IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Development And Utilization Of Inhibitors For Cathodic Protection In Reinforced Concrete

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Abstract

Reinforced concrete structures, widely used in construction due to their strength and durability, are highly vulnerable to corrosion, especially in aggressive environments. This study explores the use of organic and inorganic inhibitors for cathodic protection in reinforced concrete structures, aiming to mitigate corrosion, a leading cause of deterioration in such infrastructure. This study aims to understand the influence of organic and non-organic corrosion inhibitors on the strength and corrosion resistance properties of concrete by admixing locally available materials with M30 grade concrete mixes. These materials include sodium nitrite, sodium silicate, di-ethanolamine, and hexamine. Admixed inhibitor dosages range from 1% to 5% by cement weight. Sodium nitrite (3%), calcium nitrite (4%), hexamine (2%), and di-ethanolamine (3%), as corrosion inhibitor admixtures, were determined to be the most effective for M30 grade concrete. At 56 days, the compressive, split-tensile, and flexural strengths are higher when calcium nitrite is added to other corrosion inhibitors. The research found that all of the corrosion inhibitors tested improved concrete durability, flexural strength, compressive strength, and split tensile strength. The inhibitors' anodic mechanism reduced the early strength growth. The results of the electrical resistivity and half-cell potential measurements taken from all of the corrosion inhibitors added to M30 grade concrete mixes demonstrate that di-ethanolamine and sodium nitrate have the best corrosion prevention capabilities, followed by hexamine and sodium nitrite.

Index Terms: Corrosion Inhibitors Reinforced Concrete, Cathode, Organic and Inorganic.

1. Introduction

Metals, alloys, and other construction materials are widely employed in engineering. If these materials are not well covered, they are often exposed to the surrounding environment, which over time causes slow deterioration. The phenomenon of deterioration or disintegration of metals and alloys is referred to as corrosion [1]. Certain features, including chemical composition and the mechanisms of electrochemical reactions, influence certain metals, which lead to a greater corrosion rate relative to other metals. Corrosion is defined as a natural process in which a metal chemically or electrochemically interacts with its external environment, which causes the transformation of the metal from an unstable state to a more chemically stable one [2]. It is an undesirable characteristic that undermines the advantageous characteristics of metal. It is also known as an oxidation process that leads to the loss of metal.

In accordance with the National Association of Corrosion Engineers (NACE), corrosion is predicted to cost USD 2.5 trillion in total, or 3.4% of the world's gross domestic product. However, choosing suitable corrosion protection methods could decrease corrosion costs by 15%–35%, which are projected to range from USD 375 to 875 billion yearly worldwide [3]. Many methods have been developed to prevent corrosion and increase the resilience of reinforcing steel [4]. These methods are Cathodic Protection [5], Re-alkalization (ER) [6], Electrochemical Chloride Removal (ECR)

[7], Chloride Capturing materials [8,9], and so on. There are many industrial sectors that are greatly impacted by corrosion. Some of these sectors include the transportation and refining industries [10,11], nuclear facilities [12], oil and gas buildings [13], industrial wastewater treatment systems [14], food processing factories [15], marine infrastructures [16,17], metallic implant fields [18], and many more [19,20]. The application of corrosion inhibitors is shown in Figure 1.

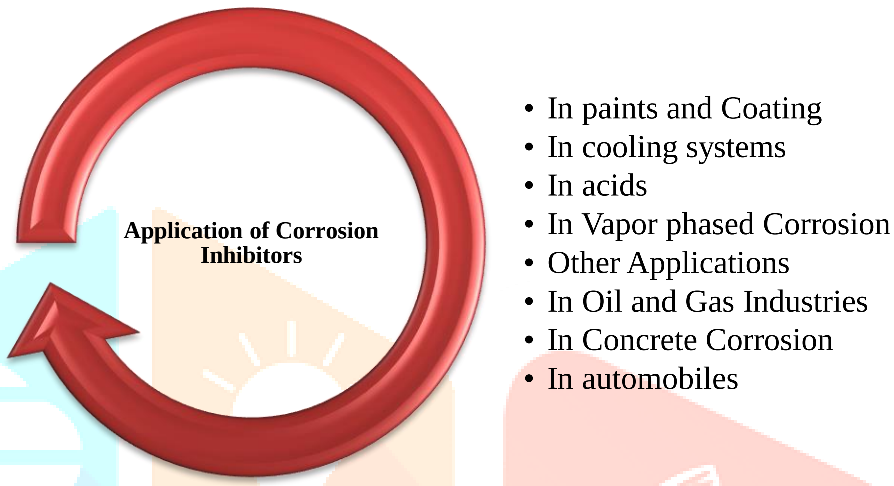

Figure 1: Applications of Corrosion Inhibitors [21].

Improving construction durability while decreasing maintenance costs has caused substantial progress in the research of organic and inorganic inhibitors for cathodic protection in reinforced concrete structures. Figure 2 shows the inhibitor categorization.

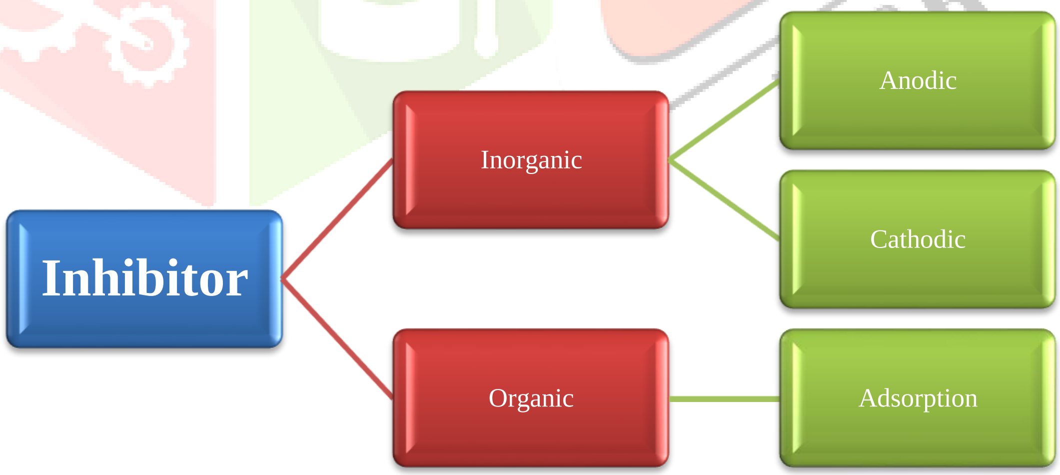

Figure 1: Classification of inhibitors [22].

Organic inhibitors, which are usually composed of amines, carboxylates, and other compounds that prevent corrosion, work by coating metal surfaces with a protective layer. This coating blocks the hostile ions, such as chloride, which can cause steel corrosion in concrete. Nitrites, phosphates, and silicates are examples of inorganic inhibitors that can passivate steel surfaces and stop corrosion in their tracks by changing the local pH and chemistry around the rebar. To provide a more robust and long-lasting protective effect, recent applications have focused on combining organic and inorganic inhibitors to make use of their respective strengths. To further improve the penetration and durability of inhibitors inside the concrete matrix, new delivery methods are being developed. These systems could involve admixtures and surface-applied treatments. Improved structural integrity, longer service life, and reduced repair costs are all benefits of cathodic protection systems that use inhibitors. This is particularly true for chloride-exposed infrastructure, like marine and highway structures. Here is some possible research objectives for studies are:

i. To investigate and classify various organic and inorganic inhibitors used for cathodic protection in reinforced concrete.

ii. To ascertain the dose of multiple corrosion inhibitors.

iii. To compare the effectiveness of organic versus inorganic inhibitors in protecting the cathodic surfaces of reinforced concrete. Examine factors such as Compressive strength, durability, Split-tensile strength, and flexural strength.

iv. To identify the main application of organic and inorganic inhibitors in cathodic protection. Suggest areas for future research, such as exploring new materials, improving inhibitor compatibility with concrete, and addressing environmental concerns.

In this paper, the authors develop and utilize inhibitors for cathodic protection in reinforced concrete. After that, the remaining parts of the paper are organized as follows: In section 2, a literature review of the study is presented. The explanation of the issue is presented in Section 3. The formulation of the suggested model and corrosion inhibitors is discussed in Section 4. The results and analysis of the study are then presented in Section 5. This research subject is brought to a conclusion in section 6.

2. Literature Review

In this section, the authors provided some previous work based on development and utilization of corrosion inhibitors for cathodic protection in reinforced concrete.

In study [23], the authors presented the synergy of galvanized coating and glutamic acid as a corrosion inhibitor for safeguarding steel rebars inside a chloride-contaminated concrete pore solution (CCCPS). There are two parts to the research. Part, one involves using theoretical and experimental methods to determine the Inhibition Efficiency (%IE) of glutamic acid at concentrations of0.25,0.50,0.75, and 1g/L. Part two involves seeing how well it works in tandem with the zinc in the galvanized coating. Findings show that scratched galvanized steel's %IE is much improved (up to 99%) when the inhibitor is present. For the purpose of evaluating the corrosion resistance performance of reinforcement bars immersed in a 0.3 M NaCl-contaminated concrete pore (NCCP) solution for different durations, [24] study compared a control sample with three different concentrations of inhibitors: calcium nitrite, dimethyl ethanol amine, and L-arginine. The concentrations of the inhibitors were 0.3, 0.6, and 1.2 M, respectively. After 168 hours of exposure, the corrosion resistance qualities were evaluated using Potentiodynamic Polarization (PDP), Open Circuit Potential (OCP), and Electrochemical Impedance Spectroscopy (EIS) with immersion time. The CN inhibitor outperformed expectations in terms of corrosion resistance, with an IE of over 97%.

In study [25], investigated the use of Schiff base ligand (HL), a cheap corrosion inhibitor, to protect steel against acid washouts. The corrosion rates of steel and IE were measured after adding HL to the test solution at different concentrations ranging from 0 to 25 ppm. Based on the findings, HL is a useful steel inhibitor in HCl solutions; at a concentration of 25 ppm, it exhibited an inhibition effectiveness of 87.3%. As the immersion period increased up to 24 hours, the IE increased by up to 94.6%. In study [26], suggested effect of nitrite/molybdate mixture on chloride-containing solutions' suppression of carbon steel. At a lower concentration of 2 g/L, 65% and 53% efficiency were reached, respectively, within the range of NaNO2 and Na2MoO4 concentrations employed independently. In contrast, the addition of molybdate to the blend at lower concentrations (2g/L) produced a synergism score of 8.6. The efficiency increased to 93% using a 1:1 combination of lower concentrations.

In study [27], investigated the effects of 4 distinct pyridine derivatives on the corrosion of mild steel in a solution of water-based perchloric acid. MD, Density Functional Theory (DFT), and Monte Carlo computations were used to get molecular insights into the corrosion process. To get a molecular understanding of the examined compounds' adsorption capacity onto the Fe (110) surface, Monte Carlo and Molecular Dynamic simulation were used. Important support for understanding the corrosion inhibition mechanism indicated by the pyridine molecules was given by experimental findings and theoretical computations. In study [28], suggested the impact of molecular structure on the effectiveness of 3 triazole derivatives—benzotriazole (BZT), 5-methyl-1H-benzotriazole (5MBZT), and 3-amino-5-methylthio-1H-1,2,4, triazole (3AMT)—as corrosion inhibitors for C1020 steel and pure copper in a 2% hydrochloric acid (HCl) solution, mirroring the descaling process in a conventional desalination plant. This investigation made use of theoretical models, electrochemical characterization methods including EIS and PDP, and linear polarization resistance (LPR) techniques. For example, after 24 hours of immersion, the IE for C1020 steel, according to EIS data, was as follows: 5MBZT (91.8%), BZT (78.1%), and 3AMT (24.8%).

Reinforced concrete structures are widely used in construction due to their durability and strength. However, their longevity is often compromised by corrosion of the embedded steel reinforcement, primarily due to exposure to aggressive environmental conditions such as chloride ingress and carbonation. Traditional corrosion prevention methods, while effective to an extent, are often insufficient in providing long-term protection. Cathodic protection has emerged as a viable solution to mitigate corrosion, but its effectiveness heavily depends on the appropriate use of inhibitors.

The development and utilization of organic and inorganic inhibitors for cathodic protection have gained significant attention as they enhance the performance and sustainability of reinforced concrete. However, challenges such as optimizing the efficiency of inhibitors, understanding their long-term impact on concrete properties, and assessing their environmental compatibility remain critical areas of concern. Addressing these challenges is essential to improving the durability of reinforced concrete structures and ensuring cost-effective maintenance strategies.

3. Material and Methods

This section provides research methodology based on recent advances and application of organic and inorganic inhibitors for cathode protection for reinforced concrete structure. Figure 3 shows the framework of the proposed method. It illustrates a systematic methodology for investigating the performance characteristics of M30 grade concrete with corrosion inhibitors. The process begins by defining the research problem, followed by a thorough literature review, and setting clear objectives. Material selection involves cement, fine aggregates, coarse aggregates of sizes 10mm and 20mm, along with organic and inorganic corrosion inhibitors. Once the materials are selected, a mix proportion for M30 grade concrete is determined, and samples are prepared accordingly. Various tests are conducted to evaluate the concrete's properties, including CS, STS, FS, and durability tests. Finally, the results of these tests are analyzed to assess the impact of the selected materials and inhibitors on the overall performance and durability of the concrete.

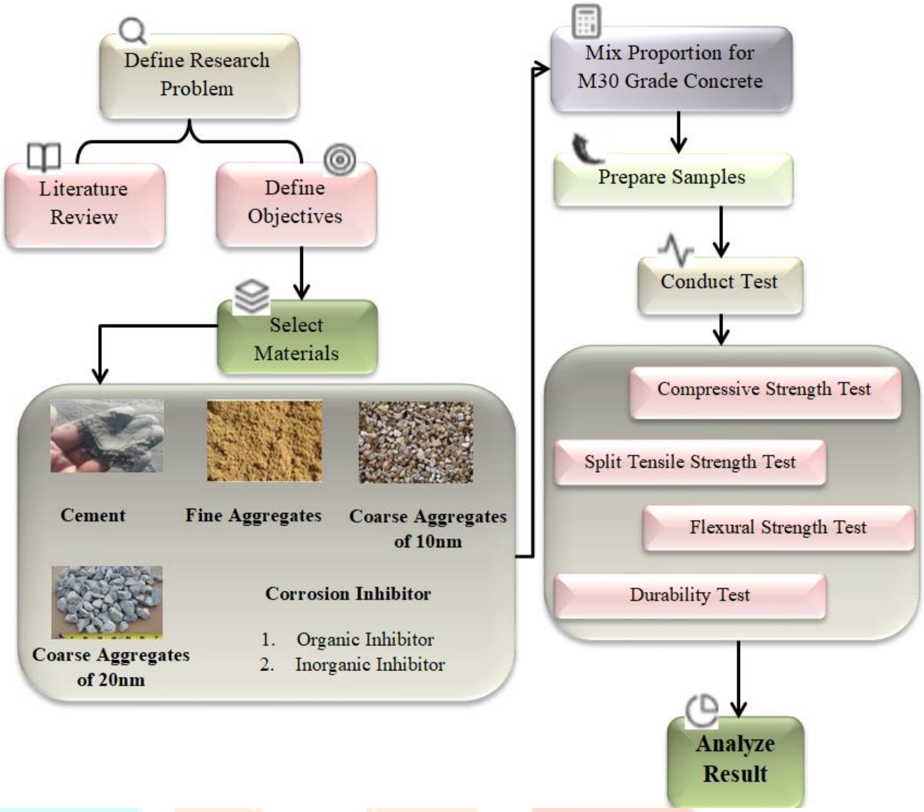

Figure 3: Framework of Proposed work

3.1 Corrosion Inhibitors Used for the Present Study

There were four potential corrosion inhibitors investigated for this research: two inorganic and two organics. These individuals are (Table 1):

Table 1: Organic and Inorganic Corrosion Inhibitors

Corrosion Inhibitors	Types
Di-ethanolamine [$C_4H_{11}NO_2$]	Organic
Hexamine [$C_6H_{12}N_4$]	Organic
0.05M Sodium Silicate [Na_2SiO_3]	Inorganic
0.05 M Sodium Nitrate [$NaNO_2$]	Inorganic

3.2 Materials and Mix Proportions

a) Cement

The project work makes use of Pozzolana Portland cement (PPC), which is easily accessible in the local market. The cement that was used for the project has been subjected to testing in accordance with IS: 4031-1988 and has been determined to meet several requirements outlined in IS: 1489-1991. Particular gravity was 3.6.

Figure 4: Testing of Cement

b) Fine aggregate

River sand that is readily accessible in the area and meets the requirements of IS: 383-1970 Grade 2. The clean local river sand that is accessible would be used. For the casting of all specimens, sand would be passed through an IS 4.75mm sieve.

Figure 5: Fine aggregate

c) Coarse aggregate

Aggregate for the project was crushed annular granite that was mined in the area. The coarse aggregate used in the project work consisted of 60% for 20mm aggregate, with a specific gravity of 2.7.

Figure 6: Coarse Aggregate a) 10nm b) 20nm

d) Water

Water used in concrete projects must not include harmful amounts of dirt, acids, alkalis, or inorganic contaminants; moreover, it must not contain iron or plant matter that might damage concrete or reinforcement.

e) Mix Proportion for M30 Grade Concrete

The components and their quantities for the M30 grade concrete mix utilized in the current investigation are explained in this section. All 53 grades of PPC have been tested and found to comply with IS: 4031-1988 and IS: 1489-1991. Clean, locally accessible Grade-II river sand is utilized as fine aggregate, and its qualities meet IS: 383-1970 standards. Coarse aggregates are made from locally available properly graded granite aggregates with a maximum size of 20mm and 10mm. The current research does not use chemical admixtures, namely super-plasticizers, to mitigate the influence of other chemicals in the assessment of corrosion inhibitors' effects. This research selects M30 grade concrete to evaluate the effects of corrosion inhibitors on concrete characteristics. The mix proportions were determined using the BIS design approach. Position the specimens in a curing tank and allow them to cure for 7, 14, 28, or 56 days. The materials needed for 1m^3 of concrete are (Table 2):

Table 2: Mix Proportion

Grade of Concrete	Cement	Fine Aggregate	Coarse Aggregate	Water
M30	385.11 kg	932.12 kg	712.04 kg	224.47 liters

3.3 Conduct Testing

a. Compressive Strength (CS)

The CS was measured by utilizing 150 mm concrete cubes. Cubes of cast concrete are submerged in water to cure after 24 hours of casting [29]. The specimens are subjected to compression testing on 7, 14, 28, and 56 days. The specimens undergo a series of progressively heavier loads until they rupture, reaching their ultimate capacity at a rate of 140 kg/cm2 per minute. Dividing the load at failure by the specimen's cross-sectional area provides the concrete's CS.

$$\text{Compressive Strength} = \frac{\text{Load}}{\text{Cross-sectional Area}} \quad (1)$$

b. Flexural Strength (FS)

The FS was used to assess the bending behaviour of the foamed concrete specimens at the maximum failure load [30]. On 7, 14, 28, and 56 days, the test was conducted. Over the rollers, the specimen was placed on the bottom plate. The specimen was subjected to a two-point force in the centre until it broke. The formula for determining FS is [31]:

$$F = PL/bd^2 \quad (2)$$

In this equation, F stands for the concrete's FS in MPa,

P for the failure load in N,

L for the beam's effective span in mm, and

b for the beam's width in mm.

c. Split-Tensile Strength (STS)

Tensile strength (TS) is one of the most important and basic properties of concrete. In order to design concrete structural components that are susceptible to temperature, transverse shear, torsion, and shrinkage effects, and its value must be known. Its significance is also considered while designing liquid retaining structures, highways [32], runway slabs, and prestressed concrete structures. It is common practice to calculate the Direct Tensile Strength (DTS) of concrete by first determining its FS or STS, as the DTS of concrete is notoriously difficult to measure. The specimen's splitting tensile strength can be determined by following equation [33]:

$$T = 2P/ \text{pi}\, LD \quad (3)$$

In the above equation: T = Tensile strength upon splitting, measured in MPa,

P: The testing machine's maximum applied load as shown in N,

L: The specimen's length in millimetres and

D: The specimen's diameter is millimeters.

d. Durability

The durability of concrete refers to its capacity to resist the damaging impacts of the environment that it would encounter over its lifespan, preventing it from deteriorating to an unacceptable degree. A minimum grade of concrete, an upper limit on the water-to-cement ratio, and the structure's exposure to the environment are all factors that contribute to the material's durability.

4. Test Result and Discussion

The test findings derived from the experimental studies are provided as follows:

4.1 Compressive Strength (CS)

Figure 7 and Table 3 show the CS of M30 concrete that has been produced using Sodium Nitrate. Table 3 provides data on the CS of concrete at various curing times—7, 14, 28, and 56 days—corresponding to different percentages of sodium nitrate additive. At 0% sodium nitrate, the initial 7-day CS was 19.43MPa, which then increased progressively to 32.9MPa by the 56th day. When 1% sodium

nitrate was introduced, the initial strength at 7 days dropped to 13.25MPa but saw significant improvement over time, reaching 36.01MPa by 56 days. However, at 5% sodium nitrate, the strength started at 18.41MPa, demonstrating only moderate gains over time, reaching 38.26MPa at 56 days.

Table 3: CS of M30 Concrete made with sodium nitrite.

Percentage of Sodium Nitrate	CS for 7 days (MPa)	CS at 14 days (MPa)	CS for 28 days (MPa)	CS for 56 days (MPa)
0	19.43	20.64	21.5	32.9
1	13.25	20.64	26.38	36.01
2	16.02	20.64	27.16	37.26
3	17.12	21.5	28.41	38.05
4	19.63	23.44	29.74	39.73
5	18.41	21.5	26.47	38.26

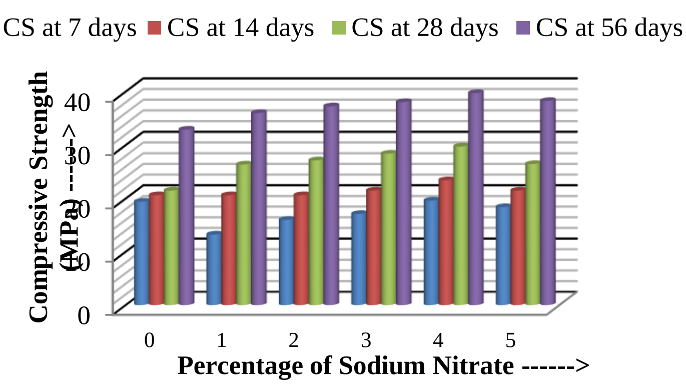

Figure 7: CS of M30 Concrete made with sodium nitrite.

Figure 8 and Table 4 show the CS of M30 concrete that has been produced using Sodium Silicate. Among the five various sodium silicate doses by cement weight that were tested, the findings showed that the 3% dosage achieved the highest CS at 56 days. At 0% sodium nitrate, the CS gradually increases from 19.43MPa at 7 days to 32.9MPa at 56 days. However, at 5% sodium nitrate, the 7-day CS is 18.41MPa, and despite a slight increase, it reaches only 38.26MPa by 56 days. At 7 days, the anodic process makes it very clear that the CS growth in M30 concrete mixes with corrosion inhibitors is much slower than in regular mixes. The strength increase is enhanced after the oxide passive layer is created over the rebar as a result of the anodic process of inhibitor admixture.

Table 4: CS of M30 Concrete made with sodium silicate.

Percentage of Sodium Silicate	CS for 7 days (MPa)	CS at 14 days (MPa)	CS for 28 days (MPa)	CS for 56 days (MPa)
0	18.41	20.64	22.57	32.9
1	16.44	18.45	24.18	33.24
2	17.35	19.31	24.18	34.6
3	18.43	20.67	26.01	36.05
4	16.37	18.51	24.15	30.47
5	15.71	17.84	23.52	28.45

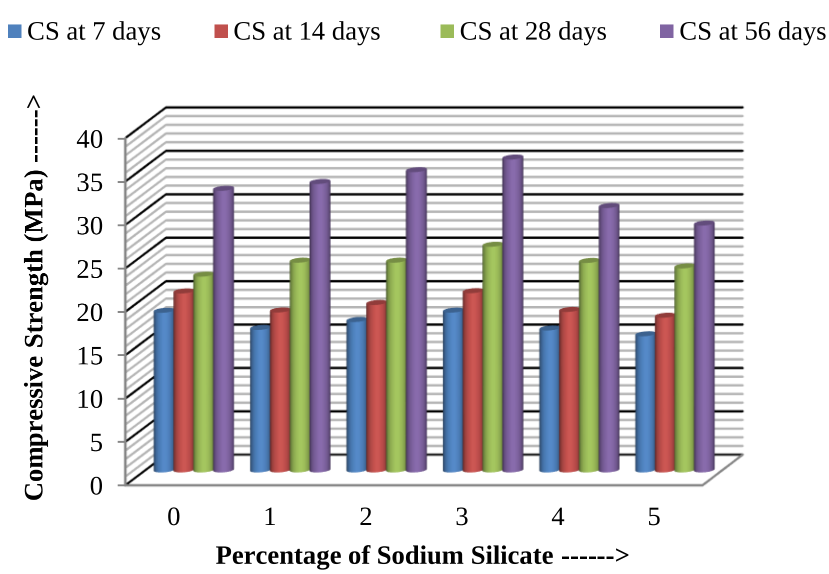

Figure 8: CS of M30 Concrete made with sodium silicate.

Figure 9 and Table 5 show the CS of M30 concrete that has been produced using Di-ethanolamine. At 0% Di-ethanolamine, the CS values are 13.56MPa at 7 days, 16.45MPa at 14 days, and 22.56MPa at 28 days, and 32.9MPa at 56 days. As the Di-ethanolamine content increases to 1%, the CS improves, reaching 15.31MPa at 7 days, 17.48MPa at 14 days, and 24.17MPa at 28 days, and 36.06MPa at 56 days. However, at 5% Di-ethanolamine, the CS is the lowest, with values of 13.35MPa at 7 days, 16.45MPa at 14 days, 21.6MPa at 28 days, and 29.16MPa at 56 days. Overall, the highest CS is observed at 3% Di-ethanolamine, while both lower and higher concentrations result in a decrease in strength over time.

Table 5: CS of M30 Concrete made with Di-ethanolamine.

Percentage of Di-ethanolamine	CS for 7 days (MPa)	CS at 14 days (MPa)	CS for 28 days (MPa)	CS for 56 days (MPa)
0	13.56	16.45	22.56	32.9
1	15.31	17.48	24.17	36.06
2	17.27	18.51	26.31	36.06
3	19.55	20.57	29.48	37.58
4	15.72	19.54	24.04	32.57
5	13.35	16.45	21.6	29.16

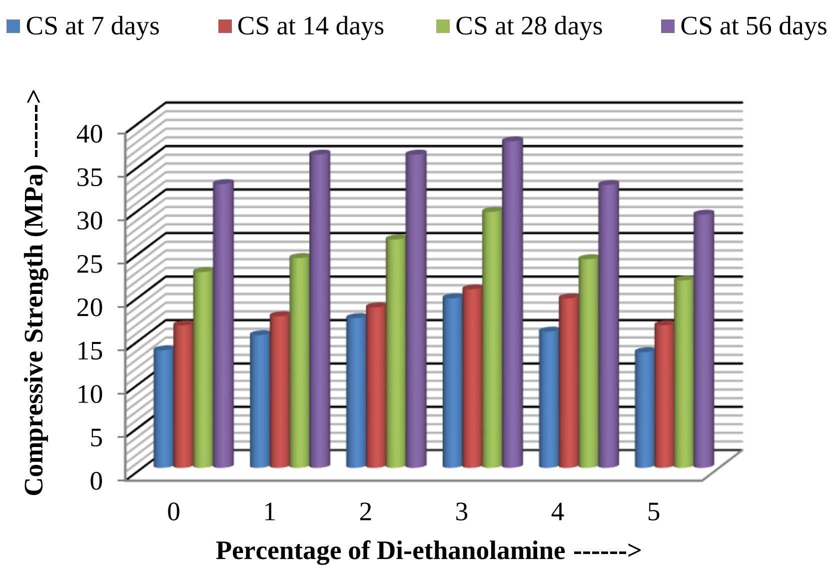

Figure 9: CS of M30 Concrete made with Di-ethanolamine.

Figure 10 and Table 6 show the CS of M30 concrete that has been produced using Hexamine. On 7 days, the CS increases with the addition of Hexamine, peaking at 4% and then slightly decreasing at 5%. A similar trend is observed in 14 days, where the CS remains relatively stable across different percentages, with the highest value at 4%. Over 28 days, the CS is at its highest for the 1% and 2% Hexamine mixtures, followed by a slight drop at higher percentages. Over 56 days, the CS continues to rise with a similar pattern, with the 1% and 2% Hexamine mixes showing the highest values. This indicates that the optimal percentage of Hexamine for achieving higher CS in M30 concrete is around 2%, and excess amounts may lead to a decrease in strength after longer curing periods.

Table 6: CS of M30 concrète made with Hexamine

Percentage of Hexamine	CS for 7 days (MPa)	CS at 14 days (MPa)	CS for 28 days (MPa)	CS for 56 days (MPa)
0	19.53	20.57	22.36	32.9
1	17.25	21.7	26.41	33.7
2	18.61	22.46	28.57	33.7
3	18.61	21.7	27.42	32.73
4	12.77	20.57	27.42	32.73
5	11.40	17.35	22.83	31.27

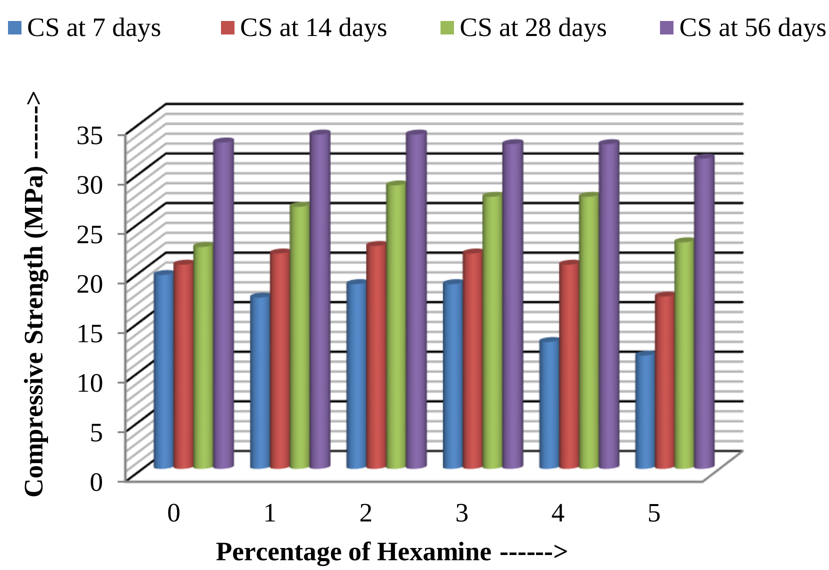

Figure 10: CS of M30 Concrete made with Hexamine.

Table 7 and Figure 11 illustrate the impact that a variety of corrosion inhibitors have on the corrosion strength (CS) of M30 Concrete.

Table 7: Variety of corrosion inhibitors have on the CS of M30 Concrete

	No corrosion inhibitors	Corrosion Inhibitors			
		Sodium Nitrate	Sodium Silicate	Di-ethanolamine	Hexamine
CS (MPa) of M30 Concrete	32.9	39.73	36.05	37.58	33.7
Percentage Increase	__	22.67%	9.8%	13.1%	3.7%

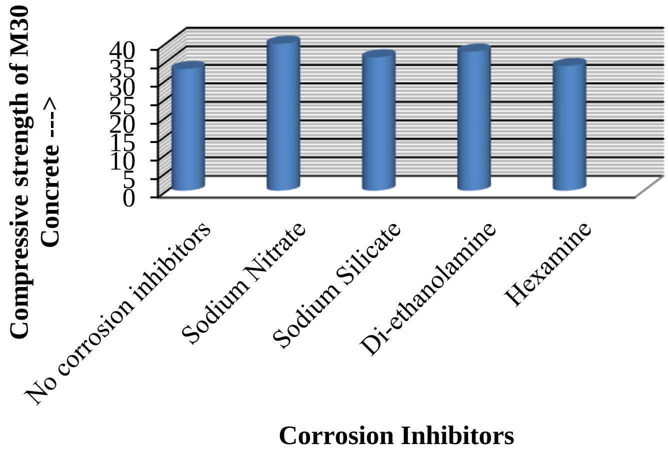

Figure 11: Different Corrosion Inhibitors' Effects on the CS of M30 Concrete at 56 Days

The findings clearly demonstrated that the kind of corrosion inhibitor admitted did not correlate with the growth of the concrete's CS. Sodium nitrite is more effective in inhibiting CS gain among inorganic inhibitors. Despite the facts that the anodic process of inhibitors reduced the early strength increase.

4.2 Split Tensile Strength (STS)

Figure 12 displays the STS of M30 concrete made with inorganic and organic corrosion inhibitors. Table 8 presents the STS of M30 concrete mixes incorporating different corrosion inhibitors at 56 days, with varying percentages of the inhibitors. For the mix without any corrosion inhibitor (0%), the STS values for Sodium Nitrate, Sodium Silicate, Di-ethanolamine, and Hexamine are all close, ranging from 4.49MPa to 4.57MPa. At 1% inhibitor concentration, the STS slightly improves for all mixes, with values of 4.56MPa for Sodium Nitrate, 4.57MPa for Sodium Silicate, 4.52MPa for Di-ethanolamine and 4.52MPa for Hexamine. However, at 5%, the STS decreases slightly across all mixes, with Sodium Nitrate showing 4.78MPa, Sodium Silicate 4.66MPa, Di-ethanolamine 4.61MPa, and Hexamine 4.60MPa. Overall, the best STS is observed at 4% concentration of Sodium Nitrate, while higher or lower concentrations tend to show slightly reduced values.

Table 8: STS (MPa) of M30 concrete mixtures using different corrosion inhibitors at 56 days.

Percentage of Corrosion Inhibitors	**STS (MPa) of M30 concrete mixtures using different corrosion inhibitors at 56 days**			
	Sodium Nitrate	**Sodium Silicate**	**Di-ethanolamine**	**Hexamine**
0	4.50	4.50	4.50	4.50
1	4.56	4.57	4.52	4.52
2	4.63	4.65	4.74	4.65
3	4.74	4.70	4.63	4.67
4	4.80	4.67	4.68	4.63
5	4.78	4.66	4.61	4.60

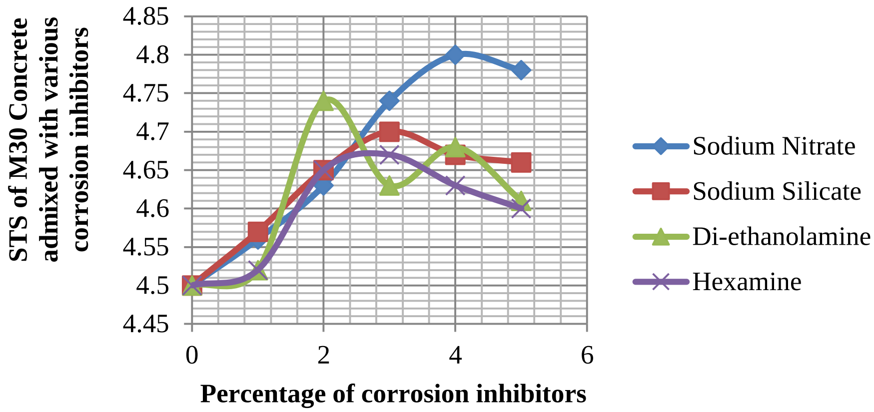

Figure 12: STS of M30 concrete mixtures using different corrosion inhibitors at 56 days

4.3 Flexural Strength (FS)

Table 9 displays the FS of M30 concrete made with inorganic and organic corrosion inhibitors. Sodium Nitrate shows a continuous increase in FS as the percentage of the inhibitor rises, peaking at around 4% with a value slightly above 7MPa, after which it slightly declines. Similarly, Sodium Silicate also exhibits an upward trend, reaching its maximum FS around 3% to 4% concentration, and then showing a minor drop at 5%. Di-ethanolamine follows a similar pattern, with a noticeable increase in FS at 2% and 3%, peaking around 3% and then slightly decreasing at 5%. Hexamine shows a different trend, with its FS increasing slightly at 1% and 2%, peaking at around 3%, but then experiencing a sharper decrease as the percentage of Hexamine increases.

Overall, Figure 13 indicates that the FS increases with the addition of corrosion inhibitors up to a certain percentage, with Sodium Nitrate performing the best among the inhibitors at around 4%. Beyond that point, the FS tends to decrease for all inhibitors, with Hexamine showing the sharpest decline.

Table 9: FS of M30 concrete mixtures using different corrosion inhibitors at 56 days

Percentage of Corrosion Inhibitors	FS (MPa) of M30 concrete mixtures using different corrosion inhibitors for 56 days			
	Sodium Nitrate	**Sodium Silicate**	**Di-ethanolamine**	**Hexamine**
0	4.65	4.65	4.65	4.65
1	6.16	6.16	6.16	6.16
2	6.47	6.47	6.57	6.47
3	6.77	6.66	6.47	6.77
4	6.88	6.57	6.47	6.67
5	6.57	6.26	5.75	6.37

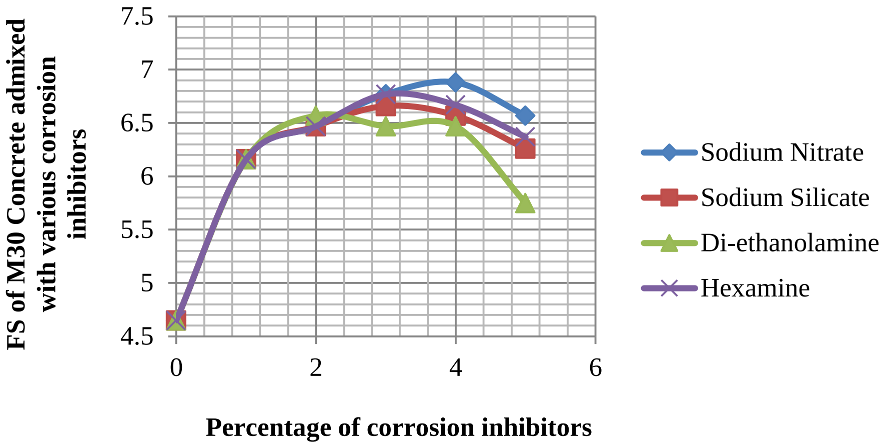

Figure 13: FS of M30 concrete mixtures using different corrosion inhibitors at 56 days

4.4 Durability

Table 10 shows the durability of M30 concrete made with inorganic and organic corrosion inhibitors. Figure 14 presents the durability (measured in MPa) of M30 concrete mixes containing various corrosion inhibitors at different percentages, assessed after 56 days. For the control mix without any corrosion inhibitors (0%), the durability is consistent across all mixes, with a value of 5.23MPa. As the percentage of corrosion inhibitors increases, there is a significant improvement in durability. At 1% inhibitor concentration, the durability increases for all inhibitors, with Sodium Nitrate showing a durability of 7.14MPa, Sodium Silicate at 7.31MPa, Di-ethanolamine at 7.13MPa, and Hexamine at 7.24MPa. This upward trend continues at 2%, where Sodium Nitrate reaches 7.23MPa, Sodium Silicate 7.47MPa, Di-ethanolamine 7.46MPa, and Hexamine 7.48MPa, marking this level as one of the highest for durability

across the inhibitors. At 5%, a slight reduction in durability is observed for most inhibitors, with Sodium Nitrate at 7.38MPa, Sodium Silicate at 7.53MPa, and Hexamine at 7.15MPa. Di-ethanolamine, however, shows a more substantial decrease in durability, dropping to 6.48MPa.

In summary, the highest durability values for each inhibitor are generally observed between 2% and 4% concentrations, with Sodium Silicate showing the most notable peak at 4%. Increasing the inhibitor percentage beyond this range generally leads to a reduction in durability, especially for Di-ethanolamine at 5%.

Table 10: Durability of M30 concrete mixtures using different corrosion inhibitors at 56 days

Percentage of Corrosion Inhibitors	Durability (MPa) of M30 concrete mixtures using different corrosion inhibitors at 56 days			
	Sodium Nitrate	Sodium Silicate	Di-ethanolamine	Hexamine
0	5.23	5.23	5.23	5.23
1	7.14	7.31	7.13	7.24
2	7.23	7.47	7.46	7.48
3	7.63	7.24	7.52	7.35
4	7.67	7.72	7.57	7.63

5	7.38	7.53	6.48	7.15

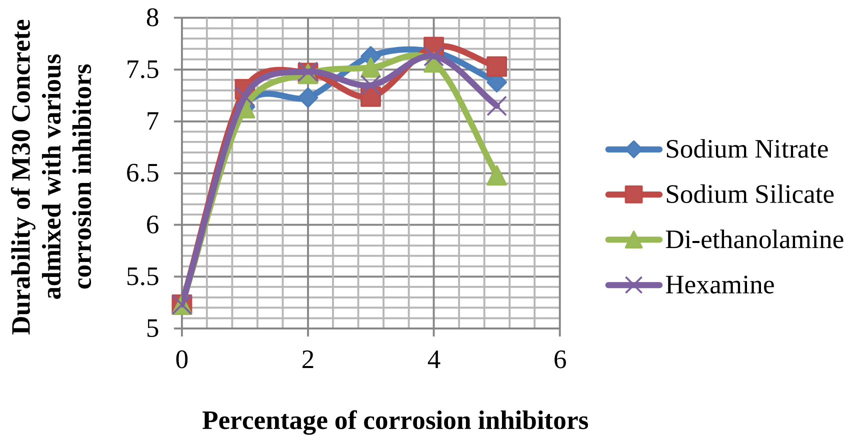

Figure 14: Durability of M30 concrete mixtures using different corrosion inhibitors at 56 days

5. Conclusion

Cathodic protection of reinforced concrete structures is a key strategy to prevent corrosion, with organic and inorganic inhibitors playing essential roles. Both types of inhibitors act to slow down the corrosion rate of steel reinforcements embedded in concrete, effectively extending the service life of structures exposed to corrosive environments. The study examined the effects of adding four corrosion inhibitor admixtures—sodium nitrite, sodium silicate, hexamine, and di-ethanolamine—to M30 grade concrete on the material's strength and corrosion resistance. The experimental result show that at 4%, the STS increases slightly across all mixes, with Sodium Nitrate showing 4.80, Sodium Silicate 4.67MPa, Di-ethanolamine 4.68MPa, and Hexamine 4.63MPa. Similarly, CS increases, with Sodium Nitrate 39.73MPa, Sodium Silicate 30.47MPa, Di-ethanolamine 32.97MPa, and Hexamine 32.73MPa. At 56 days, the CS, STS, and FS are higher when inorganic and organic corrosion inhibitors are used together, in comparison to other corrosion inhibitors. Finally, Sodium nitrite has been shown to

be an effective additive to concrete, particularly in increasing its CS. It has also been seen to have a comparable effect on the STS and FS of concrete mixtures. This may be due to the presence of sodium ions.

Further research can focus on developing new organic and inorganic inhibitors that offer extended durability and stability in diverse environmental conditions. This will be essential for long-term protection in reinforced concrete structures exposed to varying climates.

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