"A STUDY ON CORROSION OF REINFORCEMENT IN CONCRETE AND EFFECT OF INHIBITOR ON SERVICE LIFE OF REINFORCED CEMENT CONCRETE"

A

PROJECT REPORT

Submitted in partial fulfilment of the requirements for the award of the degree

of

BACHELOR OF TECHNOLOGY
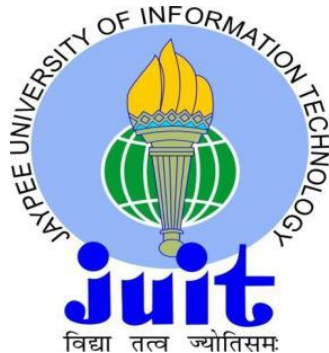
IN

CIVIL ENGINEERING

Under the supervision

of

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by

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to

JAYPEE UNIVERSITY OF INFORMATION TECHNOLOGY

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HIMACHAL PRADESH INDIA

JUNE, 2020

DECLARATION

I hereby declare that the work presented in the Project report entitled **"A STUDY ON CORROSION OF REINFORCEMENT IN CONCRETE AND EFFECT OF INHIBITOR ON SERVICE LIFE OF REINFORCEMENT CEMENT CONCRETE"** submitted for partial fulfilment of the requirements for the degree of Bachelor of Technology in Civil Engineering at **Jaypee University of Information Technology, Waknaghat** is an authentic record of my work carried out under the supervision of **Dr. Saurav.** This work has not been submitted elsewhere for the reward of any other degree/diploma. I am fully responsible for the contents of my project report.

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CERTIFICATE

This is to certify that the work which is being presented in the project report titled **"A STUDY ON CORROSION OF REINFORCEMENT IN CONCRETE AND EFFECT OF INHIBITOR ON SERVICE LIFE OF REINFORCEMENT CEMENT CONCRETE"** in partial fulfilment of the requirements for the award of the degree of Bachelor of Technology in Civil Engineering submitted to the Department of Civil Engineering, **Jaypee University of Information Technology, Waknaghat** is an authentic record of work carried out by **Sonam Tshomo (161631) and Pema Yangden (161694)** during a period from July 2019 to November, 2019 under the supervision of **Dr. Saurav** (Assistant professor), Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

The above statement made is correct to the best of our knowledge.

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ABSTRACT

Reinforced concrete is one of the most widely used construction material in infrastructure development. To increase the tensile stress, reinforcing bar is embedded in concrete structure. These reinforcing bars embedded in concrete structure get corroded due to chlorination and carbonation affecting its service life which leads to increase in maintenance and repair cost of the structure. For this reason, various methods have been developed to prevent the corrosion and to increase the service life of the structure. From various method developed, corrosion inhibitor is found to be the most efficient and appropriate method for corrosion protection of reinforced concrete structures due to low cost, excellent corrosion resistant effect and easy operation. The study shows, the effect of corrosion inhibitors with respect to different diameters of steel bars embedded in concrete beam. An experimental work is carried out using a mixed corrosion inhibitor Zinc Oxide and Sodium Nitrite with different diameter 8 mm and 16 mm of steel bar embedded in concrete. Current is impressed on reinforced bar in concrete to increase the rate of corrosion. The significance of Zinc Oxide and Sodium Nitrite which are used as a corrosion inhibitor of steel bar embedded in concrete and immersed in 3% Sodium Chloride solution was investigated. The comparisons are made between the result obtained from the concrete beam casted with and without the use of corrosion inhibitors.

Key words: Reinforced concrete, Corrosion, Service life, Corrosion inhibitor.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Corrosion of concrete steel reinforcement is one of the main causes of early failure of reinforced concrete structure throughout the world. The corroded reinforcing bar severely affects the durability of reinforced concrete and the service life is shortened adversely. Corrosion of the reinforcement takes place when exposed to environment where engrossment of chloride and carbon dioxide or hydrogen sulfide is a common occurrence.

In order to improve the service life of reinforced concrete structure which are susceptible to such environment, certain method such as epoxy-coated reinforced steel, cathodic protection, corrosion inhibitor has been developed, among which the use of corrosion inhibitor is the better-known technological advancement for corrosion protection of reinforced concrete structure. Corrosion inhibitor is defined as "a chemical compound, which, when added in adequate amounts to concrete, can prevent corrosion embedded steel and has no adverse effect on properties of concrete" [1]. Corrosion inhibitors form a protective film over the face of the steel bar which helps in delaying and slowing down of the rate of corrosion in reinforced concrete.

1.2 CORROSION OF STEEL IN REINFORCED CONCRETE

1.2.1 Mechanism of corrosion

Corrosion is the gradual destruction of metal by electrochemical reaction with environment. As shown in figure 1.1 in electrochemical theory of corrosion some part of it will act as anode and some part as cathode. In the anodic area the metal will oxidize and will generate some electrons. These electrons will flow toward cathode and will be used for three reactions that is electroplating, liberation of hydrogen and absorption of oxygen. As the electron is being consumed the process will continue and the flow of electron will generate some potential on the metal surface. Because of this flow of electron, the metal will get corroded.
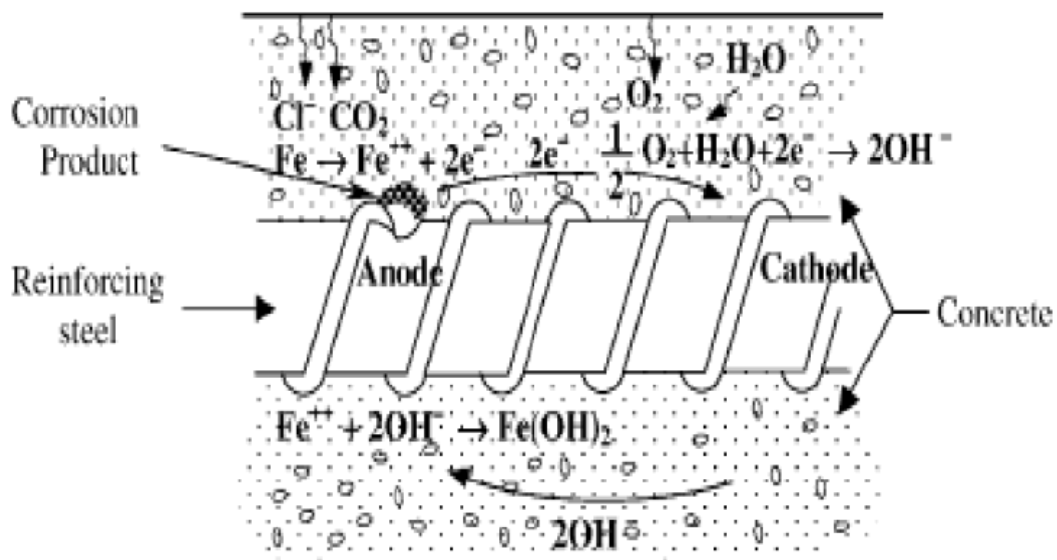
Figure 1.1: Electrochemical process of corrosion (Source: Quraishi, M et al [2])

The following reactions occur at anode and cathode as shown in equation 1.1-1.3 [2]

Anode:

$Fe \rightarrow Fe^{2+} + 2e-$ (Metallic iron) .... Eq. 1.1

$FeO.(H_2O)_x$ (Rust) .... Eq. 1.2

Cathode:

$\frac{1}{2}O_2 + H_2O + 2e- \rightarrow 2OH-$ .... Eq. 1.3
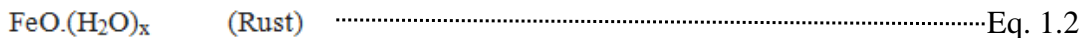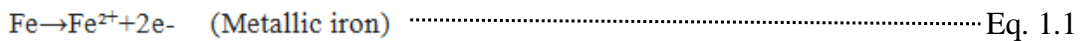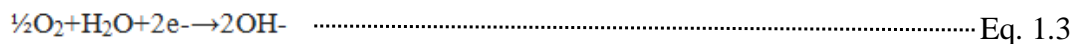
1.2.2 Factors affecting reinforcement corrosion

i. Entry of gaseous pollutants and carbonation

The drop in pH of the concrete to certain level may cause:

- The corrosion of reinforcement,
- Destruction of passive layer and
- Catastrophic corrosion

This pH is reduced mainly due to the ingress of sodium dioxide and nitrogen dioxide (acidic gaseous pollutant). Carbonation which are caused due to the reaction of carbon dioxide with calcium also result in the fall of pH.

Onset of steel corrosion occur when the pH of concrete falls below 9.5. Similarly, the passive film on the surface of the steel starts to disappear when the pH of the concrete is 8 and catastrophic corrosion begins below pH 7. [3]

ii. Bacterial action

Differential aeration cell which are formed due to aerobic bacteria and causes corrosion of steel. [3]. The iron sulphides produced by anaerobic bacteria in sewer concrete enables the corrosion to carry on even without the presence of oxygen. These bacteria cause the degradation of the cementitious material and reduce the cover.

iii. Water cement ratio

Water cement ratio does not affect the rate of corrosion but the parameters such as durability, permeability and strength of concrete which depends upon water cement ratio affects the rate of corrosion [5].

iv. Cover thickness of reinforcement concrete

Cover thickness of concrete play an essential role in protecting the rebar from corrosion due to penetration of chloride and carbonation. Studies observed that the cover depth provided is directly proportional to the time taken for penetration of the chemicals.

v. Humidity

Water (specially oxygenated water) increases the rate of corrosion. The transfers of electrons between cathodic and anodic portion of the metal which are facilitated by an electrolyte solution are compromised by water and its dissolved solutes.

vi. Temperature

The rate of corrosion depends upon the temperature since it affects the transportation rate and electrochemical processes of corrosion of steel in concrete. Higher the temperature, higher will be the reaction rate of all these processes leading to increase rate of corrosion.

The molecules and other element cannot move at a very low temperature, below freezing point hence, corrosion of reinforcement does not occur or stops even when active previously. It is found that at temperatures above 55°C chloride content contaminated the pore solution. This

was due to the higher temperature that caused the release of originally bind chloride ions into pore solution [4].

1.2.3   Effects of corrosion on reinforced concrete structure

i.   Reduces bond strength

The capacity of reinforced concrete element depends on the characteristics of concrete-rebar interface. Due to the corrosion of the steel the rust is formed with a volume of 3 to 6 times greater than that of the steel and causes internal stresses leading to cracking and spalling of the concrete surrounding the reinforcement. This process leads to poor bond with adjoining concrete and reduces the strength of the section.

ii.   Loss of strength

Corrosion causes the gradual destruction of rebar resulting in reduction of the effective cross section of structural components. This causes the reduction of axial strength and flexural strength of the structure making them structurally weak. Loss of strength can occur both in concrete as well as steel structure.

iii.   Reduces Ductility

Corrosion greatly affects the ductility of reinforced concrete section and is critical in earthquake design and its evaluation. Part of the structure which are corroded have low ductility affecting the seismic response due to limited plastic deformation.

iv.   Reduces shear capacity

Corrosion reduces the cross-sectional area of reinforcement in columns and beams hence, reducing the shear capacity of the section. The reduction of shear strength of the concrete slab increases the chances of two-way shear failure.

1.3 CORROSION INHIBITOR

1.3.1   General

Corrosion inhibitor has been defined as "a chemical compound, which, when added in adequate amounts to concrete, can prevent corrosion embedded steel and has no adverse effect on properties of concrete" [1]. Corrosion inhibitors are usually mixed with the concrete to slow and delay the onset of corrosion in reinforced concrete. Inhibitors can be either directly added to the concrete as admixture for new construction works or can be applied on the surface of the

concrete for repair works. Inhibitors protect the reinforced concrete structure from corrosion by creating a protective film over the steel surface and reduces the permeability of the concrete.

Inhibitors slow down the corrosion process by [5]:

- Polarization behavior of the anodic or cathodic are increased;
- Reducing the movement of ions of the metallic surface;
- Increasing the resistance of the metallic surface.
- The way of application; either mixed with concrete or applied on hardened concrete (migrating inhibitors).

1.3.2   Classification of corrosion inhibitors

The detailed classification is as shown in figure 1.2.
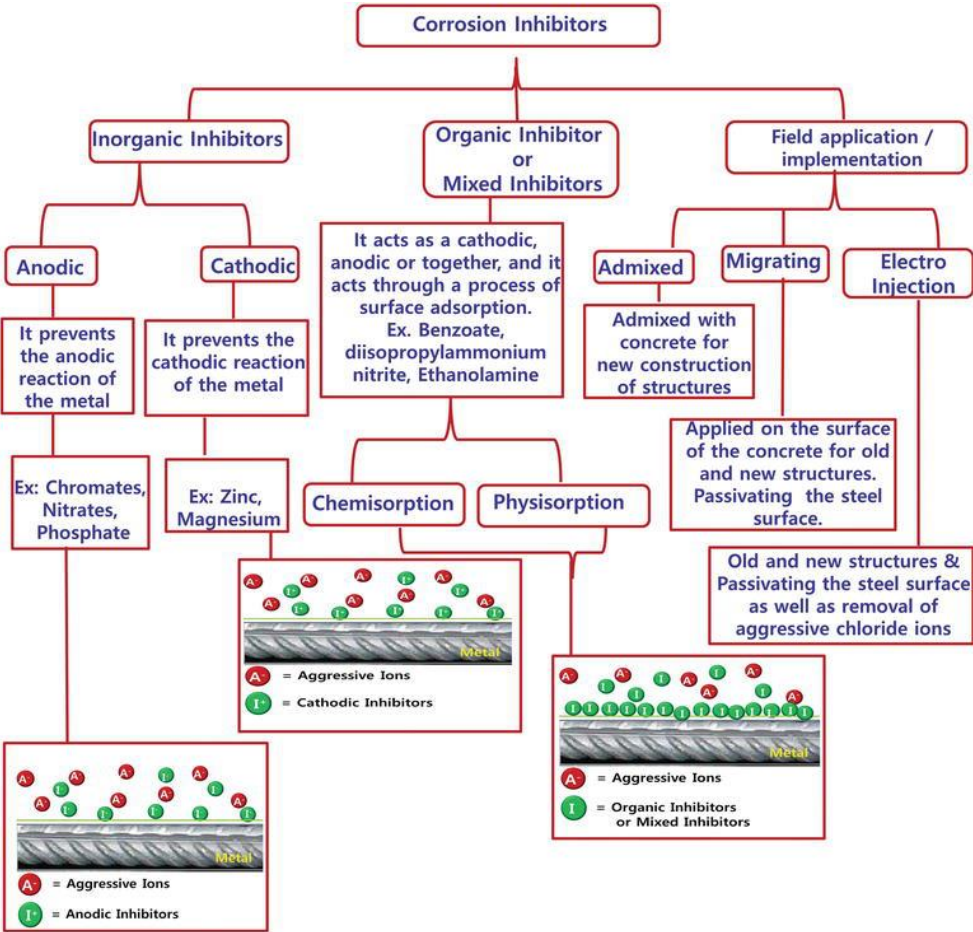
Figure 1.2: Classifications of corrosion inhibitors (Source: Lee, H et al [5])

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1.3.3   Benefits

- Corrosion inhibitors expand the structural life of concrete.
- Inhibitors ensure corrosion protection even when the harmful substances are already present.
- It reduces the maintenance or repair cost due to corrosion damage.

1.4 ELECTROCHEMICAL TECHNIQUES USEED

1.4.1   Linear polarization resistance

Linear polarization resistance (LPR) methods are also used by scanning the current the current potential-potential (i-E) to characteristic the medium pair of materials. The linear polarization resistance approach consists of adding very small changes in voltage (less than 30 mV) above and below their potential for corrosion to the metal. The current response obtained is linear over the narrow spectrum in the vicinity of the corrosion potential. Therefore, the polarization resistance (R_p), characterized as the slope of this current –potential curve, is constant. According to the Stern –Geary equation, the polarization resistance is inversely proportional to the instantaneous corrosion rate, under some conditions [27].

1.4.2   Half-cell potential test

Half-cell potential test is used to measure the corrosion of reinforced concrete structures where, it gives the probability of corrosion rather than indicating the rate of corrosion. The exposed reinforcement is attached to the positive terminal of the probe and the electrode of known reference is connected to the negative terminal (figure 1.3). This reference electrode is placed at several defined points where readings are taken at each interval as the electrode placed on concrete closes the circuit and the voltmeter measure the electrical potential difference between the electrode and the reinforcement nearest to that point.
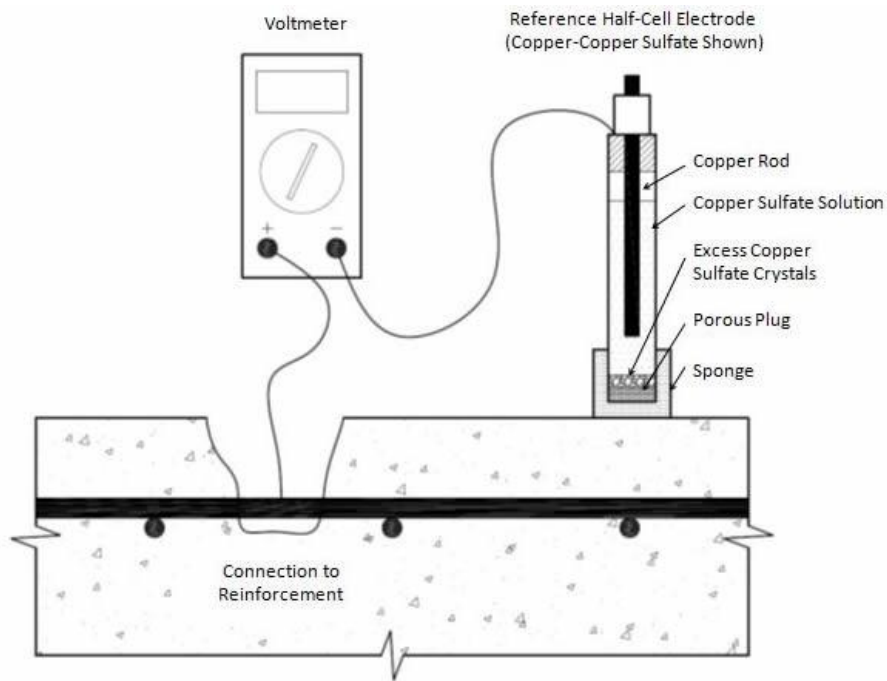
Figure 1.3: Half-cell potential test setup (Source: Giatec Scientific Inc [14])

As per ATSM (Advanced Training Skills Modules) standard C876- 91 1999 the chances of occurrence of corrosion is given in the Table 1.1.

Table 1.1 Probability of corrosion as per ATSM standard (Source: Unitedscanning.com.au [15])

Value (mV)	< -500mV	< -350mV	-350mV to -200mV	> -200mV
Interpretation	Severe corrosion	Corrosion likely	Uncertain	Corrosion unlikely
Chance of corrosion	>90%	>90%	>10% and <90%	<10%

1.4.3 Rapid chloride ion penetration test (RCPT)

Rapid Chloride ion Penetration Test is a method for evaluation of concrete's ability to resist penetration of chloride ions. This method consists of observing the amount of charge passed through the specimen over a certain period of time. This charge passed shows the permeability of the concrete i.e. higher the charge passed, higher will be the permeability [28].

1.4.4 Cyclic potentiodynamic polarization test (CPPT)

Cyclic potentiodynamic polarization test is commonly used to determine localized corrosion resistance or corrosion rate in a very short time. This technique is thus applicable as a method for predicting localized corrosion, as well as valuable for alloys which are spontaneously passivated and experienced localized corrosion. After moving through the area of active corrosion, the current density decreases to a critical potential called "flade potential" or "primary passivation potential". This decrease is due to the development of metal surface or passivated layer [29].

1.4.5 Weight loss method

Weight loss method is a simple method for measuring the rate of corrosion over a longer period of time. Weight loss methods are much slower as compared to electrochemical process. However, no specialized equipment and knowledge are required making it easy to understand. Multiple sample can be tested at the same time with no specialized equipment other than an accurate balance for measuring the weight. The test is carried out by measuring the weight of the rebar (which is taken as initial weight) embedded in the specimen and then placing these specimens with and without inhibitor in 3% NaCl and accelerating the rate of corrosion using impressed current method over a certain period of time. After corrosion are generated over a certain period of time, the steel embedded in the specimen are then removed and its weight are measured (finial weight). Comparing the weight (initial and final weight) of the steel embedded in the specimen, the gravimetric loss is determined which helps in finding the rate of corrosion [30].

1.4.6 Open circuit potential (OPC) measurement

An open circuit potential measurement also called as equilibrium potential or the rest potential is the method where no current flows through the cell. OPC measurement is done using a voltmeter connected to a reference electrode and the positive terminal to the rebar. The average of OPC measured at different location near the rebar is noted and a time versus potential plot is drawn [31].

1.5 IMPRESSED CURRENT METHOD

The impressed current method is used for creating an accelerated corrosion to the steel embedded in the concrete by constant supply of current from the power supply. Then the specimen which is immersed in the 3% NaCl solution is taken. The steel which will act as anode

is connected to the positive terminal of the power supply and the counter electrode which act as a cathode is connected to the negative terminal. The current will start to flow from counter electrode to the steel embedded in the concrete with the help of sodium chloride (NaCl) solution which will act as an electrolyte as shown in figure 1.4.
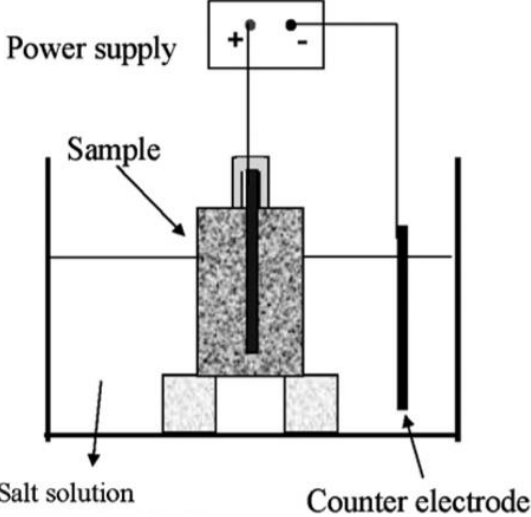
Figure 1.4: Experimental set up of impressed current method (Source: Ahmad, S [13])

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

This chapter includes the critical analysis of various articles, books and journals about the corrosion of reinforcement. Different literature has been evaluated, which helped us in understanding different methods and techniques used in detection and protection against corrosion. It also helped us in identifying research gaps and summery of few literatures has been provided below.

James et al [6]- This study examines the process of corrosion undertaken in concrete in coastal regions. It also explains how chlorination and carbonation enters in reinforced concrete structure and its effect on the service life of the structure. In order to find out the chloride ion induced corrosion, test such as corrosion potential, chloride ion permeability, chloride concentration, chloride penetration and concrete resistivity were performed. Similarly, for the determination of carbonation, carbonation depth, carbonation induced corrosion potential and carbonation induced mass loss measurement test are performed. The test and methods for maintenance, repair and protection against induction of corrosion in reinforced concrete structure are explained.

Lopez-Calvo et al [7]- This paper investigated the effect on corrosion of steel in high performance concrete due to crack width, cover depth and concrete quality. The test was performed using disodium tetrapropenyl succinate and calcium nitrite in combination with 20% fly ash in concrete specimen with 25mm and 45mm reinforcement cover. It was found that the presences of cracks increase the corrosion rate with either 25mm and 45mm concrete cover and depends greatly
on the crack thickness. Only after one year of exposure, majority of the concrete specimen with 25mm concrete cover showed more corrosion activity as compared to that of 45mm concrete cover. The use of inhibitors was found to be effective in reducing corrosion rate in both cracked and uncracked concrete with no regard to the crack width and reinforcement cover.

Elsener, Angst [8]- This paper presents the main corrosion mechanisms of steel in concrete, focusing on chloride induced corrosion and emphasises on field studies with corrosion inhibitors. From both laboratory and field studies shows that sufficient dosage of addition of

corrosion inhibitors can highly delay the rate of corrosion caused due to induction of chloride. The water-cement ratio, curing, supplementary cementitious materials and execution have more impact on corrosion performance.

Loto et al [9]- The study was carried for determining the effect of zinc oxide as a corrosion inhibitor on mild steel using potential measurement, pH and gravimetric methods (figure 2.1). The experiment was carried out by taking 200 gram of zinc oxide in four different concentration of 25, 50, 75 and 100 zinc oxide solution, out of which 75 and 100% concentration performed comparatively better. The studies also found out that the use of zinc oxide within the percentage concentrations has no effect on the compressive strength of concrete.
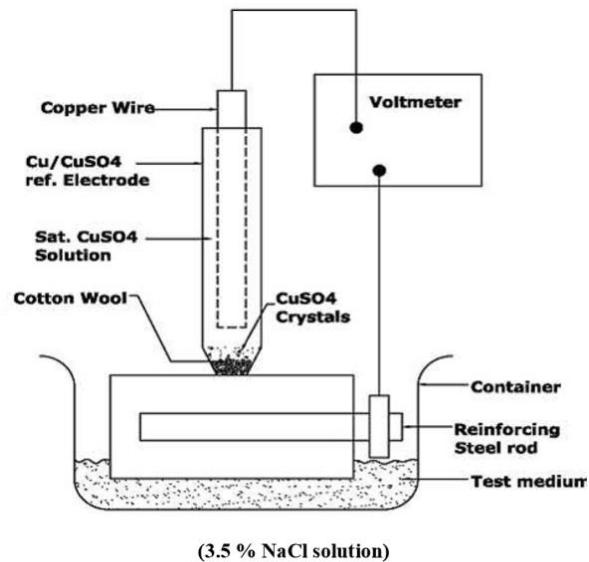
Figure 2.1: Schematic representation for potential and pH measurements [9]

Choi et al [10]- This study examined and compared the bond property of corroded rebar at each corrosion stage due to different corroding methods. It was found that, for the high strength concrete corrosion has more significant in reduction of bond load. It was found that high level of corrosion (when exceeded 2%), more cracks were observed in concrete which causes great reduction in the bond strength. The concrete properties and concentration of chlorides present in the concrete was not adversely affected by the use of   polarization resistance technique hence, this technique was found more effective in assessing the corrosion levels.

Kumar et al [3]-This study explains various aspect of reinforced concrete structure affected by corrosion, predicting its service life and the role of corrosion inhibitors on its service life. The rate of corrosion is dependent on carbonation and entry of gaseous pollutants, presence of aggressive anions which may be present as acid soluble chloride, permeability which is a function of water-cement ratio and cover over reinforcing steel. This study was carried out using calcium palmitate and calcium nitrite as a corrosion inhibitor which shows that the compressive strength of concrete was reduced by 41% with the use of 3% calcium palmitate but the service life of reinforced concrete structure was increased almost ten times. Figure 2.2 shows the different stages of corrosion of rebar which is dependent on time period.
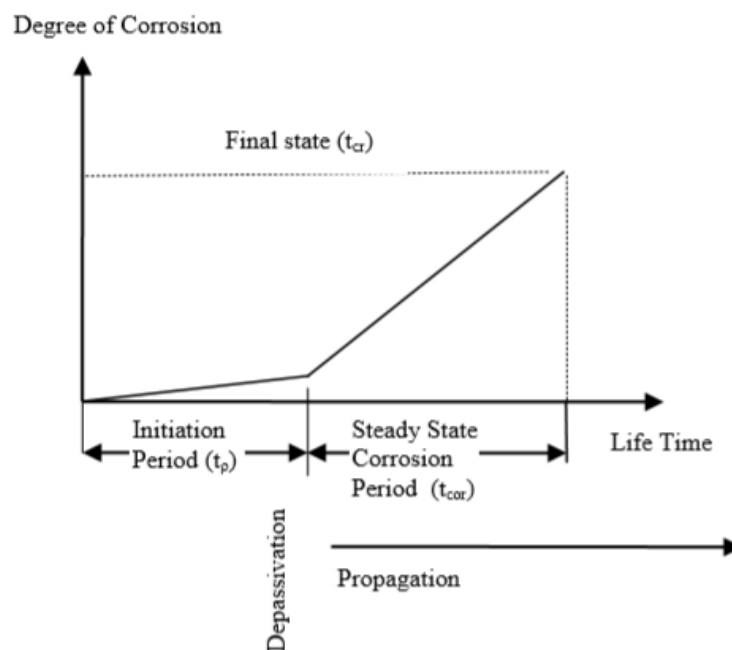
Figure 2.2: The stages showing the corrosion of rebar [3]

Ormellese et al [11]- The research was carried out for the duration of seven-years for finding out a new organic inhibitor to prevent chloride-induced corrosion. The paper mainly focuses on the efficiency of nine selected compounds such as dimethylethanolamine, triethylenetetramine, aspartate, asparagine, glutamate, glutamine, tartrate, benzoate and ethylenediaminetetraacetate. In solution test, the inhibitor containing carboxylic group were found more effective. In the presence of dimethylethanolamine, triethylenetetramine and glutamine the critical chlorides threshold value is increased by about 50% with respect to reference condition.

Devi, Kannan [25]- The test was performed with the use of quarry dust as a fine aggregate along with zinc oxide and sodium nitrite as a corrosion inhibitor. The effectiveness of corrosion inhibitor on concrete was analysed using weight loss measurement, impressed voltage method, AC impedance measurement and rapid iron chloride penetration test (RCPT). After performing various test such as split tensile, compressive strength test, water absorption and permeability test, 2 % dosage of inhibitors was found to be more successful in resisting the corrosion. Use of 2 % inhibitor show increase in strength while lowering the water absorption and permeability as shown in figure 2.3 and 2.4.
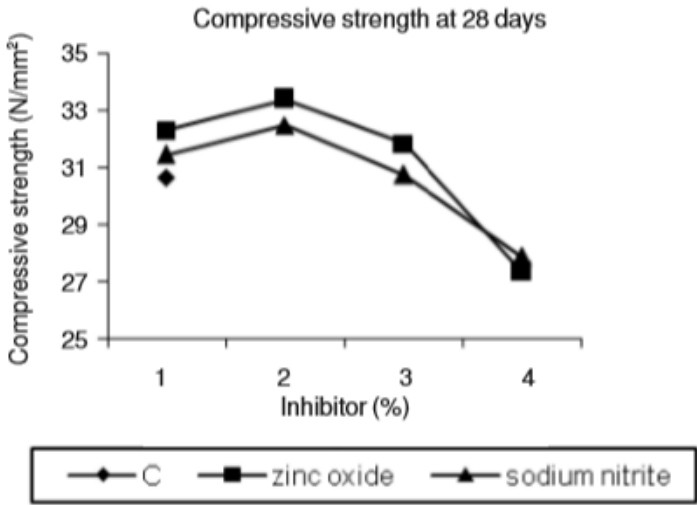
Figure 2.3 Development of compressive strength [25]
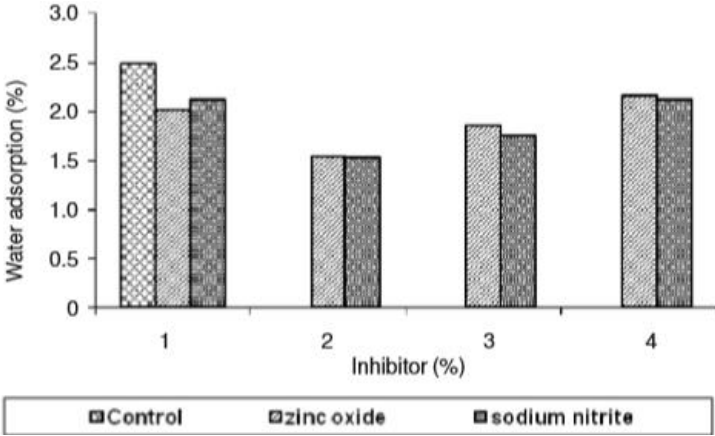
Figure 2.4 Water absorption [25]

2.2 RESEARCH GAPS

- From the literature most of the experiments were performed using either organic or inorganic inhibitors.
- Low strength concrete such as M15, M20 grade concrete is used for the experiment.
- Limited literatures are available which provide the use of admixture corrosion inhibitor (ACI).

2.3 RESEARCH OBJECTIVES

- To quantify the damage caused by corrosion of steel bar having variable diameters embedded in a concrete beam.
- Study the effect of corrosion inhibitor in steel bar of variable diameter embedded in concrete and damage quantification.
- Comparison between corroded rebars with inhibitor and without inhibitor.

CHAPTER 3

EXPERIMENTAL STUDIES

3.1 GENERAL

In order to find out the property of material that are being used in the experiment; various test was performed. The values that are obtained from the test are used for mix design of M40, M50 and M60 grade concrete. It also helped in knowing whether the specific material or treatment is suitable for a particular application.

3.2 MATERIALS USED

- Cement (Ordinary Portland cement 43 grade)
- Sand
- Coarse aggregate (angular, 20mm)
- Steel reinforcement (8mm and 16mm) of grade Fe500
- Curing tank
- Sodium chloride (NaCl) solution
- Super plasticizer (third generation super plasticizer)
- Mixed corrosion inhibitor (Zinc oxide and Sodium nitrite)
- Power supply
- Multimeter
- Connection wires

3.3 TESTING OF MATERIALS

3.3.1 Cement

i. Normal consistency (IS: 4031 (Part 4)- 1988) [18]

Normal consistency of cement is done to find the quantity of water needed to produce a cement paste of normal consistency. Standard consistency is a consistency which permits the Vicat plunger of 10 mm diameter to penetrate up to a depth of 5mm - 6mm above the bottom of the Vicat's mould with top diameter of 70mm, bottom diameter of 80mm and height of 40mm (figure 3.1).

Type of cement used: Ordinary Portland Cement

Room temperature: 22ºC

Table 3.1 Normal consistency of OPC

Trial No.	Weight of cement (gram)	Percentage by water of dry cement (%)	Amount of water added (ml)	Penetration (mm)
1	400	30	120	9
2	400	32	128	7.5
3	400	34	136	5.5

The normal consistency for OPC 43 grade is 34% as depicted in table 3.1.

Figure 3.1 Determination of normal consistency of cement using Vicat apparatus

ii.   Initial setting time (IS: 4031 (part 4)- 1988) [19]

Initial setting time of a concrete is the time at which needle of 1mm sq. (figure 3.2) section fails to penetrate to the depth of 33-35 mm into the mould from top.

After performing the test initial setting time is found out to be 90 minutes.
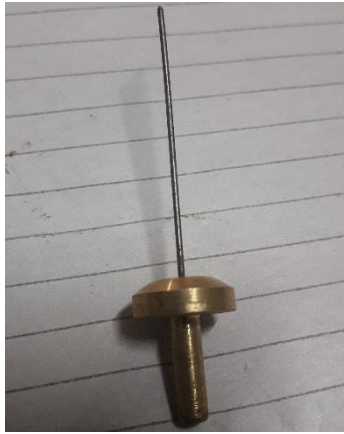
Figure 3.2 Needle for finding initial setting time

iii.   Final setting time (IS: 4031 (part 5)- 1988) [19]

Final setting time of concrete is the time period between addition of water to cement till the time at which 1mm needle makes an impression on the surface of the test block while 5mm needle (figure 3.3) fails to do so.

After performing the test, the final setting time of OPC 43 grade was found out to be 310 minutes.

Figure 3.3 Needle with annual attachment

iv.   Specific gravity of cement

Specific gravity of cement is defined as the ratio between the volume of the cement to the same volume of water provided that the temperature remains constant. As per Portland Cement Association (PCA) 1988, the Portland cement have a specific gravity of around 3.15. The specific gravity test of OPC was performed using Le Chatelier's flask (figure 3.4) and it came out to be 3.12.

Figure 3.4 Determination of specific gravity of cement using Le Chatelier's flask

3.3.2 Sand

i. Sieve analysis

The test was done to determine the grading of given fine aggregate. Fine aggregate is graded into four different zones on the basis of particle size, as shown in table 3.2 and table 3.3. The test was done using 1000 gram of sand which is sieved through sieves arranged in chronological order as shown in figure 3.5 for 3 to 5 minutes and the zone of sand is determined using equation 3.1.

Table 3.2: Fine aggregates (As per IS: 383- 2016) [20]

IS Sieve	Percentage passing by weight			
	Grading Zone I	**Grading Zone II**	**Grading Zone III**	**Grading Zone IV**
10 mm	100	100	100	100
4.45 mm	90 - 100	90 - 100	90 - 100	95 - 100
2.36 mm	60 - 95	75 - 100	85 - 100	95 - 100
1.18 mm	30 - 70	55 - 90	75 - 100	90 - 100
0.60 mm	15 - 34	35 - 59	60 - 79	80 - 100
0.30 mm	5 - 20	8 - 30	12 - 40	15 - 50
0.15 mm	0 - 10	0 - 10	0 - 10	0 - 15

Table 3.3: Observation table of fine aggregate

IS Sieve Size	Weight of fine aggregate retained (gm)	Cumulative weight retained (gm)	Cumulative % retained	Cumulative % passing
10mm	0.0	0.0	0.0	100
4.75mm	20.18	20.18	2.018	97.98
2.36mm	43.45	63.63	6.363	93.64
1.18mm	44.85	108.48	10.848	89.15
600micron	498.75	607.23	60.723	39.28
300micron	279.85	887.08	88.708	11.23
150micron	54.65	941.73	94.173	5.83
Pan	58.30	1000	100	0.0
Total			**260.833**	

Fineness modulus= (Σ cumulative % retained)/100 ⸻⸻⸻⸻⸻⸻⸻⸻ Eq 3.1

$$= 260.833/100$$

$$= 2.61 \text{ (Zone II)}$$

From the test, it was found that the given sample falls under zone II with a fineness modulus of 2.61.

Figure 3.5 Sieves arranged in chronological order

ii. **Specific gravity**

The specific gravity of fine aggregate is defined as the ratio of density of sand to the density of water at 4ºC. The test was performed in the laboratory by placing 500g of sand in the pycnometer (figure 3.6). Specific gravity is an important property which helps in determining the quality and strength of the material.

Figure 3.6 Determination of specific gravity of sand using pycnometer

3.3.3   Coarse aggregate

i.   Water adsorption test (IS: 2386 (part 3)- 1963) [21]

As shown in figure 3.7 water adsorption test is performed to find the water holding capacity of coarse aggregate. The test is performed by taking 2000g of aggregate sample placed in a wire basket and submerged in distilled water for a duration of 24 hours. The specimen is then removed from the water and allowed to dry for a few minutes and surface dried with a dry cloth. The sample is then weighed. The sample is then placed in the oven for 24 hours and weighed. Equation 3.2 is used to find the water adsorption of given sample. The water adsorption of aggregate ranges from 0.1 to 2.0%.

Observation:

Weight of saturated aggregate suspended in water with the basket (W_1)	0.865 kg
Weight of basket suspended in water (W_2)	0.48 kg
Weight of saturated aggregate in water (W_1-W_2= Ws)	0.385 kg
Weight of saturated surface dry aggregate in air (W_3)	0.617 kg
Weight of oven dry aggregate in air (W_4)	0.609 kg

Weight of water equal to the volume of the aggregate (W_3-W_S)　　　　0.232 kg

Figure 3.7 water absorption test by density bucket

Water adsorption = [(W_3-W_4)/ W_4] x 100　⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯ Eq 3.2

$\qquad$ = [(0.617-0.609) / 0.609]x 100

$\qquad$ = 1.31 %

ii.　Specific gravity (IS: 2386 (part 3)- 1963) [21]

specific gravity (SG) can be defined as the ratio of the weight of aggregate in air to the weight of equal volume of water displaced by saturated surface dry aggregate. The test results of water adsorption test can be used to find the SG of aggregate. The SG of aggregate ranges from 2.5 to 3.

Using equation 3.3 specific gravity of coarse aggregate as 2.65.

Specific gravity = W_4/[W_3–(W_1–W_2)]　⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯⋯ Eq 3.3

$\qquad$ = 609/ (617-385)

$$= 2.65$$

3.3.4   Workability of concrete by slump cone test

Workability of concrete is easiness with which it can be mixed, placed, compacted and finished. A concrete is said to be workable if no difficulty is faced during laying of concrete, mixing and during finishing. The following table 3.4 shows the relation between degree of workability and slump value.

Table 3.4: Relationship between degree of workability and slump value [7].

Degree of workability	Very low	Low	Medium	High
Slump value (mm)	0-25	25-50	50-100	100-175

The workability for M40 concrete is 170 mm as depicted in figure 3.8.

Figure 3.8 Determination of workability by slump cone test

3.3.5　Compressive strength

Compressive strength is the resistance offered by the concrete towards compression. It shows how much a concrete structure can carry a compressive load safely.

To check the compressive strength of different grades of concrete (M40, M50 and M60), three concrete cubes for each grade of dimension 150 mm X 150 mm X 150 mm were casted as depicted in figure 3.9 and cured for 7, 21 and 28 days. After curing, compressive strength of each cube were found out as shown in table 3.5, using compression testing machine (figure 3.10).

Table 3.5: Compressive strength of concrete cubes

Grade of concrete	Age in days	Compressive strength (N/mm^2)
M40	7	28
	21	40
	28	45
M50	7	43
	21	54
	28	56
M60	7	45
	21	58
	28	67

Figure 3.9: Concrete cubes of different grades

Figure 3.10: Testing of cube using compression testing machine

3.4 MIX DESIGN (IS: 10262- 2019) [24]

3.4.1 General

Concrete mix design is the method of determining the right proportions of the concrete ingredients in terms of ratio. For e.g., a concrete mix of proportions 1:1:2 denote that the ingredients of concrete i.e. cement, fine aggregate and coarse aggregate are in a ratio of 1:1:2. It is important to ensure that the concrete attains its target strength, workability, durability and other desirable properties as well as to produce the concrete at lower cost as possible. The mix is expressed either by mass or by volume and the water cement ratio is expressed in mass. The design of concrete mix is done according to IS 102602:2019. It is important to determine the physical properties of the ingredients since this will make sure the concrete gains it required properties and prevent the mix from failing. Some of the factors which affect the concrete mix design are as follow:

i. **Grade designation:** the grade of concrete to be used determines the compressive strength of the concrete which is measured in N/mm^2. For example, the concrete grade of M40 denotes characteristics compressive strength of 40 N/mm^2 and the concrete mix is designed for this target strength.

ii. **Type of cement:** cement choice depends on the usage and it is important to test before being used for mix. Type of cement influence the rate of development of strength of concrete as higher the strength of cement, lesser will be the quantity of cement used and it will be more economical since cement weighs more percentage in cost than the other ingredients.

iii. **Choice of aggregate size:** larger size aggregate increases the workability while the smaller aggregates provide larger surface area increasing the strength of concrete. The aggregates needed must be of quality size before use in mix.

iv. **Water cement ratio:** water cement ratio greatly affects the strength, workability and durability of the concrete. Higher water cement ratio leads to segregation, shrinkage and internal cracks which reduces the strength of concrete. Hence, use of lower ratio is the common way to increase the strength and super plasticizers are also added to increase the flowability.

v. **Workability:** workability of the concrete depends on the slump value and it denotes the easiness of the concrete with which it can be mixed, transferred, laid, compacted and finished without bleeding and segregation.

vi. **Durability:** high strength concrete is more durable than the low strength one. Depending on the exposure condition, concrete needs different durability. Lower water cement ratio provides more durable concrete.

Required data for concrete mix design calculation

a) Cement used- Ordinary Portland cement 43 grade

a) Maximum size of aggregate= 20 mm

b) Maximum cement content= 450 kg/m^3

c) Maximum water cement= 0.45

d) Workability= 100mm (slump)

e) Exposure condition- severe

f) Type of aggregate- crushed angular

g) Type of sand- zone II

Required test data for materials

a) Specific of cement= 3.15

b) Specific gravity of fine aggregate= 2.65

c) Specific gravity of coarse aggregate= 2.65

d) Water adsorption of coarse aggregate= 1.3%

3.4.2   Mix design calculation

A. M40 mix design

Grade designation: M40

Water cement ratio= 0.40

1) Target mean strength

$f_{ck} = f_{ck} + 1,65 \, s$

$= 40 + 1.65 \times 5$

$= 48.25 \, N/mm^2$

2) Water / cement ratio

For severe condition water cement ratio = 0.45

But we adopt water cement ratio = 0.4

0.4 < 0.45   hence ok

3) Water content

Maximum water content for 20 mm aggregate = 186 litre for 25 to 50 mm

slump range

% increase for every 25 mm slump

So, water content for 100 mm slump = 186 + 6/100

= 197 litres

4) Cement content

w/c = 0.40

cement content = 197 / 0.40

= 492.5 kg/m^3

In accordance to IS: 456-2000, clause 8.2.4.2 the maximum content of cement

should not exceed 450 kg/m^3

Therefore, we reduce the cement content to 450 kg/m^3

5) Volume of coarse aggregate and fine aggregate

As per IS: 10262, table number 3, volume of course for 20 mm size aggregate

and fine aggregate (zone II) for w/c ratio of 0.5 = 0.62

For every increase and decrease in water cement ratio by 0.05, the rate of

change is -/+ 0.01

Therefore, for water cement ratio 0.4, volume of coarse aggregate

= 0.62 + 0.01 + 0.01

= 0.64

Volume of fine aggregate = 1 – 0.64

= 0.36

6) Mix calculation

a) Volume of concrete = 1 m^3

b) Volume of cement = (450/3.15) x (1/1000)

= 0.143 m^3

c) Volume of water = (197/1) x (1/1000)

= 0.197 m^3

d) Volume of all aggregate = 1 – (0.143 + 0.197)

= 0.66 m^3

e) Mass of coarse aggregate = volume of all aggregate x volume of coarse

aggregate x specific gravity of coarse aggregate

$$= 0.66 \times 0.64 \times 2.65 \times 1000$$

$$= 1119.36 \text{ kg/m}^3$$

f) Mass of fine aggregate $= 0.66 \times 0.36 \times 2.65 \times 1000$

$$= 641.52 \text{ kg/m}^3$$

Water	Cement	Fine aggregate	Coarse aggregate
197 kg/m^3	450 kg/m^3	642 kg/m^3	1119 kg/m^3
0.40	1	1.43	2.5

B. M50

Grade designation: M50

Water cement ratio = 0.35

1) Target mean strength

$f_{ck} = f_{ck} + 1,65 \text{ s}$

$= 40 + 1.65 \times 5$

$= 48.25 \text{ N/mm}^2$

2) Water / cement ratio

For severe condition water cement ratio = 0.45

But we adopt water cement ratio = 0.35

$0.35 < 0.45$ hence ok

3) Water content

Maximum water content for 20 mm aggregate = 186 litre for 25 to 50 mm slump range

% increase for every 25 mm slump

So, water content for 100 mm slump = 186 + 6/100

$$= 197 \text{ litres}$$

As superplasticizer is proposed, we have to decrease the water content by 20 - 30%

Taking 25 %

Water content = 197 – (25/100) x 197

$$= 148 \text{ kg/m}^3$$

4) Cement content

   w/c = 0.35

   cement content = 148 / 0.35

   $\qquad$ = 422.85 kg/m^3

5) Volume of coarse aggregate and fine aggregate

   As per IS: 10262, table number 3, volume of course for 20 mm size aggregate and fine aggregate (zone II) for w/c ratio of 0.5 = 0.62

   For every increase and decrease in water cement ratio by 0.05, the rate of change is -/+ 0.01

   Therefore, for water cement ratio 0.35, volume of coarse aggregate

   $\qquad$ = 0.62 + $\quad$ 0.01 + 0.01 + 0.01

   $\qquad$ = 0.65 m^3

   Volume of fine aggregate = 1 – 0.65

   $\qquad$ = 0.35 m^3

6) Mix calculation

   a) Volume of concrete = 1 m^3

   b) Volume of cement = (423/3.15) x (1/1000)

   $\qquad$ = 0.134 m^3

   c) Volume of water = (148/1) x (1/1000)

   $\qquad$ = 0.148 m^3

   d) Volume of chemical admixture = 4.23/(1.1 x 1000)

   $\qquad$ (1 % by weight of cement) = 0.004

   e) Volume of all aggregate = 1 – (0.134 + 0.148 + 0.004)

   $\qquad$ = 0.714 m^3

   f) Mass of coarse aggregate = volume of all aggregate x volume of coarse aggregate x specific gravity of coarse aggregate

   $\qquad$ = 0.714 x 0.65 x 2.65 x 1000

   $\qquad$ = 1230 kg/m^3

   g) Mass of fine aggregate = 0.714 x 0.35 x 2.65 x 1000

   $\qquad$ = 675 kg/m^3

Water	Cement	Fine aggregate	Coarse aggregate
148 kg/m^3	423 kg/m^3	675 kg/m^3	1230 kg/m^3
0.35	1	1.6	2.9

C. M60

Grade designation: M60

Water cement ratio: 0.40

1) Target mean strength

$f_{ck} = f_{ck} + 1,65\ s$

$= 40 + 1.65 \times 5$

$= 48.25$ N/mm^2

2) Water / cement ratio

For severe condition water cement ratio $= 0.45$

But we adopt water cement ratio $= 0.4$

$0.4 < 0.45$ hence ok

3) Water content

Maximum water content for 20 mm aggregate $= 186$ litre for 25 to 50 mm

slump range

% increase for every 25 mm slump

So, water content for 100 mm slump $= 186 + 6/100$

$= 197$ litres

As superplasticizer is proposed, we have to decrease the water content by 20 - 30%

Taking 25 %

Water content $= 197 – (25/100) \times 197$

$= 148$ kg/m^3

4) Cement content

w/c $= 0.40$

cement content $= 148 / 0.40$

$= 370$ kg/m^3

5) Volume of coarse aggregate and fine aggregate

As per IS: 10262, table number 3, volume of course for 20 mm size aggregate and fine aggregate (zone II) for w/c ratio of 0.5 = 0.62

For every increase and decrease in water cement ratio by 0.05, the rate of change is -/+ 0.01

Therefore, for water cement ratio 0.4, volume of coarse aggregate

$$= 0.62 + 0.01 + 0.01$$
$$= 0.64$$

Volume of fine aggregate = 1 – 0.64

$$= 0.36$$

6) Mix calculation

   a) Volume of concrete = 1 m^3

   b) Volume of cement = (370/3.15) x (1/1000)

   $$= 0.117 \text{ m}^3$$

   c) Volume of water = (148/1) x (1/1000)

   $$= 0.148 \text{ m}^3$$

   d) Volume of chemical admixture = 3.7/ (1.1 x 1000)

   (1 % by weight of cement) = 0.003

   e) Volume of all aggregate = 1 – (0.117 + 0.148 + 0.003)

   $$= 0.732 \text{ m}^3$$

   f) Mass of coarse aggregate = volume of all aggregate x volume of coarse aggregate x specific gravity of coarse aggregate

   $$= 0.732 \text{ x } 0.64 \text{ x } 2.65 \text{ x } 1000$$
   $$= 1242 \text{ kg/m}^3$$

   g) Mass of fine aggregate =0.732 x 0.36 x 2.65 x 1000

   $$= 712 \text{ kg/m}^3$$

Water	Cement	Fine aggregate	Coarse aggregate
148 kg/m^3	370 kg/m^3	712 kg/m^3	1241 kg/m^3
0.4	1	1.9	3.4

3.5 SPECIMEN DISCREPTION

A total of 12 beams with a length of 450 mm, 100 mm thickness and 100 mm width were casted with a help of rectangular mould of size 500X100X100mm as shown in figure 3.11. These beams were casted (figure 3.12) without inhibitors and with inhibitors, out of which four beams were casted for M40, four for M50 and other four for M60 with an effective cover of 50 mm. The steel bars of 8 mm and 16 mm diameter were embedded in each beam. The embedded reinforcing steel has a total length of 450 mm in which 400 mm was embedded in the concrete and the rest 50 mm were left unembedded.

M40 concrete of water cement ratio 0.40 were casted without the use of superplasticizer. For M50 and M60 concrete, 1% by weight of cement PCE (polycarboxylate ether) based superplasticizer were used with a water cement ratio of 0.35 and 0.40 respectively. The beams were then cured for 28 days (figure 3.13) in order to achieve its required strength. Designation of concrete beam with different diameter are given in table 3.6 and 3.7.

Table 3.6: Concrete beam casted without inhibitor

Grade of concrete	Specimen	Reinforcement diameter (mm)
M 40	X_1	8
	X_2	16
M 50	Y_1	8
	Y_2	16
M60	Z_1	8
	Z_2	16

Table 3.7: Concrete beam casted with inhibitor

Grade of concrete	Specimen	Reinforcement diameter (mm)
M 40	$X_1{}'$	8
	$X_2{}'$	16
M 50	$Y_1{}'$	8
	$Y_2{}'$	16
M60	$Z_1{}'$	8
	$Z_2{}'$	16

Figure 3.11 Concrete beam mould
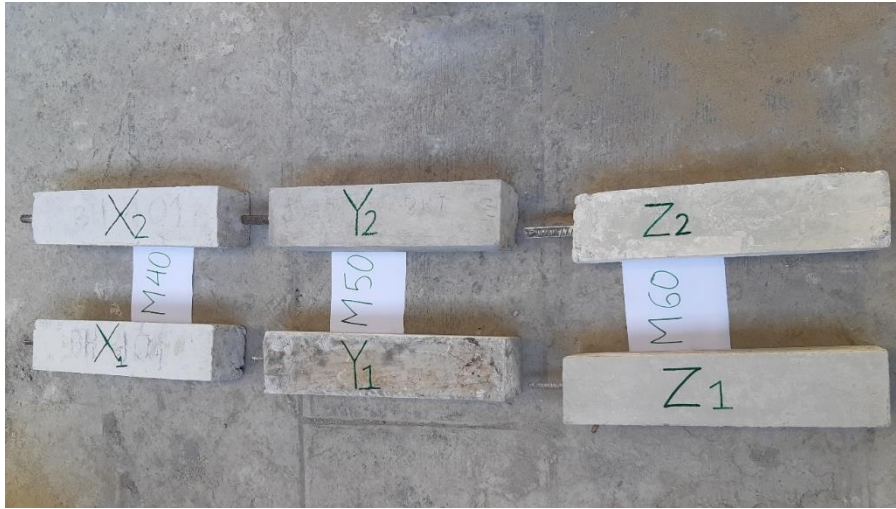
Figure 3.12 Concrete beam

Figure 3.13: Curing of specimen

3.6 PROCEDURE AND TEST SET UP OF IMPRESSED CURRENT METHOD

3.6.1 Procedure of impressed current method

Impressed current method, which is also known also galvanostatic method is used for creating an accelerated corrosion (increasing the rate of corrosion). It involves passing of continuous current from a DC source to the reinforcement embedded in concrete to generate notable amount of corrosion in a short duration. The degree of corrosion generated in the concrete after constant supply of current can be determined using Faraday's law.

3.6.2 Set up of impressed current method

The test set up was done using DC source (figure 3.14), a working electrode (rebar), counter anode and an electrolyte (NaCl solution). The steel which act as anode is connected to the positive terminal of the power supply and the counter electrode which acts as cathode is connected to the negative terminal. In order to achieve a desired degree of corrosion over a short period of time a constant current of 0.12 Ampere is supplied from the counter anode to the reinforcement embedded in concrete with the help of sodium chloride solution acting as an electrolyte. After the curing, the samples are taken out from the tank and is left to dry at a room temperature. In a large barrel sodium chloride solution is prepared by adding 3% NaCl by the weight of water and the concrete specimens are immersed in the solution such that the water does not touch the reinforcement and is just below the peak of concrete as shown in figure 3.15. The connection for the flow of current with a fixed voltage of 10 V are then made. This connection is left undisturbed for 1 to 6 days for generation of corrosion. After 6 days the connection is removed and the sample is taken out for the testing of weight loss method.

Figure 3.14: DC source used for the supply of current

Figure 3.15: Experimental set up of impressed current methods

3.7 WEIGHT LOSS

In the weight loss method, the reinforcement (figure 3.16) before embedding in concrete is measured and this weight is taken as the initial weight. Then the reinforcement (figure 3.17) which is removed from the accelerated current method is measured and is taken as the final weight. Both the weight of reinforcement with and without inhibitor is measured. Faraday's law is being used and length of the actual mass loss is determined.

Figure 3.16: Rebar embedded in beam casted without and with inhibitor

Figure 3.17: Corroded rebar

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

This chapter includes the results obtained after performing various tests on beam with different diameter (with and without inhibitor) placed in a water containing 3% NaCl and the rate of corrosion accelerated with the help of impressed current method. The degree of current applied is determined using Faraday's law and difference between actual and theoretical mass loss are given in this chapter.

4.2 CALCULATION AND RESULTS

4.2.1   Flexural strength (IS: 516- 1959)

After inducing current in the beam for the generation of corrosion for 1 to 6 days, the beam is then left in the sun for surface dry. After 24 hours, in order to find the flexural strength of the beam, four-point loading is done as shown in figure 4.1.

Figure 4.1: Testing for flexural strength

Flexural strength using four-point loading that is modulus of rupture (f_{bt}) is given by equation 4.1 and the flexural strength of beam casted without and with inhibitor is given in table 4.1 and

table 4.2 respectively [27]. Corresponding graphs of flexural strength are also plotted as shown in figure 4.2 and figure 4.3.

$$F_{bt} = \frac{Pl}{bd2} \quad \text{...} \quad \text{Eq 4.1}$$

p= Max total load

l= Span length

d= depth of the beam

b= width of the beam

Table 4.1: Flexural strength of specimens without inhibitor

S.No	Specimens	Diameter of bar (mm)	Flexural strength of corroded specimen (N/mm^2)
1	X$_1$	8	13.05
2	X$_2$	16	17.55
3	Y$_1$	8	13.95
4	Y$_2$	16	17.77
5	Z$_1$	8	14.40
6	Z$_2$	16	18.90
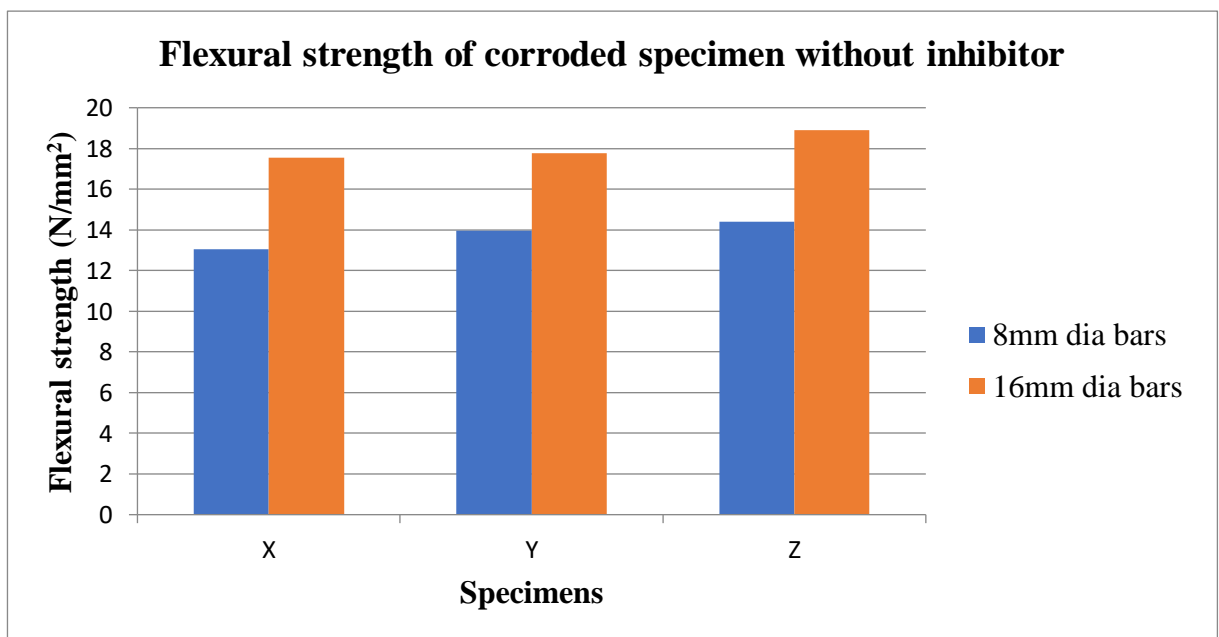
Figure 4.2: Flexural strength of corroded specimen without inhibitor

Table 4.2: Flexural strength of specimens with inhibitor

S.No	Specimens	Diameter of bar (mm)	Flexural strength of corroded specimen (N/mm^2)
1	X_1'	8	14.36
2	X_2'	16	19.48
3	Y_1'	8	15.41
4	Y_2'	16	19.90
5	Z_1'	8	15.99
6	Z_2'	16	21.36

Figure 4.3: Flexural strength of corroded specimen with inhibitor

4.2.2 Percentage weight loss

The mass of rust produced per unit surface area of the bar can be determined theoretically using the following equation 4.2 based on the Faraday's law [28].

$$M_{th} = \frac{W I_{app} T}{F} \text{ -- Eq 4.2}$$

M_{th}=theoretical mass of rust per unit surface area of the bar (g/cm^2)

W=equivalent weight of steel which is taken as the ratio of atomic weight of iron to the valency of iron (27.925g)

I_{app}=applied current density (Amp/cm^2)

T=duration of induced corrosion (sec)

F=Faraday's constant (96487Amp-sec)

The actual mass loss of rust per unit surface area is determined using equation 4.3 [28].

$$M_{ac} = \frac{W_i - W_f}{\pi D L} \text{ --- Eq 4.3}$$

Where Mac =actual mass of rust per unit area of the bar (g/cm^2)

W_i =initial weight of the bar before corrosion (g)

W_f = weight after corrosion (g) for a given duration of induced corrosion (T)

D = diameter of the rebar (cm)

L=Length of the rebar sample (cm)

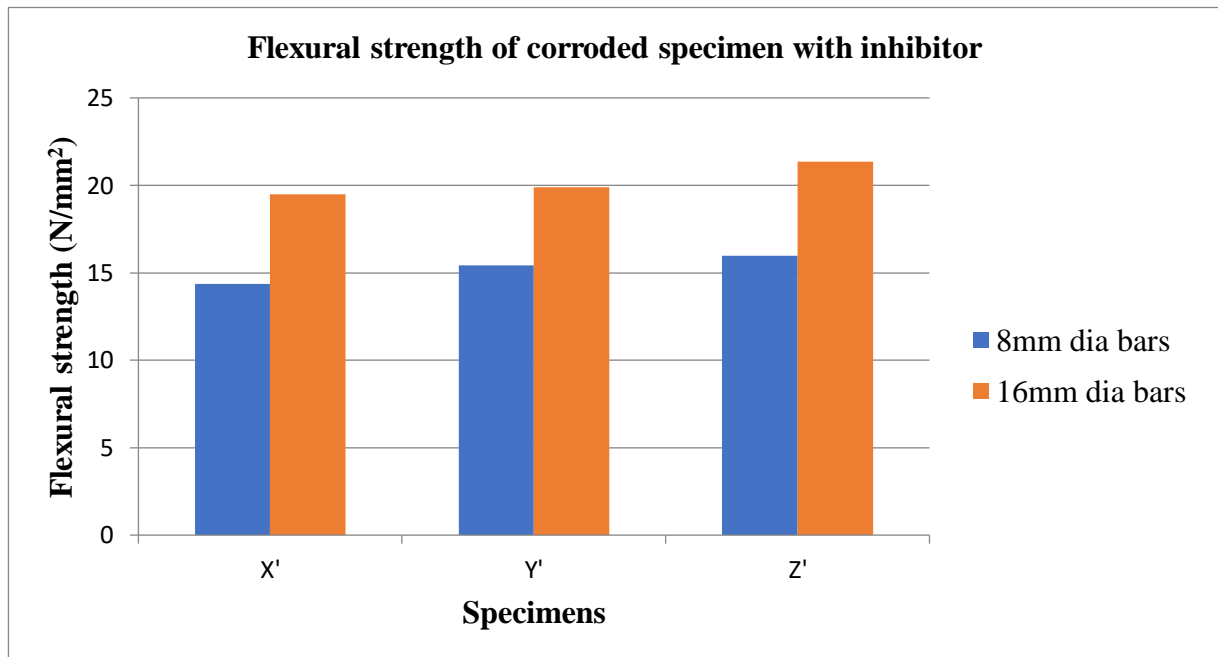The degree of induced corrosion also expressed in terms of the percentage weight loss (ρ) using equation 4.4 and the results are as shown in table 4.3 and table 4.5 [13].

$$\rho = \frac{W_i - W_f}{W_i} \times 100 \text{ --- Eq 4.4}$$

The comparison of actual mass loss and theoretical mass loss without inhibitor (table 4.4) and with inhibitor (table 4.6) are calculated, and graphs are plotted as shown in figure 4.4 and figure 4.5.

Table 4.3: Calculation of degree of induced corrosion in beam casted without inhibitor

Specimen	Initial weight of bar(gm) W_i	Final weight of bar (gm) W_f	Loss (gm) (W_i-W_f)	Degree of induced corrosion (%) ρ
X_1	180	166	14	7.778
X_2	690	670	20	2.898
Y_1	180	170	10	5.556
Y_2	690	676	14	2.029
Z_1	180	173	7	3.889
Z_2	690	678	12	1.739

Table 4.4: Comparison of Actual mass loss and Theoretical mass loss (without inhibitor)

Specimen	Dia. (cm) D	Length of bar (cm) L	Loss (gm) (W_i-W_f)	Time (s) T	Current (amp/cm^2) I_{app}	M_{ac} (gm/cm sq.)	M_{th} (gm/cm sq.)
X_1	0.8	45	14	86400	0.012	0.124	0.300
X_2	1.6	45	20	172800	0.012	0.088	0.600
Y_1	0.8	45	10	259200	0.012	0.088	0.900
Y_2	1.6	45	14	345600	0.012	0.062	1.200
Z_1	0.8	45	7	432000	0.012	0.062	1.500
Z_2	1.6	45	12	518400	0.012	0.053	1.800
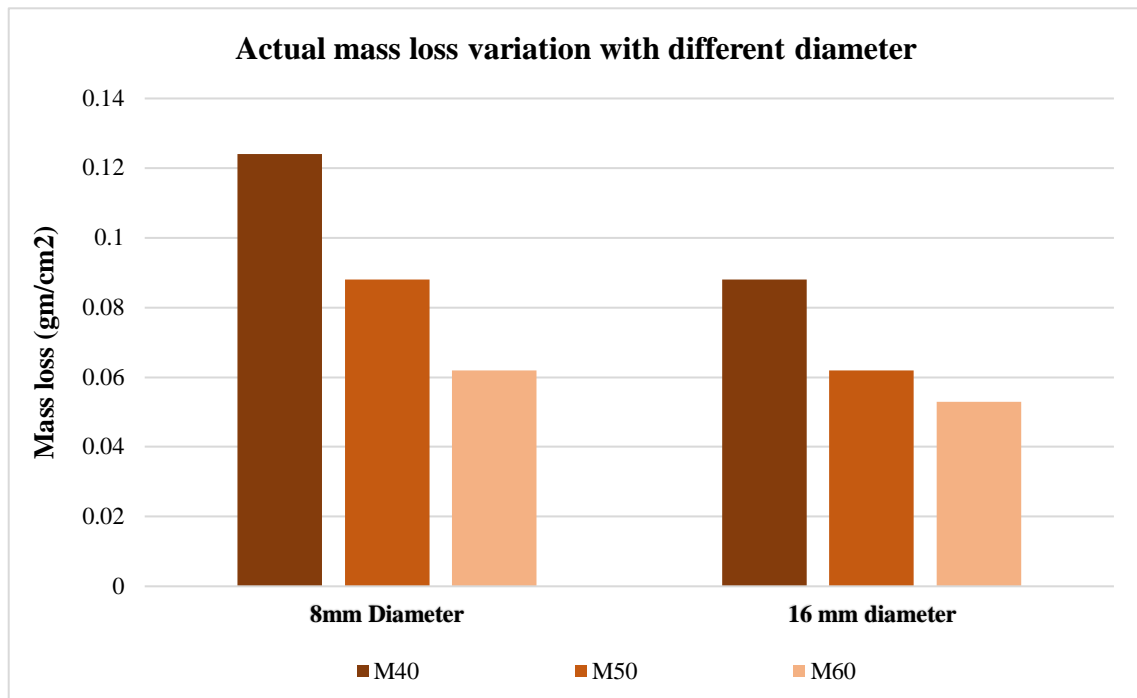
Figure 4.4: Actual mass loss variation for different diameter of rebar without the inhibitor

Table 4.5: Calculation of degree of induced corrosion in beam casted with inhibitor

Specimen	Initial weight of bar(gm) W_i	Final weight of bar (gm) W_f	Loss (gm) (W_i-W_f)	Degree of induced corrosion (%) ρ
X_1'	181	168.33	12.67	7.000
X_2'	691	673.18	17.82	2.579
Y_1'	181	171.97	9.03	4.989
Y_2'	691	678.59	12.41	1.796
Z_1'	181	174.74	6.26	3.458
Z_2'	691	680.43	10.57	1.530

Table 4.6: Comparison of Actual mass loss and Theoretical mass loss (with inhibitor)

Specimen	Dia. (cm) D	Length of bar (cm) L	Loss (gm) (W_i-W_f)	Time (s) T	Current (amp/cm^2) I_{app}	M_{ac} (gm/cm sq.)	M_{th} (gm/cm sq.)
$X_1{}'$	0.8	45	14	86400	0.012	0.112	0.300
$X_2{}'$	1.6	45	20	172800	0.012	0.079	0.600
$Y_1{}'$	0.8	45	10	259200	0.012	0.080	0.900
$Y_2{}'$	1.6	45	14	345600	0.012	0.055	1.200
$Z_1{}'$	0.8	45	7	432000	0.012	0.055	1.500
$Z_2{}'$	1.6	45	12	518400	0.012	0.047	1.800

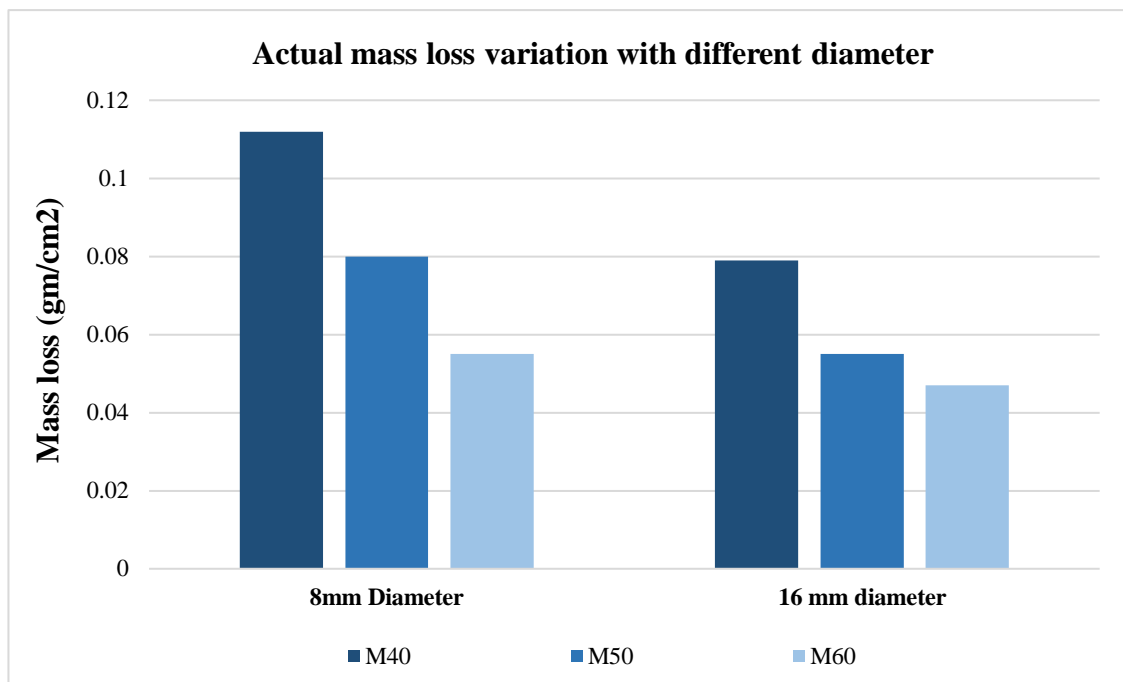**Figure 4.5:** Actual mass loss variation for different diameter of rebar with the inhibitor

CHAPTER 5

CONCLUSIONS

Reinforced concrete is one of the most widely used construction material in infrastructure development and it is largely affected by corrosion leading to higher maintenance and repair cost. Therefore, a through laboratory experiments were carried out on the reinforced concrete specimen accelerating the rate of corrosion and using inhibitors to see its effect. The conclusions of the experiments are as follows:

- The flexural strength of the reinforced concrete coated with inhibitor showed more strength in bending than the reinforcement without inhibitor.
- Larger diameter of bar i.e. 16mm was found to possess more strength and the mass loss is also less compared to smaller diameter i.e. 8mm.
- Higher grade of concrete was found more corrosion resistant than the lower grade.

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