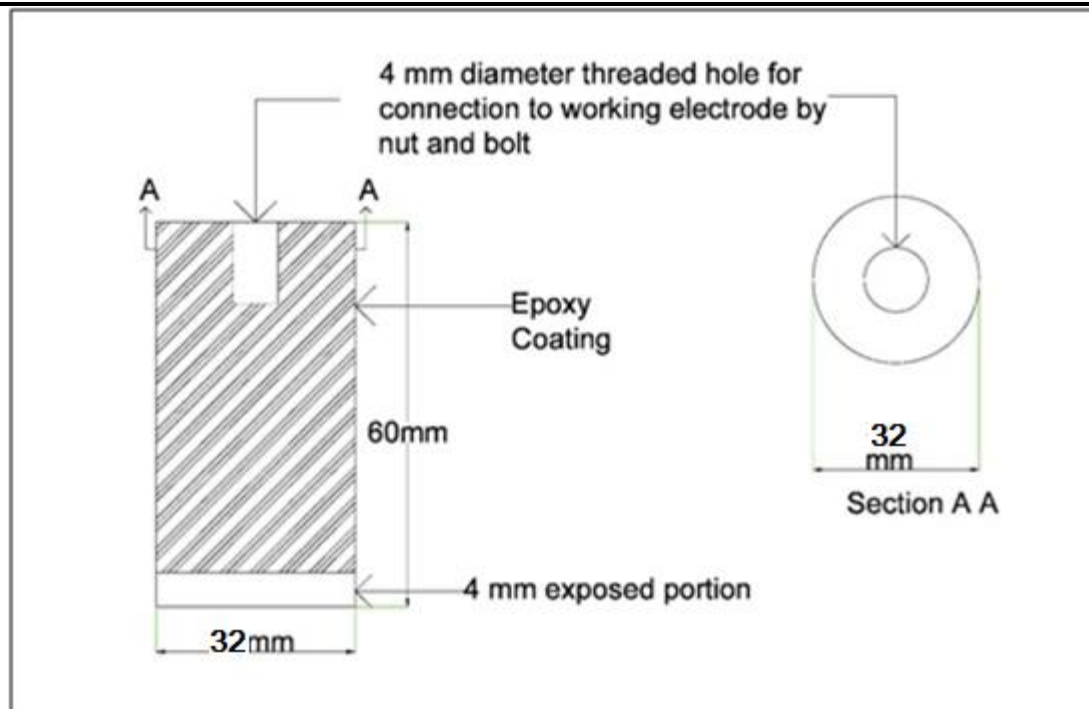


Figure 4.3: Line diagram of prepared steel specimen

#### 4.7 Preparation of Synthetic Pore Solutions

Calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ) saturated solution is used to simulate newly produced concrete. Lime water is another term for calcium hydroxide solution. A 2.7 gm/l (0.035M solution) dilution of calcium hydroxide in deionized or distilled water results in a completely saturated solution (to ensure there will not be any foreign mineral or chemical that are present in tap water, which can affect the resultant pH of solution). In order to prevent  $\text{CO}_2$  absorption, the solution must then be blended and stored for at least 24 hours in a container that is tightly sealed. In a sealed container, a filter paper is used to remove the remaining impurities from the final solution after 24 hours of incubation. Solution exposure should be maintained to a minimum to provide best outcomes.

Calcium hydroxide solution was reduced from 12 to 7.4 pH to create a synthetic solution that mimics the effects of chloride and carbonation on concrete. In order to create the carbonated solution, 99% pure  $\text{CO}_2$  gas was simply blasted into the pore solution. The carbonation state in the pore solution was achieved by bubbling  $\text{CO}_2$  gas. In order to mimic a corrosion-prone carbonation state in the pore solution, this method was used in this experiment. Carbonation of calcium hydroxide lowered the pH of the solution from 12 to 7.4. The severe carbonation in pore solution was achieved by lowering the pH of the solution to 7.4.

Table 4.5 indicates the ultimate pH of the liquids in which the steel specimens were stored. In lime water, carbon dioxide ( $\text{CO}_2$ ) interacts with calcium hydroxide to form calcium carbonate precipitates. A close check on the pH should be kept on the process during the conversion of calcium hydroxide to calcium carbonate when  $\text{CO}_2$  is bubbling, and this is being done properly. 3.5 percent w/w of pure NaCl was added to the final



solution. After that, filter paper should be used to purify the resulting solution. Solution of Chemical Inhibitors in Carbonated NaCl is shown in Figure 4.4.

Table 4.5: Final pH of solutions in which steel specimens were kept.

Sr. No.	Abbreviations	Sample	pH value
1	Sol. 1	Saturated Ca(OH) <sub>2</sub>	12.4
2	Sol. 2	Carbonated and saturated chloride solution	7.4
3	Sol. 3	2-Aminopyridine	9
4	Sol. 4	Picolinic Acid	7.1
5	Sol. 5	Salicylaldehyde	6.8
6	Sol. 6	4-Aminobenzoic Acid	6.9



Figure 4.4: Solutions of Chemical Inhibitors in Carbonated Saturated NaCl

#### 4.8 Testing procedure for Corrosion

Steel bars of 32 mm diameter and 60 mm length are used. Following the procedure outlined in the preceding sections, the steel bars are coated with one layer of epoxy along their entire length, leaving a length of 4 mm from the bottom. To guarantee that the epoxy coating does not break during the experiment, a second layer of epoxy is added once the first layer has completely cured. Six distinct steel bars, each with an uncoated bottom, were submerged in four different solutions of corrosion inhibitors in order to determine the efficiency of each. A calcium hydroxide solution and a carbonated solution with chlorides were used as control solutions for two test specimens to compare the outcomes of the un-carbonated and carbonated phases. Samples ready for analysis are shown in Figure 4.5.

Specimens were observed for several amounts of time, such as one hour, 24 hours, 48 hours, 120 hours, 240 hours, and 480 hours. A specimen could only be tracked for 480 hours at a time. However, the same working electrode was utilised in all of these studies. As a result, the solution was tampered with during the reading. The equipment was left unattended for 45 minutes before to LPR and OPC readings in order to avoid any possible mistakes.

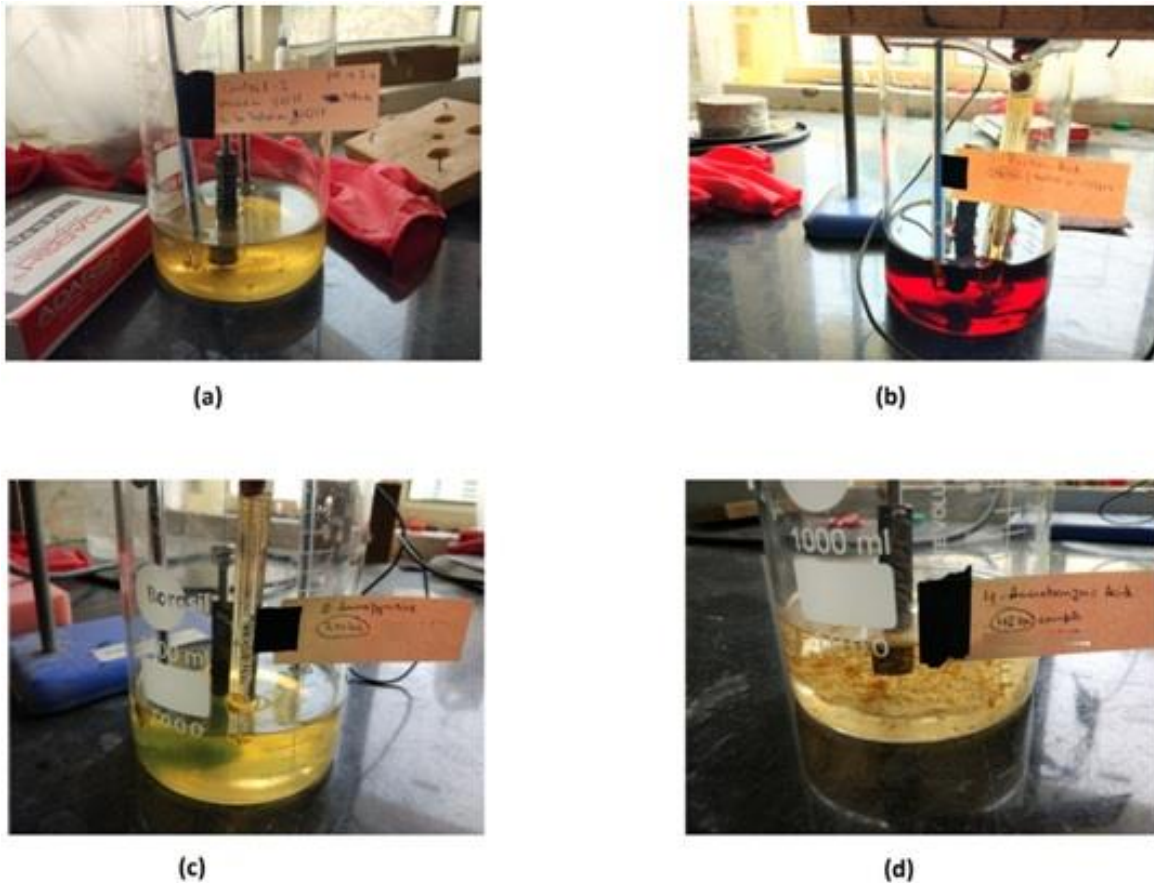


Figure 4.5: Final prepared specimens.

A solution containing corrosion inhibitors was prepared, and steel specimens were then submerged in it for corrosion studies. An open circuit potential measurement and corrosion current density measurement were conducted to monitor corrosive activities after epoxy had cured and dried. To measure corrosion, the ACM field machine has been used.

ACM Model: Serial No. 1463 Corrosion was monitored with a Field Machine. Corrosion monitoring may be done with the ACM field machine using a variety of electrochemical techniques such as current and voltage / time, long term-LPR sweep, long term LPR step, Galvanostatic and AC impedance. This experiment made use of long-term-LPR sweep methods, which monitor current and voltage over time. As seen in figure 4.6, the ACM field machine that was used in the experiment:



Figure 4.6: ACM Model: Serial No. 1463 Field Machine

#### 4.8.1 Half Cell Potential Measurements

A half-cell potential is measured on the steel bars. For half-cell potential measurements, the Saturated Calomel electrode is used as a reference electrode (Potassium chloride). Steel de-passivation and subsequent corrosion can be detected by measuring the half-cell potential. Saturated calomel reference electrodes (KCl) were used in this investigation to measure half-cell potentials at predetermined periods on the specimens. ASTM Standard technique for conducting a test. Corrosion surveys on bridge decks most often employ the half-cell potential measurement. The potential difference between a standard portable half-cell and the steel rebar beneath it can be used to obtain an empirical indicator of the relative likelihood of corrosion activity. A summary of ASTM's interpretation of half-cell potential is provided in Table 4 .

Table 4.6: ASTM Interpretation of Half-Cell Potential Readings

Half Cell Potential values	Corrosion condition
< -426 mV	Severe corrosion, corrosion induced cracking may occur
< -276 mV	High risk, 90% probability of corrosion
-126mV to -275 mV	Intermediate risk, corrosion activity in reduction
0 to -125 mV	Low risk, 10% probability of corrosion

#### 4.8.2 Linear Polarization Resistance (LPR)

To determine corrosion current density, a long-term LPR sweep or potentiodynamic polarisation has been used. Reinforcing steel in concrete may be measured using the LPR methodology, which has become a well-established approach. In order to make an electrical connection to the reinforcing steel, only minor damage must be performed to the concrete cover. Reinforcing steel in concrete structures has corroded to such an extent that non-destructive methods of evaluating the state of reinforced concrete structures have become more popular. These needs have been met by LPR monitoring. The process is quick and painless, requiring only a connection to the reinforcing steel to get started. The immediate corrosion rate of the steel reinforcement is provided by the data, which is more thorough than a basic potential survey can offer. The LPR data provides a more accurate evaluation of the structure's state and is a critical factor in determining the best repair method. As a result, the accuracy of the LPR readings is critical. During LPR measurements, the equilibrium potential of the reinforcing steel is somewhat disrupted. Changes in the potential of the reinforcing steel can be made potentiostatically in order to do this by measuring the rate of current decay ( $\Delta I$ ) and making adjustments to the applied voltage ( $\Delta E$ ). Galvanostatically, a tiny fixed current,  $\Delta I$ , may be applied to the reinforcing steel and the potential change,  $E$ , can be monitored after a set time period. Conditions are chosen so that the change in potential ( $\Delta E$ ) falls within the linear Stern–Geary range of 10 to 30 mV in each example.

The polarization resistance,  $R_p$  of the steel is then calculated from equation

$$R_p = \Delta E / \Delta I$$

From which the corrosion rate,  $I_{corr}$  can be then calculated

$$I_{corr} = B / R_p$$

Where,  $B$  is the Stern-Geary constant and is given by  $B = \frac{(\beta_a \times \beta_c)}{2.3 (\beta_a + \beta_c)}$

$\beta_a$  and  $\beta_c$  are the anodic and cathodic tafel constants. Assuming that the steel is in an active state, the value of  $B$  is set at 26 mV. The polarisation resistance is  $R_p$ . For active steel, a voltage of 26 mV was selected, while for passive steel, a voltage of 50 mV was chosen. Surface area ( $A$ ) of steel that has been polarised must be correctly understood in order to establish the corrosion current density ( $i_{corr}$ ):

$$i_{corr} = I_{corr} / A$$

The structure's remaining service life may then be determined based on the structure's current residual strength. The ACM Field Machine was used to conduct a potentiostatic linear sweep test on bare steel specimens. Beaker with wooden lid is the electrochemical cell. The auxiliary electrode, reference electrode, and specimen may all be connected using the included fittings. The reference electrode utilised throughout



the test was a saturated calomel electrode (SCE). The electrochemical cell was used to test the bare steel specimen screwed to the working electrode, as well as the reference electrode, auxiliary electrode, and noise reduction probe. At a sweep rate of 50 mV per minute, the potentiostatic linear sweep test was performed from -300 mV to 1500 mV with offset from corrosion potential.



## CHAPTER 5

### RESULTS AND DISCUSSIONS

#### 5.1 General

In this chapter, the results obtained from the different tests conducted on the specimen, have been elaborated. The attempt has been made to discuss the results with standards of different IS codes and to study the comparison and effect on the performance of the structures. Experiment findings and their importance are described in this section. In order to determine which corrosion inhibitors provide the best corrosion resistance, the primary objective of this study was to test them. What follows are discussions of OCP and LPR sweep testing results.

#### 5.2 Chemical Properties of the test specimen

All of the TMT Fe500D steel bars utilised in the testing were produced following the normal techniques outlined in the previous chapters. Table 5.1 shows the specimen's chemical properties:

Table 5.1: Chemical properties of TMT Fe500D steel bars

Test Parameter	Test Result		Permissible limit as per IS 1786-2013
	New Steel bars	Collected from Partially completed structures	
Carbon (%)	0.228	0.155	Max. $0.25 \pm 0.02$
Sulphur (%)	0.017	0.033	Max. $0.040 \pm 0.005$
Phosphorous (%)	0.022	0.018	Max. $0.040 \pm 0.005$
Sulphur + Phosphorous (%)	0.039	0.051	Max. $0.075 \pm 0.01$

#### 5.3 Mechanical Properties of the test specimen

The various mechanical characteristics of TMT Fe500D steel bars utilised in the experimentation were acquired using the conventional methods stated in the previous chapter. Table 5.2 shows the specimen's mechanical characteristics.:

Table 5.2: Mechanical Properties of TMT Fe500D steel bars

Test Parameter	Test Result		Permissible limit as per IS 1786-2013
	New Steel bars	Collected from Partially completed structures	
Yield Stress (N/mm <sup>2</sup> )	548	512	Min. 500
Ultimate Tensile strength (N/mm <sup>2</sup> )	692	576	Min. 545
Ratio of TS/YS	1.26	1.19	Min. 1.08
Elongation (%)	23.00	21.00	Min. 12.00
Mass (kg/m)	6.47	6.381	6.31 ± 4%
Bend Test	No crack or rupture observed	No crack or rupture observed	There should be no any visible rupture or cracks
Rebend Test	No crack or rupture observed	No crack or rupture observed	There should be no any visible rupture or cracks

From the above tables, it can be observed that both the samples of TMT Fe500D steel bars shows the results which are under permissible limits as per respective IS codes, however, the strength has been decreased due to corrosion.

#### 5.4 Testing for Corrosion

Linear Polarization Electrochemical methods such as resistance sweep monitoring are useful in detecting corrosion. The corrosion rate of a material can be calculated using the electrochemical potential and current generated between electrically charged electrodes in a process stream. Using a pore solution LPR has proven to be the most effective and time-saving method. Operators can get practically immediate response from this monitoring of the actual corrosion rate.

Bar steel specimens have been subjected to a linear sweep test. There is an anodic polarisation curve for Sol. 1 in calcium hydroxide saturated solution for 1 hour and Sol. 2 after passing CO<sub>2</sub> gas and saturating it with NaCl shown in fig 5. 1. Different areas of corrosion have been shown in this graph for the steel reinforcement that is given:

#### Active zone

Significantly high current density promotes relatively little change to potential, which results in this zone.

## Passive zone

Current density changes very little here, but the potential dramatically increases, making it an ideal place to do experimentation. It is located above the zone of activity.

## Pitting zone

The pitting zone, where oxygen is generated, is located above the passive zone.

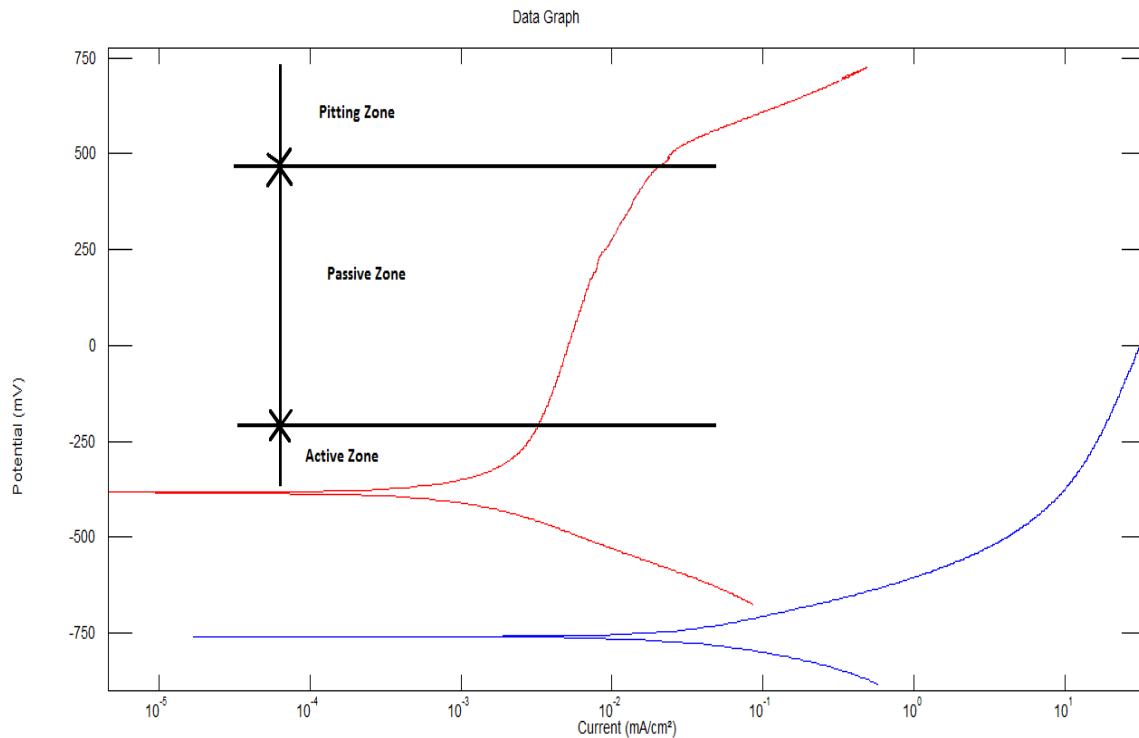


Figure 5.1: Anodic polarization curve for Sol. 1 and Sol. 2

The graph above shows that for Sol. 1, all of the zones are well delineated, unlike for Sol. 2. For Sol. 1, the steel bar is exceedingly resistive to the current density, which indicates that the passive layer around the steel has no effect. Between  $10^{-2}$  mA/cm<sup>2</sup> and 1 mA/cm<sup>2</sup> of current density, the steel bar begins to resist corrosion from  $10^{-3}$  mA/cm<sup>2</sup> and the passive layer begins to deplete between these two points and enters the pitting zone afterward. The graph for Sol. 2 did not reveal any distinct zones as CO<sub>2</sub> gas is passed through calcium hydroxide and afterwards 3.5 percent NaCl is added to the solution. Sol. 2's active zone begins with a much lower potential than Sol. 1's during the initiation period. The pH of the solution has been lowered, so we can conclude that steel did not create a passive layer. A small or nonexistent passive zone exists during the propagation period. Carbonation and chloride-induced corrosion degrade the steel bar quickly in the solution, as shown by a comparison of the two samples. So that corrosion might be prevented and their efficiency studied, several corrosion inhibitors were introduced to Sol. 2.

Tafel graphs from the ACM field machine have been reviewed for each specimen in order to better understand corrosion inhibition behaviour with regard to immersion time.

Tafel graphs show the relationship between the Y-axis potential (mV) and the X-axis current density (mA/cm<sup>2</sup>). Tafel extrapolation provides more accurate  $I_{corr}$  and corrosion rate data by using Tafel plots. It is



possible to extrapolate from a Tafel using the sequencer of the ACM field machine's Tafel ruler function. Only logarithmic current axes can be utilised with tafel rulers when plotting potential vs. current. Three rulers are placed on the graph, one of which is a horizontal ruler that indicates the resting potential. Tafel slopes are shown on the other rulers.

In order to make this comparison, Tafel plots of specimens immersed in various chemicals as corrosion inhibitors are compared to the Tafel plot of a specimen immersed in carbonated calcium hydroxide solution with NaCl (Sol. 2) More than  $10^{-4}$  mA/cm<sup>2</sup> corresponds to an active condition, whereas less than  $10^{-4}$  mA/cm<sup>2</sup> is considered moderately active. High and extremely high corrosion rates are both indicated by corrosion current density values ranging from  $10^{-3}$  mA/cm<sup>2</sup> to  $10^{-2}$  mA/cm<sup>2</sup> and from  $10^{-2}$  mA/cm<sup>2</sup> to  $10^{-1}$  mA/cm<sup>2</sup>.

### 5.5 Test Results of Various Specimens at different immersion times

1 hour, 24 hours, 48 hours, 120 hours, 240 hours, and 480 hours of immersion were used to monitor corrosion.

#### 5.5.1 Test results after 1 Hour of immersion

Each specimen was prepared and placed in the control and inhibitor solutions for an hour before conducting two tests: Current and Voltage and the LPR sweep. These tests yielded the following results, as shown in the table below.

Due to a lack of time for inhibitors to demonstrate their ability to inhibit, data obtained within one hour are not as reliable as those acquired after a longer time period.

Table 5.3: Half-Cell potential and  $I_{corr}$ . results after 1 hour of immersion

Sol. No.	Rp (-mV)	$I_{corr}$ . (mA/cm <sup>2</sup> )
Sol. 1	390.5	0.057
Sol. 2	661	1.175
Sol. 3	655	1.323
Sol. 4	545	1.315
Sol. 5	663	1.031
Sol. 6	543	0.41

There is a high possibility of corrosion in the other specimens due to the presence of chlorides and the lower pH of the solution, which is shown by the difference in half cell potential.

Figure 5.2 shows the curve produced for steel in saturated  $\text{Ca}(\text{OH})_2$  solution vs carbonated saturated  $\text{Ca}(\text{OH})_2$  vs solutions with various corrosion inhibitors @1 percent inhibitor w/w, clearly showing that except for 4-Aminobenzoic acid other inhibitors have demonstrated their inhibitory quality. The controlled specimen (Sol. 1) had an active zone where the current density was less than  $10^{-3} \text{ mA/cm}^2$  before the beginning of the breaking of the passive layer. Because of the lower pH of the carbonated  $\text{Ca}(\text{OH})_2$  solution and the presence of  $\text{Cl}^-$  ions, the significant change was a shift of the curve toward lower potentials.

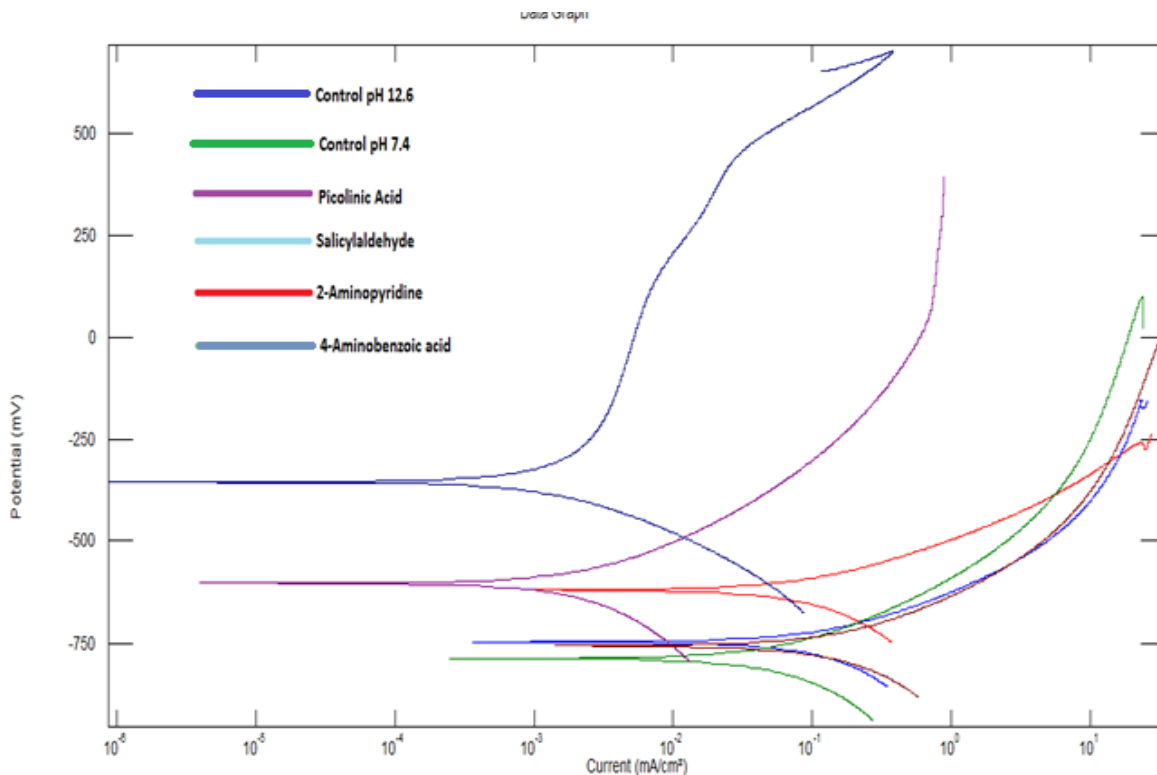


Figure 5.2: Tafel plot for various solutions immersed for 1 hour

### 5.5.2 Test results after 24 Hours of immersion

Two tests are performed on each specimen, namely the current and voltage & LPR sweep, which yield the findings shown in table 5.4 after the steel specimens have been produced and placed in the right control and inhibitor solutions for a period of 24 hours.

Table 5.4: Half-Cell potential and  $I_{corr.}$  results after 24 hour of immersion

Sol. No.	$R_p$ (-mV)	$I_{corr.}$ (mA/cm <sup>2</sup> )
Sol. 1	472.5	0.04
Sol. 2	711.1	1.275
Sol. 3	588.5	1.204
Sol. 4	660.1	1.118
Sol. 5	656.2	1.175
Sol. 6	544.2	0.525

Data Graph

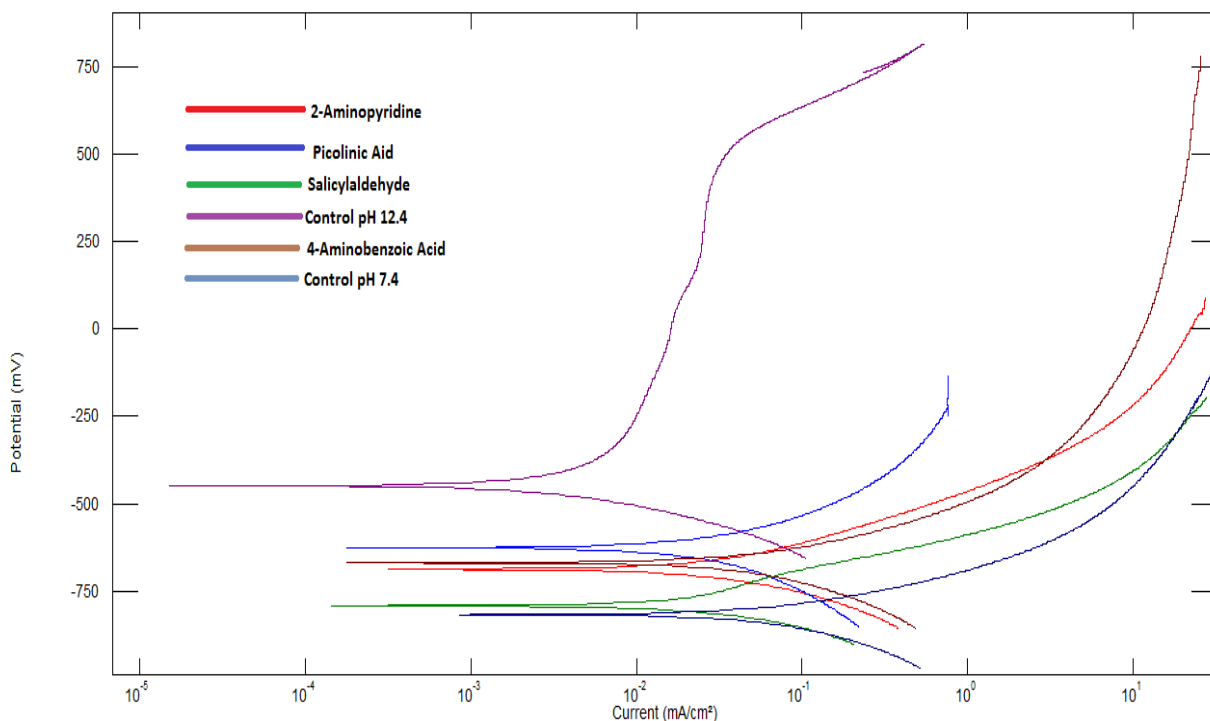


Figure 5.3: Tafel plot for various solutions immersed for 24 hour

Corrosion has begun in the control solution at a half-cell potential of -711mV, as can be seen from the current and voltage curves that provide the half-cell potential values. Compared to control Sol.2,  $I_{corr}$  measurements show that the inhibitors have begun to work.

The  $I_{corr.}$  value for 4-Aminobenzoic Acid is 0.525mA/cm<sup>2</sup> which indicates that 4-Aminobenzoic acid has fared remarkably well in the early stages compared to other corrosion inhibitors. Salicylaldehyde, on the other hand, has performed better than other inhibitors.

### 5.5.3 Test results after 48 hours of immersion

A total of two tests are carried out on each steel specimen following the preparation and 48-hour involvement in the appropriate inhibitor and control solutions. The current and voltage & LPR sweep are the terms used to describe these tests. Table 5.5 displays the findings from these assessments.

Table 5.5: Half-Cell potential and  $I_{corr}$  results after 48 hour of immersion

Sol. No.	Rp (-mV)	$I_{corr}$ (mA/cm <sup>2</sup> )
Sol. 1	511.78	0.045
Sol. 2	732.2	2.551
Sol. 3	648.30	1.841
Sol. 4	639.1	1.85
Sol. 5	680.2	1.12
Sol. 6	560	0.783

The results of the  $I_{corr}$  and Rest potential measurements suggest that the specimen in Sol. 1 has been acting in a noble passive manner up to this point. After 48 hours of immersion in Sol. 1,  $I_{corr}$  value shifted toward the active zone, whereas specimens in all inhibitors have shown an enormous increase in  $I_{corr}$  value up to this point. In the short term (up to 48 hours), Picolinic Acid is the worst inhibitor whereas 4-Aminobenzoic Acid is the best.



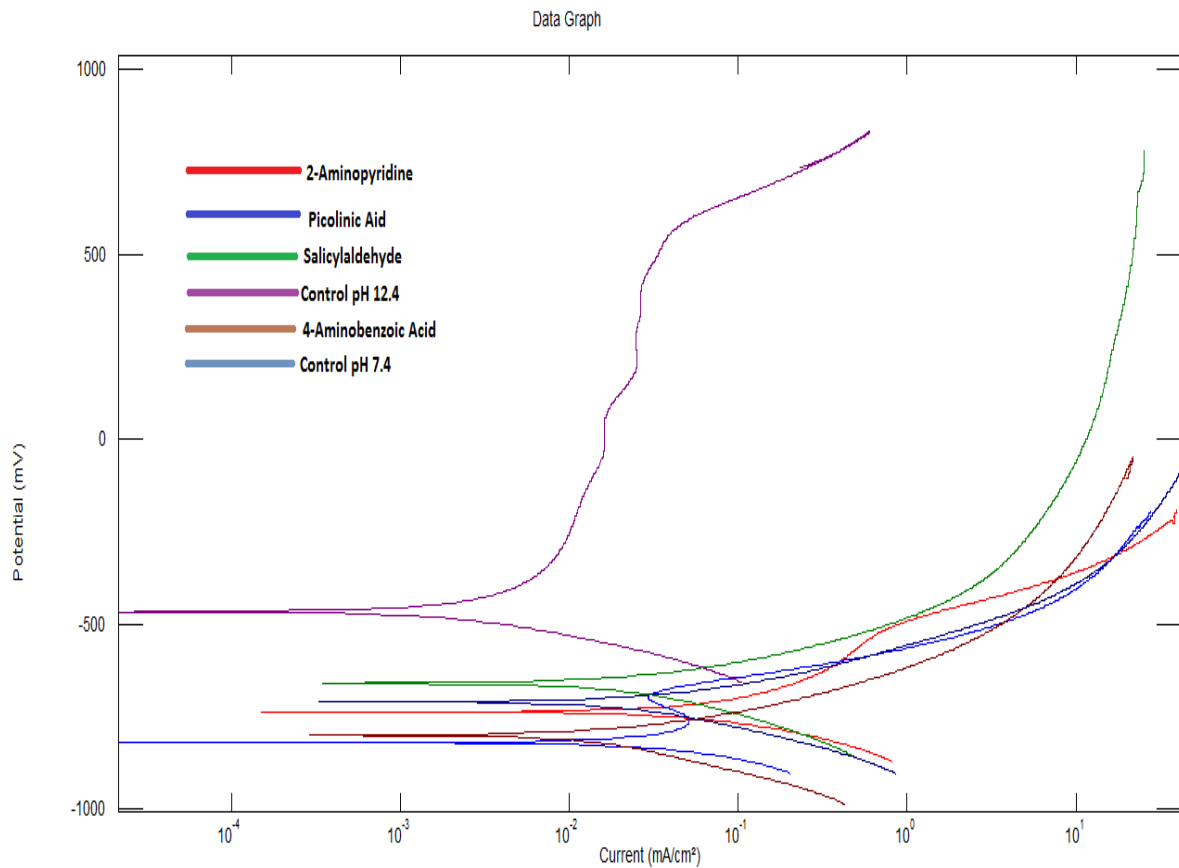


Figure 5.4: Tafel plot for various solutions immersed for 48 hour

As a result of these polarisation curves, it can be concluded that, with the exception of 4-Aminobenzoic acid, none of the chemical inhibitors have shown any significant progress in establishing passivation after 48 hours of immersion. There was a rest potential of less than  $-600\text{mV}$  for all the standard test method with corrosion inhibitors.

#### 5.5.4 Test results after 120 hours of immersion

When the steel specimens were prepared and placed in their respective control or inhibitor solutions for 120 hours, the following findings were gathered: Current and Voltage & LPR sweep, as given in table 5.6.

Table 5.6: Half-Cell potential and  $I_{corr}$  results after 120 hour of immersion

Sol. No.	$R_p$ (-mV)	$I_{corr}$ . (mA/cm <sup>2</sup> )
Sol. 1	705.5	0.38
Sol. 2	746.2	2.355
Sol. 3	674.6	1.751
Sol. 4	653.78	1.283
Sol. 5	649.5	1.552
Sol. 6	597.9	1.475

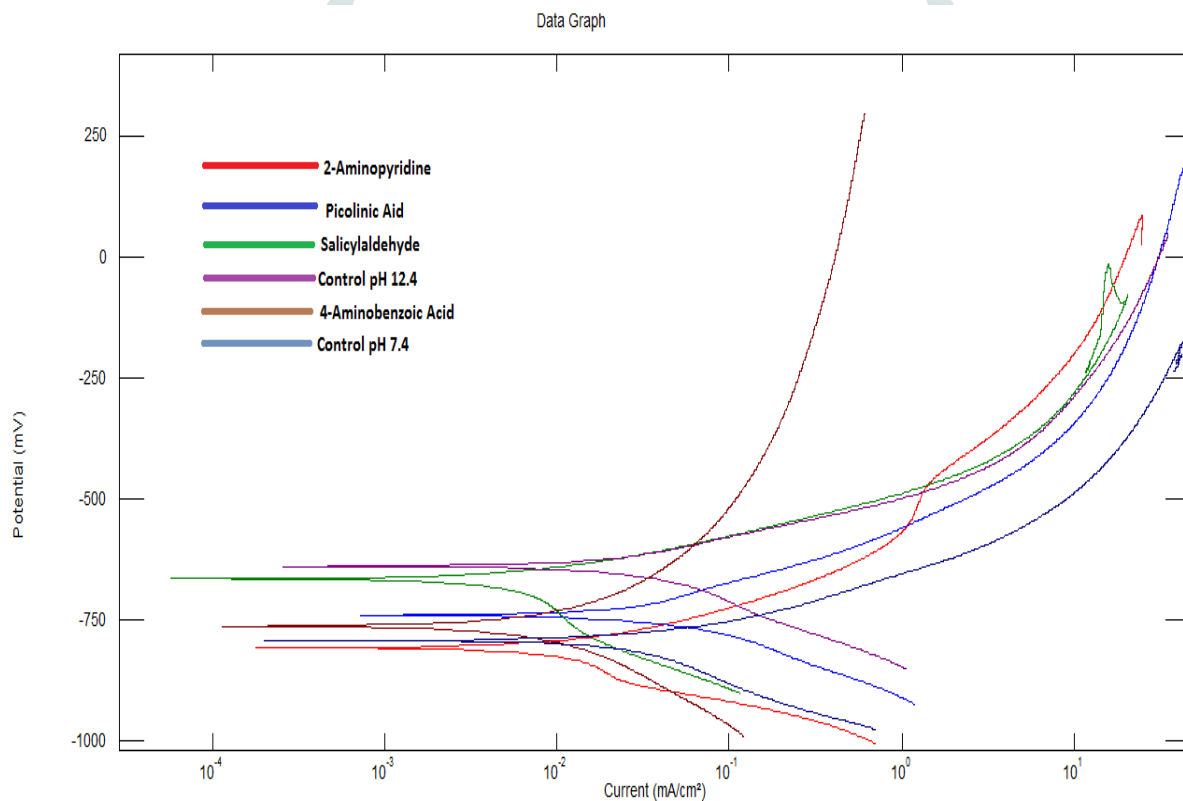


Figure 5.5: Tafel plot for various solutions immersed for 120 hour

Through the values of  $I_{corr}$  and based on the half-cell potential, the pH 12.4 control specimen is now more likely to corrode. Despite being a promising compound, 4-Aminobenzoic acid's performance has been lowered.

Fig. 5.5 shows that the  $I_{corr}$  value shifts toward the active zone as immersion duration increases, suggesting that the specimen is no more passive. This specimen's  $I_{corr}$  value was 0.057 at 1 hour of immersion, and it increased to 0.38 during 120 hours of immersion.



Figure 5.6: Steel specimens after measuring Half-cell Potential and Linear Polarization Resistance, immersed in different solutions after 120 hours

Extensive corrosion is shown in Figure 5.6 on a specimen that was submerged in Sol 2. The growth of corrosion rust can be seen in the figure, as the volume of corrosion rust is three to seven times that of iron. It is evident that all of the inhibitors are acting roughly equally up to this stage, with 2-aminopyridine taking the lead among the others.

There may be less rust on the specimen containing salicylaldehyde compared to other samples, but this sample was determined to have enough corrosion to warrant an LPR Sweep.

### 5.5.5 Test results after 240 hours of immersion

Steel specimens were tested for current and voltage as well as LPR sweep after 240 hours of immersion in the appropriate control and inhibitor solutions, as shown in Table 5.7.

Table 5.7: Half-Cell potential and  $I_{corr}$ . results after 240 hour of immersion

Sol. No.	R <sub>p</sub> (-mV)	I <sub>corr.</sub> (mA/cm <sup>2</sup> )
Sol. 1	743.5	0.0255
Sol. 2	738.08	2.276
Sol. 3	665.2	0.77
Sol. 4	496.8	0.768
Sol. 5	700	1.049
Sol. 6	692.2	1.185

There was a significant reduction in corrosion relative to the control Sol. 2 based on measurements of rest potential and  $I_{corr}$ . Sol. 5 specimens exhibit passive behaviour after 240 hours in the solutions, according to Fig. 5.6 A satisfactory shift into the passive zone can be seen in Sol. 5's  $I_{corr}$  value after 240 hours of immersion in the solution.

Figures 5.7 and 5.8 show that 2-aminopyridine, closely followed by 4-aminobenzoic acid, has performed the best of all inhibitors.

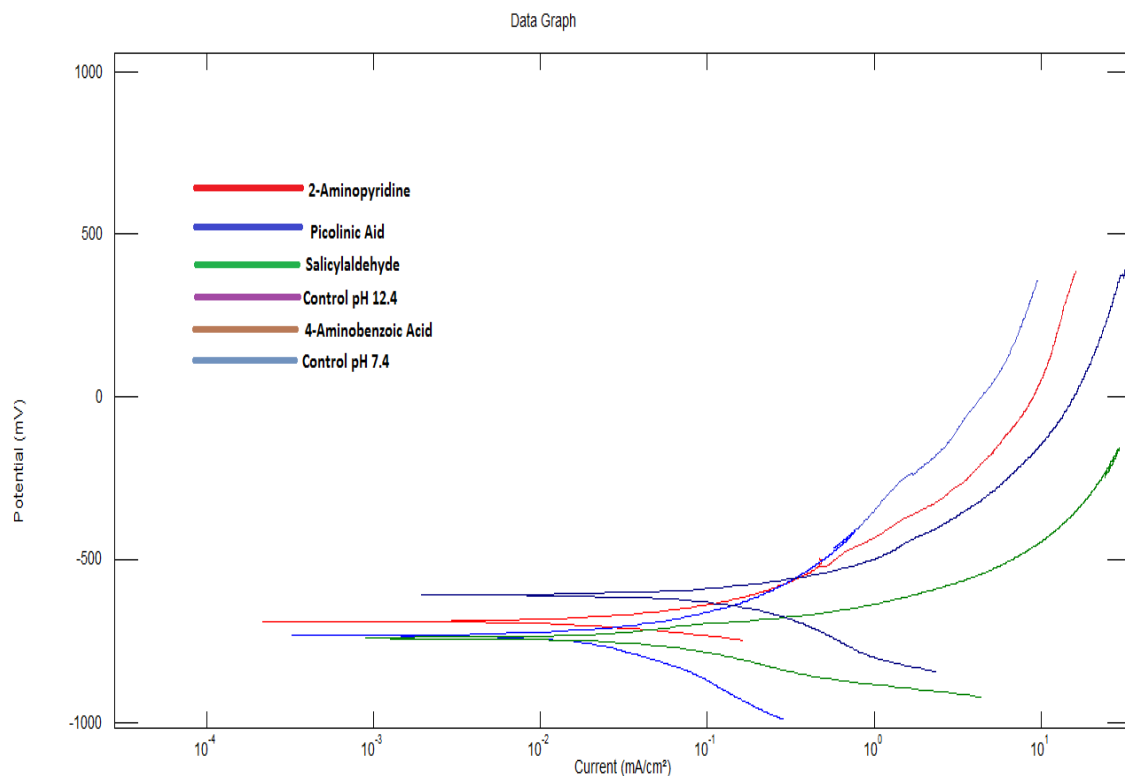


Figure 5.7: Tafel plot for various solutions immersed for 240 hours





Figure 5.8: After 240 hours of immersion in various solutions, steel samples were tested for half-cell potential and linear polarisation resistance.

### 5.5.6 Test results after 480 hours of immersion

A total of two tests, the current and voltage & LPR sweep, are performed on each steel specimen after they have been prepared and placed in the appropriate control and inhibitor solutions for a period of 480 hours. The results of these tests are provided in table 5.8.

Table 5.8: Half-Cell potential and  $I_{corr}$  results after 480 hour of immersion

Sol. No.	$R_p$ (-mV)	$I_{corr}$ (mA/cm <sup>2</sup> )
Sol. 1	769.21	0.032
Sol. 2	739.2	2.030
Sol. 3	595.2	0.085
Sol. 4	400.5	0.179
Sol. 5	577	0.033
Sol. 6	568	0.058

Even though  $I_{corr}$  and OCP fluctuate during the test, they are both much lower than predicted after 480 hours, indicating that the corrosion inhibitors have all done their research as expected in the test sample with pH=7.4 (the control).

Salicylaldehyde and 2-Aminopyridine have done the best among all the inhibitors, while there are considerable differences in the outcomes among the inhibitors itself.

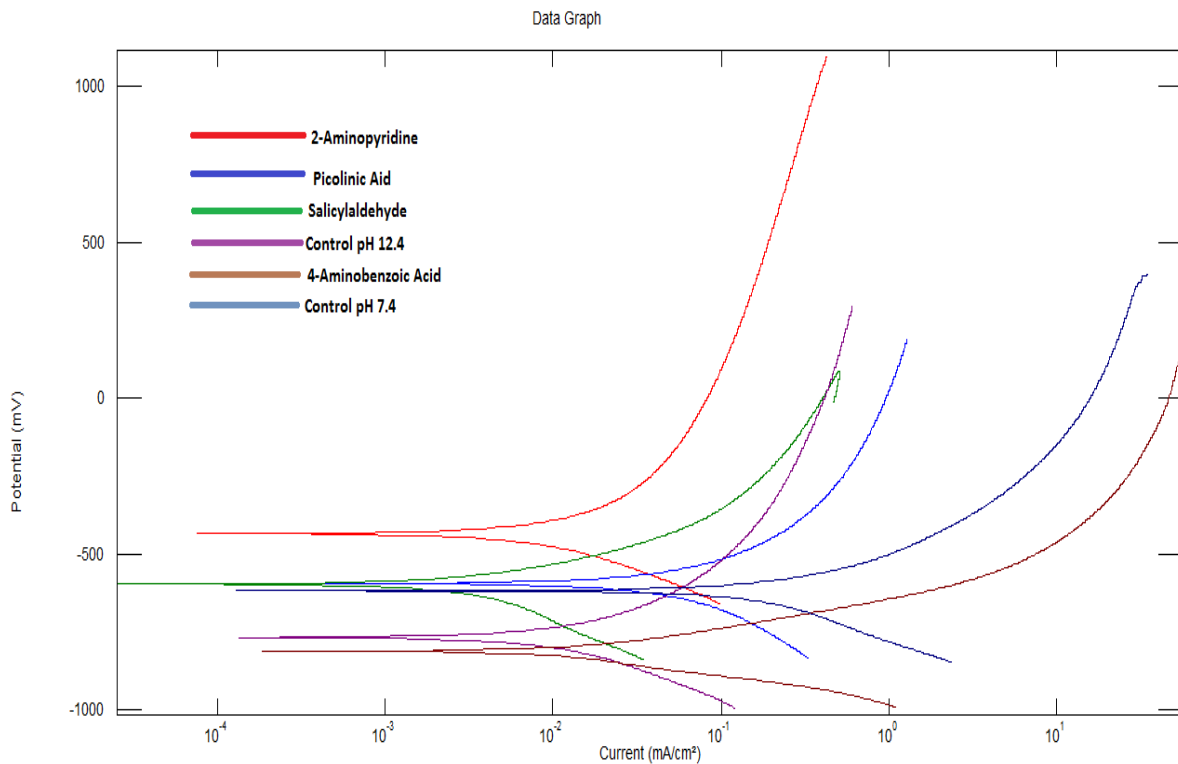


Figure 5.9: Tafel plot for various solutions immersed for 480 hour



Figure 5.10: After 480 hours of immersion in various solutions, steel specimens were measured for half-cell potential and linear polarisation resistance.

According to the figures shown in Figures 5.9 and 5.10, each of the inhibitors showed a considerable degree of inhibition when compared to the pH=7.4 control specimen. There is a lot of rust on the surface of the specimen in Sol. 2 due to extensive corrosion of the metal components.

## 5.6 Comparison of Corrosion Inhibitors with Control Solutions

The comparison of all the corrosion inhibitors used for the study with respect to the control solutions is described below:

### 5.6.1 Half cell Potentials Vs Time

The half-cell potential readings only indicate that the steel has lost its passivation, suggesting the possibility of corrosion. This provides an approximate indication of whether or not corrosion has begun. Corrosion has not yet begun because the half-cell potential is less than -250 mV.

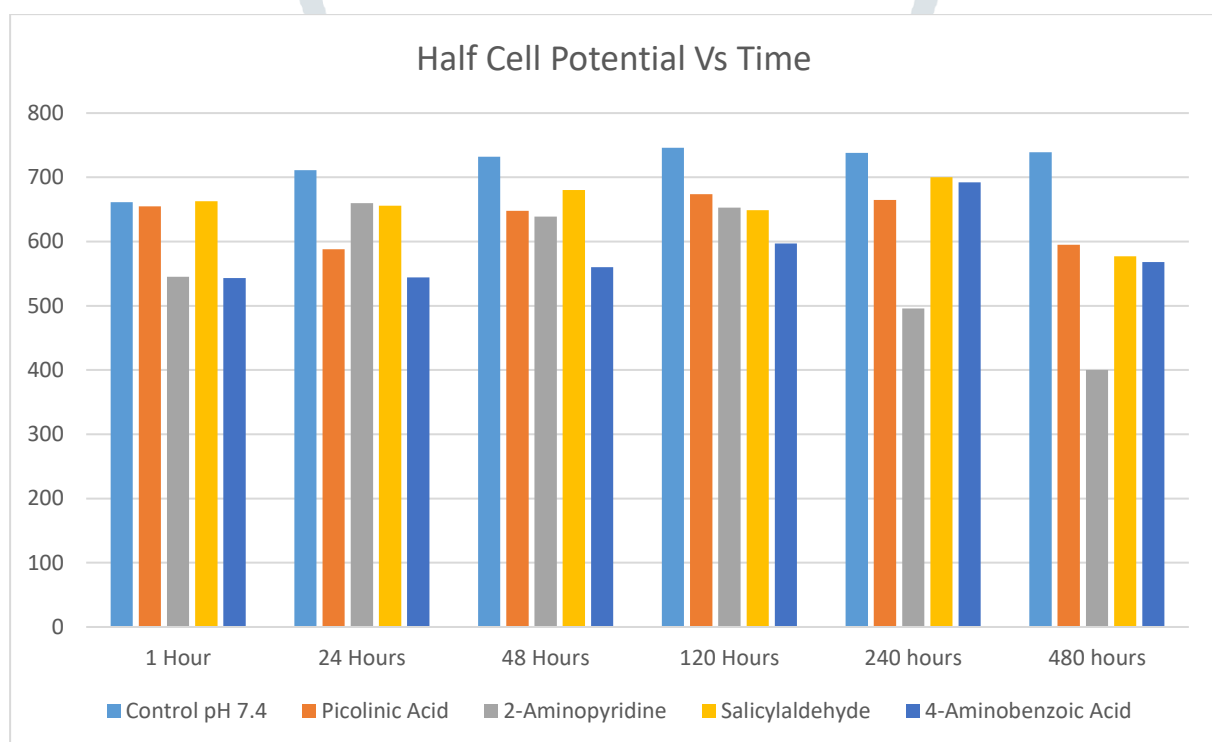


Figure 5.11: Variation of Half-cell potential (-mV) vs Time

The graph of HCP vs immersion time as shown in fig. 5.10 depicts the following:

- Half-cell potentials in the pH 7.4 control solution range from 650 to 800mV, which indicates that the risk of corrosion remains over 90 percent regardless of time variation.
- After 480 hours, the half-cell potential of 2-Aminopyridine is -400mV, which reduces the risk of corrosion. 2-Aminopyridine is the inhibitor with the lowest half-cell potential even before 480 hours, i.e. at 240 hours.

- Picolinic Acid's half-cell potential remained rather constant at -600 mV, ensuring that corrosion will remain a potential.
- This acid's half-cell potential has reduced up to a 240-hour immersion duration, but it has since risen by 125mV.

### 5.6.2 Linear polarization resistance $I_{corr}$ vs Time

Chloride ions build around the reinforcing steel, causing the reinforcing steel to lose its passivity and therefore enabling corrosion to start. Half cell potential is only useful for detecting the beginning of corrosion. As a result, LPR measurements are required because corrosion current density values can show the evolution of corrosion in the propagation phase. Each specimen's half-cell potential and LPR values were collected.

The graph of  $I_{corr}$  vs immersion time as shown in fig. 5.11 depicts the following:

- After 48 hours of immersion, Sol. 2 revealed a maximum  $I_{corr}$  value of  $2.55\text{mA}/\text{cm}^2$ .
- After 120 hours, 4-Aminobenzoic acid's performance began to decline. It is clear that 4-Aminobenzoic acid produced adequate inhibition, although only for a brief time period in the experiment described below.
- After 48 hours, 2-Aminopyridine produced the greatest decrease in  $I_{corr}$  values.
- Salicylaldehyde and picolinic acid had the same strategy when it came to  $I_{corr}$ . Both decreased  $I_{corr}$  values, however 4-Aminobenzoic acid and 2-Aminopyridine were less effective.

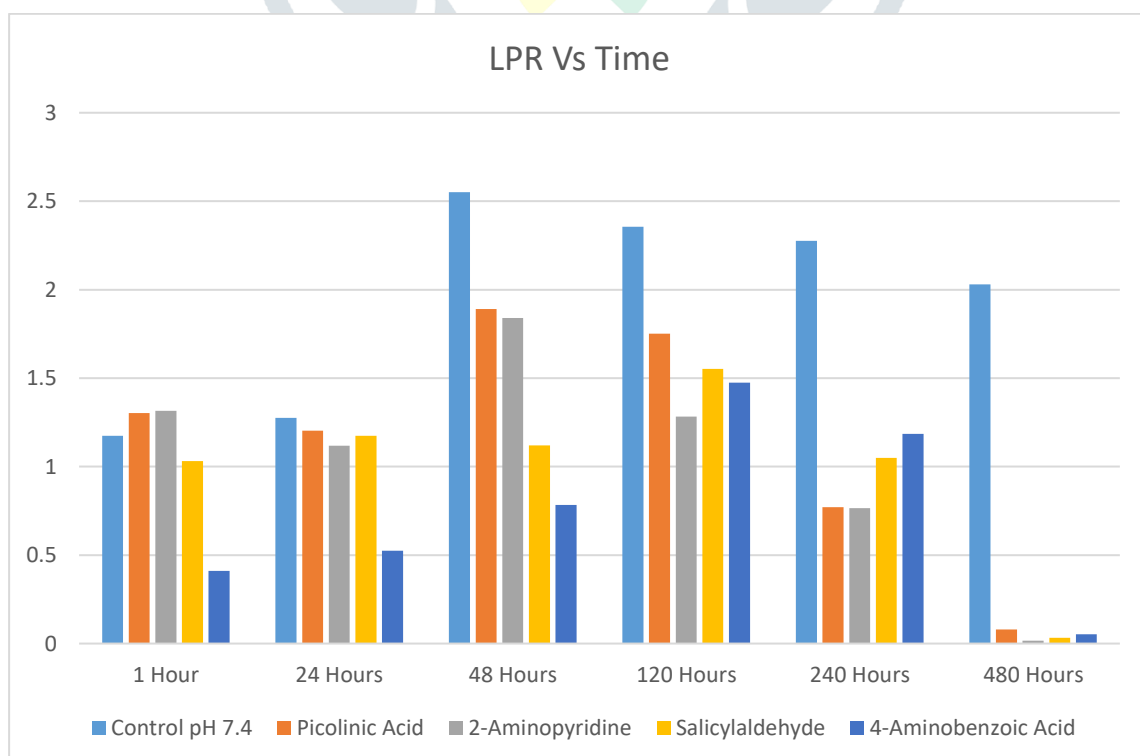


Figure 5.12: Variation of LPR  $I_{corr}$ .vs Time



## CHAPTER 6

### CONCLUSIONS AND FUTURE SCOPE

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#### 6.1 Conclusions

Based on research work carried out to study the corrosion behaviour of steel in partially completed structures and method to be used for retrofitting of columns using corrosion inhibitors for the project of NH-6 in the Khandesh region, the following conclusions are made:

1. It has been observed that both the samples of old and new TMT Fe500D steel bars, shows the results which are under permissible limits as per respective IS codes, however, the strength has been decreased by 16.8%.
2. Half Cell Potential Measurements and Linear Polarization Resistance (LPR) studies have been performed using four chemical corrosion inhibitors, namely 2-Aminopyridine, Picolinic Acid, Salicylaldehyde and 4-Aminobenzoic Acid, to explore corrosion behaviour and retrofitting utilising corrosion inhibitors.
3. Half cell potential Measurements are only useful for detecting the beginning of corrosion. However, Linear Polarization Resistance (LPR) measurements are required because corrosion current density values can show the evolution of corrosion in the propagation phase.
4. Carbonation and chloride-induced corrosion can be inhibited by all of the inhibitors.
5. Initial results show great result from 4-Aminobenzoic acid, but after 120 hours, 2-Aminopyridine has outperformed it. As a corrosion inhibitor for steel bar, 2-Aminopyridine has proved to be particularly most effective.

#### 6.2 Future Scope

1. The study can also be conducted in various corrosion media by differentiating pH values of pore solutions depending upon the nature of environment in respective area.

2. The study can be conducted in execution stage to find out the effective corrosion inhibitor to be used as admixture during concrete works..

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