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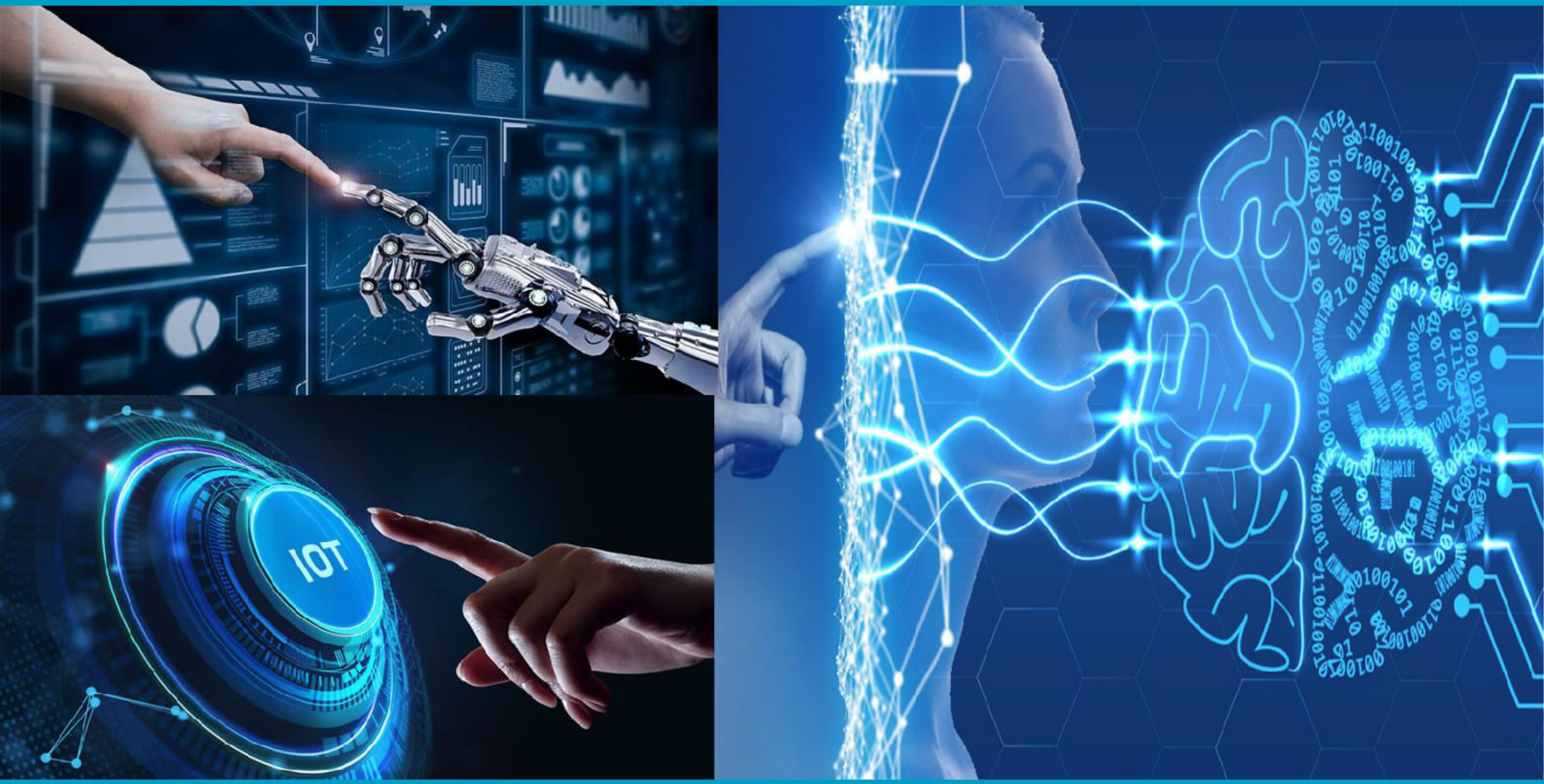

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# Chloride Induced Rebar Corrosion in Concrete under Accelerated condition: A Review

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**ABSTRACT:** As part of this paper, experimental and computational studies were conducted to investigate corrosion-induced pressure that causes concrete cover cracks to start and spread. The impressed current approach, which is a major factor in steel corrosion, relies on a considerable number of chloride ions. Using solutions similar to the concrete pore solution, researchers were able to identify the optimal chloride content. When the mixing water included a high concentration of chloride (3.5 percent mass), the actual mass loss was found to be in line with the theoretical one. There must be an initial saturation of the concrete pores with chloride ions that are close to the steel-concrete contact in order to achieve 100% current efficiency. A search and inquiry were conducted on this specific issue. A 3.5 percent chloride solution was used to immerse the cubical specimens, and the researchers found that the specimens required to be saturated for at least one day prior to the start of the testing.

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

## I. INTRODUCTION

India is classified as a deltaic country and encompasses a total size of 147,570 square kilometres. The coastal area is close to 29,000 square kilometres, which is approximately 20 percent of the total land area of the country. One of the most important and difficult maintenance problems that Bangladesh has, particularly in its coastal locations, is corrosion of the reinforcing steel (also known as "rebars") in concrete structures. Concrete, with its extremely alkaline pore solution, has its own built-in mechanism for protecting itself against corrosion. This mechanism involves the formation of a layer of passivation, which is a surface film of iron oxide. Chlorination and carbonation, on the other hand, both cause a disruption in this passive layer (Bazant, 1979).If the concentration of chloride ions in the environment is high enough, the passive layer will be destroyed, and the steel will corrode on its own. Carbonation is the name given to the chemical reaction that takes place when carbon dioxide (CO2) interacts with cement in concrete. This can lead to corrosion (Nossoni & Harichandran, 2012). A significant amount of damage can be caused to maritime structures by the high concentration of chlorides that is found in the salty water that is found in coastal areas. The rate of corrosion can be affected by a variety of parameters, including the concentration of chloride, temperature, relative humidity, cover thickness, and quality of the concrete. When the reinforcement corrodes, the change of metallic iron into oxides can result in a volume increase of up to 600 percent, depending on the final oxide form (Liu & Weyers, 1998).

This expansion causes concrete to fracture and spall, which in turn reduces the strength and durability of the concrete, which in turn compromises the serviceability of structures made of reinforced concrete.The management and upkeep of a structure is a tough endeavour, particularly in the case of marine constructions such as bridges, culverts, and buildings located in coastal locations. The phrase "Structural Health Monitoring," or SHM for short, has developed into a practical instrument for assessing the state of a structure's health and predicting the likelihood of its collapse (He et al., 2016; Kulkarni & Achenbach, 2008). Crack propagation as a result of reinforcing corrosion is one of the primary failure mechanisms for the majority of environmental risks. Corrosion damage is proportional to the amount of mass loss in steel;thus, this is a significant concern.

In point of fact, it can be extremely challenging to precisely calculate the amount of mass that is lost due to corrosion in steel that is embedded in concrete. As a consequence of this, the indirect prediction of corrosion is the strategy that is most practicable for SHM. The breadth of the cracks on the surface of the concrete might be considered one of the significant parameters. To determine the potential for failure due to corrosion This prediction may be very helpful in identifying the potential for failure due to corrosion.

In addition to the prediction of corrosion through the monitoring of crack width, a protection system is required to extend the life of marine structures. Alternatively, a prevention system is necessary when the structures have already been compromised before the issue escalates into a major concern. These days, one of the most common strategies for warding off corrosion is known as cathodic protection. Two methods of cathodic protection that have been investigated in the past are the sacrificial anode system and the impressed current system (Vrable & B., 1977). In sacrificial anode cathodic protection systems, a metal in the electrochemical series with a larger electromotive force than steel is utilised.

## II. OBJECTIVES OF THE RESEARCH WORK

Theoverallobjectives of this researchareasfollows:

1. Characterization of an accelerated corrosion test to determine the optimal chloride level and immersion time before starting the test for rated current efficiency;
2. Experiments on the growth of corrosion products and the mechanism of crack initiation due to corrosion-induced pressure, with the goal of establishing a link between crack width and corrosion level.
3. Experimenting with different concrete cover thicknesses to determine the critical pressure for cover cracking;
4. Development of a sacrificial anode system for corrosion protection using zinc and toinvestigateits effectiveness.

### 1.1. Scope of the Research

In this research, researchers used numerical modelling and experimentation to study the mechanism of concrete cover cracking induced by expansive pressure caused by reinforcement corrosion. It was also looked at monitoring the level of corrosion so that structural health monitoring in terms of crack width and crack propagation in the cover concrete might be done. In addition, the use of zinc as a sacrificial anode was investigated as a convenient means of corrosion protection. Many studies have contributed to a better understanding of the corrosion process, but the research on corrosion-induced expansive pressure and associated cover cracking is particularly noteworthy. Many investigations have contributed to a better understanding of the corrosion process, however, the study on corrosion induced expansive pressure and associated cover cracking is still has a lot of limitations (Allan & Cherry, 1992; Maaddawy & Soudki, 2003; Williamson & Clark, 2000a). Corrosion-induced cracking (Ahmed et al., 2007) and steel loss are investigated using various methodologies (Alonso et al., 1998a; Nossoni & Harichandran, 2012). The use of an impressed current system to accelerate corrosion is a common practise. Faraday's law is used to calculate the mass loss of steel in an impressed current system. The amount of chloride ions present in the electrolyte and the amount of current supplied determine the accuracy of utilising Faradays law to predict mass loss in concrete environments. As a result, more research is needed to describe the accelerated corrosion technique before it may be used in the future. In this research, the effectiveness of using Faraday's law to forecast the mass loss of reinforcement in accelerated corrosion treatments was investigated.

Few studies have been done to predict crack width in relation to corrosion penetration (Alonso et al., 1998a; Andrade et al., 1993; Vu et al., 2005) and mass loss (Tran et al., 2011), which are relevant to the present study, but no attention has been paid to those papers that relate the crack initiation mechanism with a variable cover thickness. The relationship between the amount of corrosion and the width of cover cracking with clear cover variation is still challenging in the sense that the results shown in those papers are inconsistent.

This study will provide an explanation of the mechanism of crack initiation for different clear covers, resulting in a new way of thinking about fracture mechanics and set a clear relationship between crack width and mass loss. This result would be extremely beneficial to companies working on SHM issues, since it would extend the life of structures, reduce repair bills, and save time.

Design guidelines for durable reinforced concrete structures exposed to the sea environment are lacking. The structure will be more durable if the cover concrete can withstand more expansive pressure caused by corrosion products expanding. As a result, research into the accumulation of corrosion products around the reinforcement, corrosion-induced expansive pressure, and expansion behaviour for various concrete qualities, cover thickness, and bar diameter is required. Studies, on either hand, take a long time to complete.

Numerical design is a vital tool for avoiding waste of time. In this regard, a numerical model is being developed, which will be validated through an experimental study. This numerical model would predict the capacity of the concrete cover and the pressure at which it cracks, as well as different critical pressures for various cover thickness and bar diameters. This may eventually lead to proper clear cover & rebar diameter selection. Furthermore, while there were a number of studies on cathodic protection in concrete structures (Das et al., 2015), only a few have looked at the effectiveness of a sacrificial anode in terms of mass loss. This study would conduct research to determine the efficacy of zinc as a sacrificial anode, so that it might be used for corrosion protection in low-budget projects.

## III. CORROSION MECHANISM

Corrosion is a natural process that transforms refined metals into more stable oxides. It is the gradual decomposition of materials as a result of a chemical reaction with their environment. Ordinary environments, such as air water or aqueous solution, attach most common metals and alloys to form metal compounds. All environments attack metal chemically, causing oxidation and the formation of corrosion products. Oxide, hydroxide, carbonate, sulphide, and other corrosion products are common. The corrosion products, in most situations, are insoluble in water and form a distinct phase on or close to the metal.

## IV. CORROSION REACTION

Although chemical attack can cause iron to rust, electrochemical corrosion is the most common form of corrosion in an aqueous medium. The corrosion process is similar to what happens inside a flashlight battery. In the presence of electrolytes, an electrochemical oxidation occurs in the anode and an electrochemical reduction occurs in the cathode. By electrically connecting anodes and cathodes to any metal surface where corrosion is occurring, a composite of anodes and cathodes is formed. Metals are linked through their bodies. The response of anodes and cathodes is referred to as "half-cell reaction" in general. In a simple corrosion cell, there are five essential components (Nossoni, 2010)

**Anode:**The anode corrodes when electrons are lost and the metal dissolves. The anodic reaction is influenced by the pH of the concrete's pore solution, the presence of aggressive ions, and the surface potential (Nossoni, 2010). Fe = Fe2+ + 2e-; E0 = -0.440V (Standard Redox Potential) is the general anodic reaction for steel corrosion (2.1) One way to express electromotive forces is to use the standard redox potential, which is the potential generated when a metal is connected to a hydrogen electrode. The cathodic reaction must consume the electrons produced at the anode, and the exact reaction is determined by the amount of oxygen in the atmosphere and the pH of the solution. Concrete undergoes the following reduction process:

E0 = 0.401V; H2O +1/2 O2 + 2e- = 2OH- (Standard Redox Potential)

**Metallicpath:**Metallicconnectionbetweentheanodeandcathodewhichallowsthecurrenttoflow.
**Current:**The anodic process produces electrons, which flow through the metal from the anode to the cathode, and the rate of flow is traditionally measured as current. The current is proportional to the anodic and cathodic reaction rates. When one of the reactions achieves its maximum rate due to a shortage of a required species, the current will reach its limit. The open circuit potential of the corroding iron piece is connected to the Standard Redox Potentials of the above reactions, as well as the composition, temperature, and "polarizations" of these half cells. Steel serves as both an anode and a cathode in the corrosion of steel in concrete, with the pore solution serving as the electrolyte.

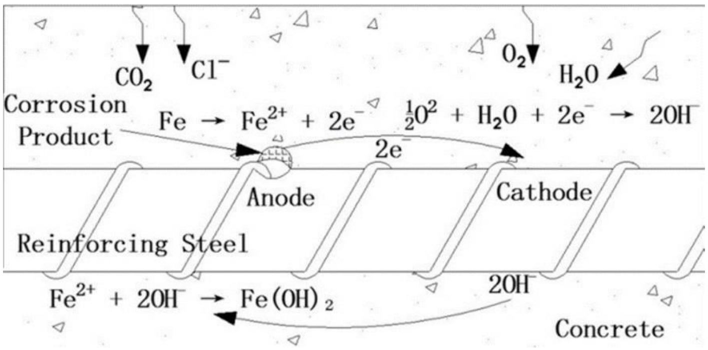

Figure 4: Corrosion process on steel bar surface (Zhao et al., 2011)

The reaction that takes place at the anode is what causes the actual mass loss due to corrosion. According to Equation 2.1, the iron atoms ionise to Fe2+ ions and are dissolved in the pore solution around the steel bar. The electrons deposit themselves on the rebar's surface, increasing its electrochemical potential. As shown in Figure 4, the electrons then move through and along the steel to a lower potential region (cathode). The cathodic reaction consumes free electrons, as stated in Equation 2.2. The flow of current in the closed loop, as shown in Figure 4, demonstrates the corrosion process' electrochemical nature. The difference in potential determines the rate of electron flow within the steel bar.

## Pourbaix Diagram

Pourbaix (1976) created a schematic for the Iron-Water system based on thermodynamic data that depicts the system's equilibrium between potential (against standard hydrogen electrode, SHE) and pH. Figure 4.1 depicts the pourbaix diagram.

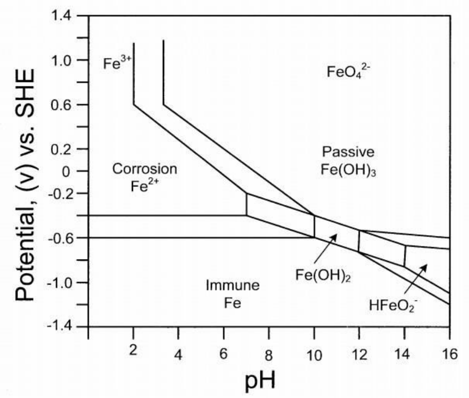

Figure4.1:Pourbaixdiagramforiron at25$^0$c(Nossoni,2010)

In the diagram, there are three regions. The first is the "immunity" region, which describes the region of stability of the base metal (Fe), where corrosion will not occur. The second is the passive region, where a stable coating of an oxide (Fe3O4) or other salt on the surface of steel, a non-protective form of corroded steel, could be expected. The third is the corrosion area, which is where general corrosion takes place. Steel naturally corrodes, but the alkaline environment of concrete (pH >12) provides both physical and chemical protection to reinforcing steels through its cover and high pH environment.

A thin oxide layer, known as passive film, forms on the steel at high pH, ranging from 10 to 100 nm (Ouglova et al., 2006). This layer prevents the steel from dissolving. This passive layer does not prevent corrosion; rather, it slows the rate of corrosion by 1000 times when compared to the passive condition (Zhang & Poursaee, 2014). When the pH falls below 10, the film breaks down. The most stable iron oxide, Fe(OH)2 (also called as 'blue rust' or 'green rust,' a rarely encountered and highly soluble type of corroded iron) is formed in the pH range of about 9.5- 13 in the corrosion area. Acidic and highly alkaline conditions produce insoluble products.

## Corrosion of Steel in Concrete

Cement, fine aggregate, and coarse aggregate make up concrete, which is a composite material. Because concrete is brittle under tension, steel reinforcement is added into the mix. Every concrete structure must be able to maintain its strength and serviceability for an extended period of time. Corrosion of reinforcing steel has become a critical process of reinforced structural deterioration. Carbonation and chloride assault are the two main causes of steel corrosion in concrete. They have no effect on the concrete's strength; instead, the aggressive ions assault the steel reinforcement.Because of the results of cement hydration, the solution in the pore spaces of the concrete is very alkaline. However, during the hydration of cement, 25-50 percent Ca(OH)2 by weight of cement is produced, resulting in a pH of at least 12.5. Calcium carbonate is formed when carbon dioxide from the atmosphere reacts with Ca(OH)2. So, because fully carbonated solution has a pH of 7.0, the high alkalinity is neutralised by the CO2.

$$H2CO3 = CO2 + H2O \quad (2.3)$$
$$CaCO3 + 2H2O = Ca(OH)2 + H2CO3$$

This process starts on the surface of the concrete and progresses to the inner zone till the whole concrete has carbonated and there is no longer any passive film in the neutralised environment. As a result, if there is a sufficient supply of H2O, local cells form and corrosion occurs.Carbonation causes the creation of a discoloured zone. The hues range from mild grey to a bright orange. The Phenolphthalein indicator can be used to detect carbonation in the field. Phenolphthalein is a crystalline material that is white or pale yellow in colour. In a % solution, the indicator is dissolved in a suitable solvent such as isopropyl alcohol (isopropanol). On a fresh concrete fracture surface, the phenolphthalein indicator solution is applied. The pH is above 8.6 if the indicator turns purple. The pH of the concrete is below 8.6, suggesting carbonation, where the solution remains colourless. The pH of a fully carbonated paste is around 8.4. A pH of 8.6 may only provide a weakly perceptible pale pink tint in practise. A sudden and dramatic change in colour to purple suggests. The chloride ions, on the other hand, have no effect on the hydration products. They get into the passive film through the pores in the concrete. So that the pH of the concrete pore solution does not vary.

$$\mathrm{Fe2+ + 2Cl- + 4H2O = FeCl2.\ 4H2O = Fe2+ + 2Cl- + 4H2O = FeCl2}\ (2.5)$$

$$\mathrm{FeCl2 + 2Cl- + 2H+ + 2H2O = Fe(OH)2 + 2Cl- + 2H+ + 2H2O = Fe(OH)2 + 2Cl- + 2H+ + 2H2O}$$

Chloride ions operate as catalysts when a portion of the passive coating on the bar surface is destroyed. The chlorides are clearly replicated based on the reactions. As a result, the chloride ions have an impact on the pace at which corrosion occurs. The concentration of hydroxide ions in the pore solution of concrete in contact with steel is usually high enough to prevent the passivation coating intact (Zhao & Jin, 2016). Depassivation happens when the concentration of chloride ions reaches a critical threshold.

Threshold ValueofChloridesCorrosion does not involve all of the chloride ions in the pore solution. Some chlorides react with cement's C3A to form calcium chloroaluminates, which are then filtered out of the solution (ACI 222R-01). The C3A and C4AF content, pH, w/c ratio, and whether the chloride ions were mixed with the mixture or pierced into the hardened concrete all influence the fraction of chlorides that participate in corrosion (ACI 222R-01).

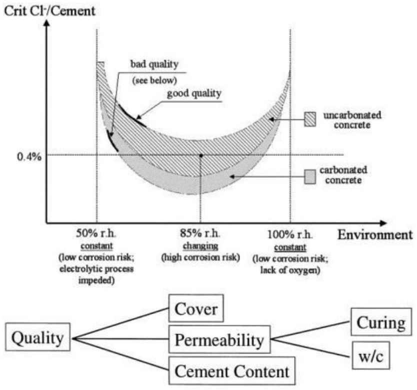

Figure5: Thecritical chloridecontent (takenfrom ACI222R)

Figure 5 indicates that when relative humidity rises, a greater chloride concentration is required to induce corrosion. With an increase in pH, the threshold value rises dramatically. The criterion was set at 0.4 % (1.4 kg/m3 of concrete) by mass of cement (CEB), whereas the US uses 0.6-0.9 kg/m3 by bulk of cement (CEB) (ACI 222R). If water and oxygen are accessible, corrosion can occur at a threshold level of % chloride by weight of cement, or up to 1.0 % or more (Broomfield, 2006). Corrosion begins when [Cl-]/[OH-] hits 0.6, as according Mindless et al., (2003). This value was 0.29 at pH = 12.6, and 0.3 at pH = 13.3, as according ACI 222R.

## V. CONCLUSIONS

The primary focus of this thesis was an experimental research and numerical analysis of the corrosion-induced pressure that causes the concrete cover crack to begin and continue to spread. The following inferences and conclusions can be made on the basis of the findings of the comprehensive study:

(a) significant amount of chloride ions is an essential component in the impressed current technique, which plays a significant role in the corrosion of steel. Experimental research was carried out in solutions that were comparable to that of the concrete pore solution in order to determine the ideal concentration of chloride. It was discovered that the real mass loss coincided with the theoretical one when there was a high percentage of chloride in the mixing water, which was 3.5 percent by mass. In order to achieve a current efficiency of one hundred percent, the chloride ions that are to be conveyed through the pore space of the concrete must first be saturated with the chlorides that are near to the steel-concrete interface. Regarding this particular point, a search and inquiry were carried out. The cubical specimens were submerged in a chloride solution containing

3.5 percent for varying amounts of time, and it was discovered that the specimens needed to be submerged for at least one day prior to the beginning of the tests in order to get saturated.

(b) For cover thicknesses of 20 mm and 37.5 mm, the principal crack began at the surface of the cover as a result of surface heaving and then propagated towards the steel concrete interface. For cover thicknesses of 50 and 75 millimetres, the primary crack began at the steel concrete contact and moved towards the surface of the cover as it spread. There was not a discernible difference in the critical amount of corrosion between the cover thicknesses of 20 and 37.5 millimetres. The critical amount of corrosion increased dramatically from 22 mg/cm2 to 129 mg/cm2 when the cover grew from 37.5 mm to 50 mm. When the cover was increased to 75 millimetres, the quantity of corrosion that was necessary to start cracking was 211 mg/cm2. In light of these findings, it has been determined that the best way to increase the service life of reinforced concrete structures that are located in maritime environments is to offer a clear cover that is at least 50 millimetres thick. Finding a linear association between crack width and level of corrosion, as was done, may make it possible to more accurately anticipate the level of corrosion in structures that are already in existence.

(c) The experimental modelling of the critical pressure for cover cracking revealed that the critical pressure was highly dependent on the cover thickness, grade of concrete, and location of the bar. This was discovered as a result of the fact that the critical pressure was investigated. The cracking pressure is proportional to the cover thickness and increases with increasing cover thickness. When a better grade of concrete was utilised, it was discovered that a higher pressure was required to get the desired results. On the other hand, a lesser pressure was required to shatter the corner bars in comparison to the pressure required to crack the side bars.

(d) A computational model was created in order to make predictions regarding the pressure and radial expansion that were caused as a result of corrosion products. The model was able to accurately forecast the patterns of cracks that would be caused by uniform corrosion. Cover thickness, the grade of concrete, the placement of the bar, and the diameter of the bar were found to have an effect on the critical pressure as well as the radial expansion that was generated due to expansive corrosion products. As the cover thickness got thicker, the required amount of pressure and radial expansion to start a crack got even higher. On the other hand, a decrease in critical pressure was seen in conjunction with an increase in the diameter of the bar.

(e) It was discovered that the zinc sacrificial anode provided only partial protection to the corroding reinforcement rather than complete protection. This conclusion was discovered in two different environments: i) in a solution that was analogous to the pore solution in concrete, and ii) in concrete itself. Instead of the complete current flowing via the sacrificial anode, the total current that was supplied through the circuit was divided up and flowed through the rebar and the sacrificial anode.

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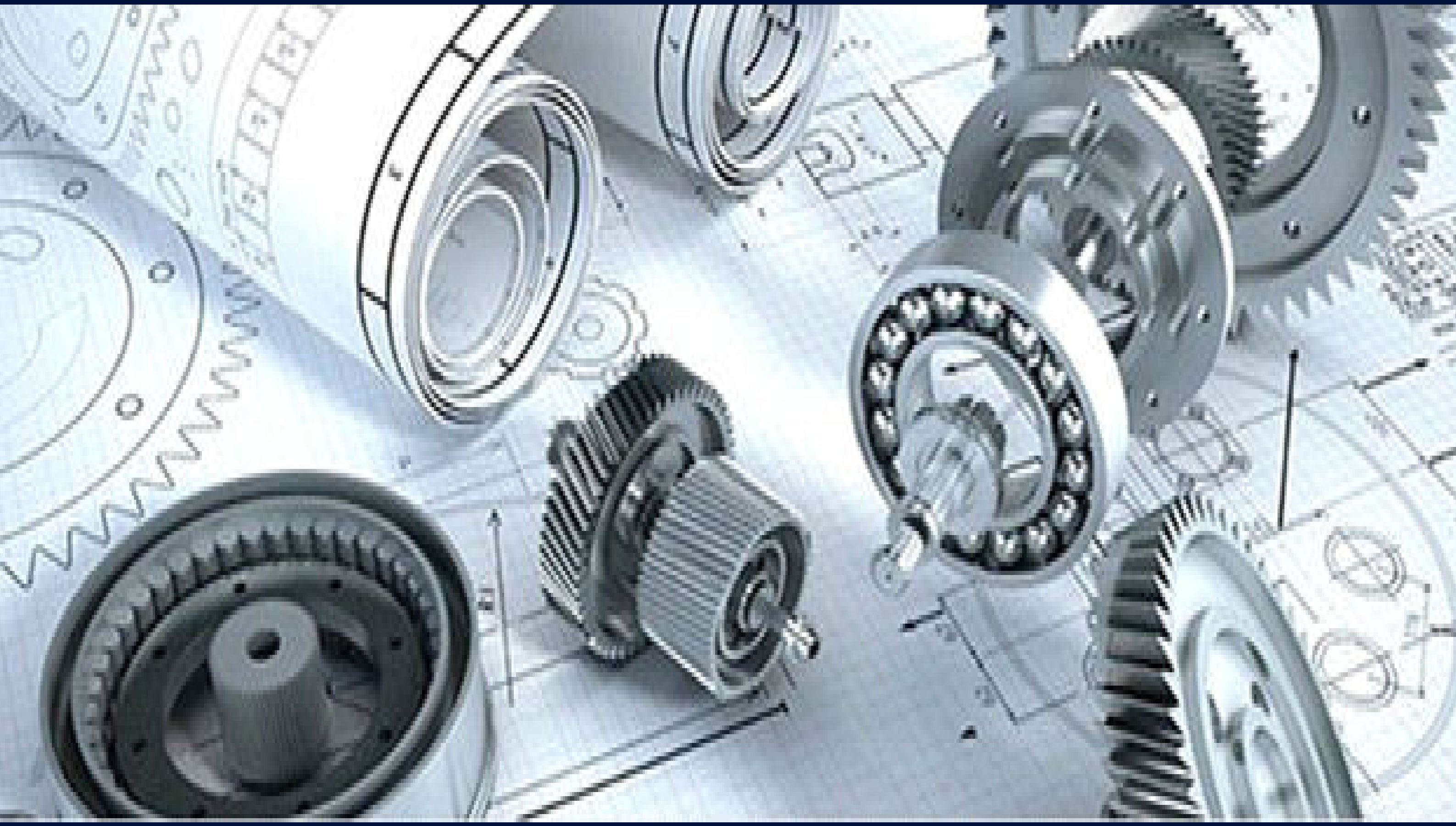

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