Nanostructured Coatings Approach for Corrosion Protection of Building Steels

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Abstract. Corrosion of steel reinforcement is a persistent durability concern for concrete structures, since conventional coatings often fail to provide lasting protection due to poor adhesion and insufficient barriers in harsh environments. This research focuses on advancing corrosion resistance by introducing nanostructured coatings that combine epoxy, cement, and nano-silica materials. Four distinct coating formulations were developed—epoxy, epoxy–cement, epoxy–nano-silica, and epoxy–cement–nano-silica—and subjected to systematic testing under accelerated corrosion conditions. We measured weight loss to see how well the material was doing, since this shows how much it had broken down. The results reveal that adding nano-silica makes the coating much denser and stronger, which lowers the rate of corrosion. The tests showed that the epoxy-nano-silica coatings were the best at keeping rebar of different sizes safe. These results support the idea that nanostructured hybrid coatings could help reinforced concrete last longer in tough conditions.

1 Introduction

Concrete is a major building material all over the world, but it has a lot of problems with sustainability since it uses a lot of cement, which releases a lot of greenhouse gases [1]. Adding nano-components can assist lower the amount of cement used and the damage it does to the environment [2]. Corrosion, which is the chemical or electrochemical breakdown of metals, weakens reinforced concrete and shortens its lifespan.

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Nanotechnology makes it possible to make better materials for protecting surfaces, which makes them last longer by adding coatings and barrier layers [3]. Inorganic nanocoatings with additional nanoparticles like TiO_2, SiO_2, ZnO, and Fe_2O_3 improve adhesion, homogeneity, impact resistance, and toughness. They also go around the limits of standard coatings and make them more resistant to corrosion [4].

1.1 Nanotechnology in Anti-Corrosion Coating

Low-alloy and carbon steels are quite strong, but they are also very likely to corrode when exposed to extreme conditions [5, 6]. Different surface treatments and anti-corrosion coatings are utilized as the main ways to keep huge steel constructions safe. Nanotechnology-based methods for protecting steel are still in the early stages of development, although research is showing encouraging results [7, 8]. To choose the correct protection, you need to match the coating systems to the environment where they will be used. Cathodic protection can also be used with low-voltage direct current to greatly slow down the oxidation and corrosion of steel that is exposed.

2 Theory of Corrosion

2.1 General

Steel in concrete rusts by an electrochemical process. An electrochemical cell forms when the electrical potential around the steel reinforcement changes [9]. The pore water in the hardened cement paste serves as the electrolyte, linking the anodic and cathodic areas on the steel surface. Iron atoms lose electrons at the anode and turn into ferrous ions (Fe^{2+}), which then enter the pore solution [10]. The electrons that are liberated move through the steel to the cathodic area, where they react with water and oxygen to make hydroxyl ions (OH^{-}) [11]. The hydroxyl ions in the electrolyte then react with the ferrous ions to make ferrous hydroxide, which is then oxidized to ferric hydroxide, which is better known as rust [12].

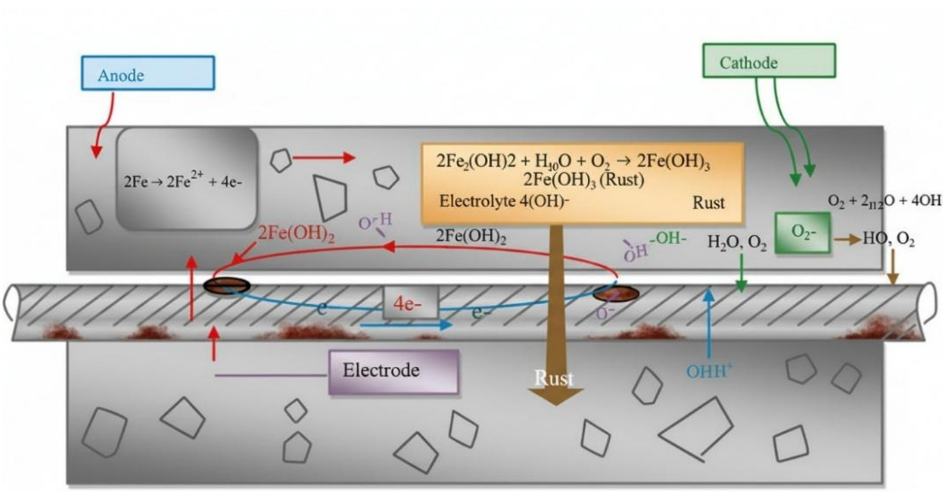

Fig. 1. Simplified Model Representing Corrosion Mechanism.

2.2 Corrosion Reactions in Iron (Fe):

Anodic Reaction:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (1)$$

Formation of Ferrous Hydroxide:

$$Fe^{2+} + 2(OH^{-}) \rightarrow Fe\,(OH)_2 (\text{Ferrous Hydroxide}) \quad (2)$$

Oxidation to Ferric Hydroxide:

$$4Fe(OH)_2 + 2H2O + O_2 \rightarrow 4Fe(OH)_3 (\text{Ferric Hydroxide}) \quad (3)$$

Cathodic Reaction:

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

2.3 Weathering Prevention by Nanotechnology

Nanotechnology makes it possible to create new coatings that change the surface of objects and offer better protection in a wide range of uses. Inorganic nano-coatings make strong barriers against corrosion. They are stronger, smoother, and more resilient than conventional coatings, which can be brittle and adhere poorly [13]. The use of nanostructured materials, which boost durability and lower the chance of breakage, solves these problems. Incorporating nanoparticles like TiO_2, SiO_2, ZnO, and FeO_3 into organic coatings also enhances their resistance to UV light and strength, enabling them to last longer and function better in difficult situations [14].

3 Experimental Investigation

3.1 Materials Used

3.1.1 Steel

The experimental investigation utilized TMT reinforcement bars with diameters of 12 mm, 16 mm, and 20 mm.

Table 1. Properties of (TMT Bar).

S. No	Size of the Rod (mm)	Yield Stress (Mega Pascal)	Ultimate Load (Mega Pascal)
1.	12.00 mm	0.698	79.04
2.	16.00 mm	0.586	118.70
3.	20.00 mm	0.654	205.11

3.1.2 Nano Silica

The nano-silica used in the study came from ORIENTAL TREXIM Pvt. Ltd. in Mumbai. CECRI in Karaikudi tested its properties, and particle size analysis showed that it was nano-silica (micro-powder).

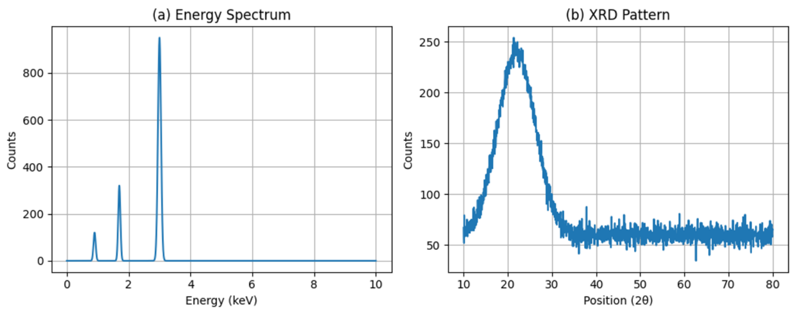

Fig. 2. Graphics, Analyse View of Nano – Silica.

Table 2. Xrd Properties of Nano – Silica.

S. No	Investigations	Investigation Results
1	Rare Data Origin	XRD measurement (*.XRDML)
2	Probe Axis	Gonio
3	Start Position [˚2 Th.]	10.0863
4	End Position [˚2 Th.]	79.9374
5	Stage Size [˚2 Th.]	0.05011
6	Scan Step Time [s]	10.1383
7	Scan Type	Constant
8	PSD Mode	Perusing
9	PSD Length [°2 Th.]	2.123
10	Offset [°2 Th.]	0.0000
11	Divergence Slot Type	Fixed
12	Departure Slit Size [°]	0.4776
13	Specimen Length [mm]	10.01
14	Measurement Temperature [°C]	25.00
15	Anode Material	Cu
16	K-Alpha1 [Å]	1.54360
17	K-Alpha2 [Å]	1.54743
18	K-Beta [Å]	1.39325
19	K-A2 / K-A1 Ratio	0.50000
20	Initiator Settings	30 mA, 40 kV
21	Diffractometer Type	0000000011034645
22	Diffractometer Number	0
23	Goniometer Range [mm]	240.00
24	Dist. Focus-Diverg. Slit [mm]	91.00
25	Instance Beam Monochromator	No

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3.1.3 Micro Structural Properties of Nano Silica

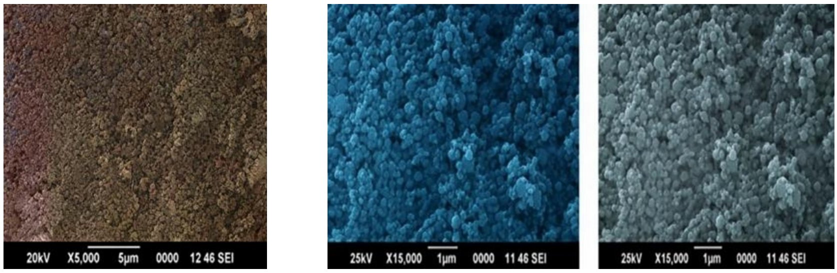

Fig. 3. Graphics, Analyse View of Nano – Silica

Fig. 4. TMT Rod Specimens for Testing

Fig. 5. TMT Bars After Coatings

3.2 Sample Preparation

3.2.1 Preparation of Steel

Before coating and corrosion tests, it is important to cut TMT rods to the right length and clean them with rough emery paper to get rid of rust and other dirt. Then, a dry cloth is used to clean and smooth the surface of the rods. This makes the test results better overall and helps the protective coatings stick better.

3.2.2 Weight Losses of Rebar

First, the steel rods were cleaned well to get rid of dirt and rust. They were first weighed, and then they were put through tests to see how quickly they would rust. We took out each rod every 25 hours, cleaned it lightly to get rid of any loose corrosion products, and then weighed it again to see how much weight it had lost during the exposure time.

$$Percentage\ of\ Weight\ Loess\ (\%) = \frac{w1-w2}{w1}\ x\ 100. \qquad (5)$$

3.3 Coating Techniques

This paper categorizes the coating techniques employed for steel reinforcement into four principal methods, specifically:

1. Epoxy coating (EC).

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2. Epoxy with a cement coating (EC + CC).

3. Epoxy with a coating of nano-silica (EC + NSC).

4. Epoxy with a cement coating and a nano silica coating (EC + CC + NSC).

For epoxy coatings, the solution was mixed well and brushed onto steel rods. It then dried in the air for 48 hours. To make epoxy–cement coatings, cement and epoxy were mixed together, brushed onto rods, and left to cure for 48 hours. To make epoxy-nano-silica coatings, nano-silica and epoxy were mixed together, put on rods, and left to cure for two days. The epoxy–nano-silica–cement coating was made by mixing nano-silica and cement with epoxy, putting the mixture on rods, and letting it dry at room temperature for 48 hours.

3.4 Experimental Setup

An accelerated corrosion test was used to make a controlled, harsh environment to see how well coated and uncoated steel reinforcement can resist corrosion. This method made it possible to systematically test how well different coatings protect steel bars in conditions that mimic corrosion.

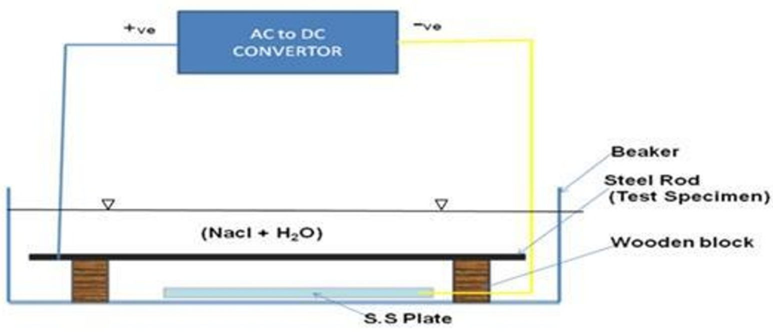

Fig. 6. Experimental Setup (Accelerated Corrosion).

3.5 Test Specimen Preparation

The experiment consisted of exposing 12 mm, 16 mm, and 20 mm TMT rebars with various coatings to 200 hours of accelerated corrosion in a 3% NaCl solution at a constant 12 V potential, with intermittent weight loss measurements to evaluate corrosion resistance.

3.6 Test Procedure

The steel rods, which were 12, 16, and 20 mm in diameter, were cleaned and put in a container with a 3% NaCl solution. They were then connected to an AC–DC converter that provided a constant 12 V for 200 hours. After that, the rods were cleaned of any loose rust and weighed to see how much corrosion had happened.

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Fig. 7. Steel Rods in 3% NaCl Solution: Before and After Corrosion Exposure.

Fig. 8. Rods after Corrosion.

3.7 Applied Voltage Test

Coating adhesion and integrity were assessed under electrical and electrochemical stress by placing coated reinforcing bars in a non-conductive container with 3% NaCl solution, applying a constant 12 V, and monitoring for early coating failures via hydrogen generation at the cathode and corrosion products at the anode, with total test duration based on the earliest detected coating defect.

Fig. 9. AC To DC Converted for Enhanced Current

Fig. 10. TMT-Rod with Nano- Silica and Epoxy Coating

4 Results and Discussions

The results section analyses percentage weight loss as the main indicator of corrosion and coating effectiveness for TMT bars exposed to 200 hours of accelerated corrosion in a 3% NaCl solution under a 12 V DC potential.

4.1 Weight loss method

4.1.1 Weight Losses of Rebar with Out Coating

Uncoated rebars exposed to 200 hours of accelerated corrosion in chloride solution showed significant mass losses (0.80% to 2.19%), with the highest loss in 16 mm bars, confirming that bare steel is highly susceptible to aggressive environments and highlighting the necessity for protective coatings.

Table 3. Percentage Weight Losses of Rebar Without Coating After 200 Hrs (WC)

S. No	Dia of Bar (mm)	Weight of Rebar in (gms)		Weight loss of Rebars in (%)
		Before Corrosion	After Corrosion	
1	12	268	265	1.12
2	16	503	492	2.19
3	20	745	739	0.80

4.1.2 Weight Losses of Rebar with Epoxy Coating (EC)

Epoxy-coated rebars had lower weight loss than uncoated specimens after 200 hours in chloride solution but still showed notable loss (0.74–2.06%), especially for 16 mm bars—indicating epoxy improves resistance but does not fully prevent corrosion under severe electrochemical stress.

Table 4. Percentage Weight Losses of Rebar with Epoxy Coating After 200 Hrs (EC)

S. No	Dia of Bar (mm)	Weight of Rebar in (gms)		Weight loss of Rebars in (%)
		Before Corrosion	After Corrosion	
1	12	271	268.50	0.92
2	16	474	464.25	2.06
3	20	748	742.50	0.74

4.1.3 Weight Losses of Rebar Epoxy with Cement Coating (EC+ CC)

After 200 hours of corrosion testing, rebar with epoxy and cement lost less weight (0.73–1.97%) than rebar with epoxy alone. This is because the cement makes the barrier denser and less permeable, but there are still some problems because it is brittle and has micro voids.

Table 5. Percentage Weight Losses of Rebar with Epoxy and Cement Coating After 200 Hrs (EC+CC).

S. No	Dia of Bar (mm)	Weight of Rebar in (gms)		Weight loss of Rebars in (%)
		Before Corrosion	After Corrosion	
1	12	274.5	272.50	0.73
2	16	483.5	474	1.97

4.1.4 Weight Losses of Rebar Epoxy with Nano Silica Coating (EC+NSC)

Table 6. Percentage Weight Losses of Rebar with Epoxy and Nano Silica Coating After 200 Hrs (EC+NSC)

S. No	Dia of Bar (mm)	Weight of Rebar in (gms)		Weight loss of Rebars in (%)
		Before Corrosion	After Corrosion	
1	12	280	279	0.36
2	16	499	492.25	1.36
3	20	756	751.75	0.56

4.1.5 Weight Losses of Rebar with Epoxy, Cement and Nano Silica Coating (EC+CC+ NSC)

Epoxy and nano-silica plus cement coatings reduced rebar weight loss to 0.55–1.93% after 200 hours, performing better than epoxy or epoxy–cement coatings alone; although the hybrid system increases coating density, variability in the matrix can occur, but the positive effect of nano-silica on corrosion resistance remains evident.

Table 7. Percentage Weight Losses of Rebar with Epoxy, Cement and Nano Silica Coating After 200 Hrs (EC+CC+ NSC)

S. No	Dia of Bar (mm)	Weight of Rebar in (gms)		Weight loss of Rebars in (%)
		Before Corrosion	After Corrosion	
1	12	273	271	0.55
2	16	468.5	459.50	1.93
3	20	745	740.25	0.64

Across all coatings, uncoated steel corroded the most, epoxy plus nano-silica consistently yielded the lowest weight loss and best protection, and the combination with cement performed well but not always better than epoxy–nano-silica alone; these results emphasize that nano-silica's pore-filling and uniformity benefits are key to minimizing corrosion damage in reinforced steel.

4.2 Combined Weight Loss Evaluation of Multiple Coating Types for Various Rebar Diameters

A comparative analysis of 12 mm, 16 mm, and 20 mm rebars subjected to accelerated corrosion revealed distinct weight-loss trends influenced by diameter and coating type, providing direct insight into the protective efficacy of each coating system across various reinforcement sizes.

4.2.1 Comparison of Coatings Effect of 12mm Diameter Rods

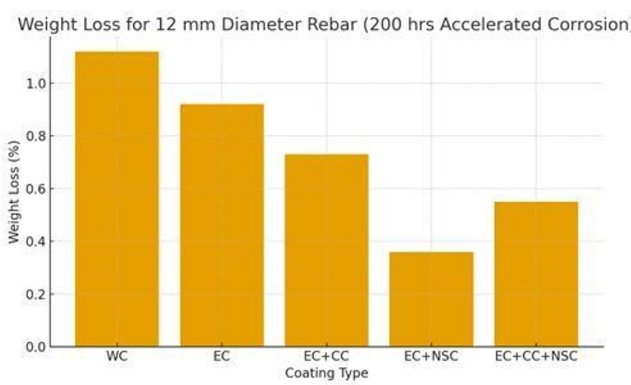

Fig. 11. Comparison of Various Coatings for 12mm Dia Rod.

The epoxy–nano silica coating reduced corrosion the most for 12 mm rebars, cutting weight loss by 67.33% compared to uncoated bars. The epoxy–cement–nano silica system came in second, and the epoxy–cement system did better than the epoxy alone. Uncoated specimens had the most severe corrosion, as shown in figure 11.

4.2.2 Comparison of Coatings Effects of 16mm Diameter of Rods

Figure 12 shows that epoxy-cement-nano silica coatings reduced corrosion the most for rebars, with 22.33% less weight loss than other coatings. Epoxy-nano silica and epoxy-cement systems also worked better than epoxy alone, and uncoated rebars were the most likely to corrode.

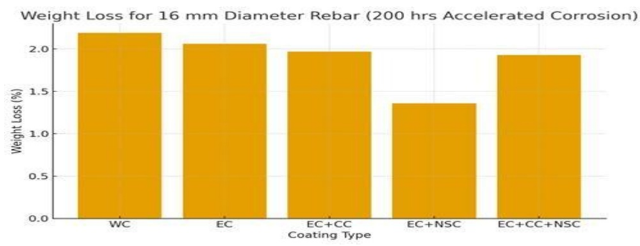

Fig. 12. Different Coatings Compared for 16 mm Dia Rod.

4.2.3 Comparison of Coatings Effects of 20mm Diameter of Rods

Figure 13 shows that the epoxy-nano silica coating had the best corrosion resistance and the lowest percentage weight loss for 20 mm rebars. The epoxy–cement–nano silica coating cut down on weight loss even more than epoxy and epoxy–cement did. Uncoated bars were the most affected by corrosion. This shows how well nano silica and hybrid systems can protect things.

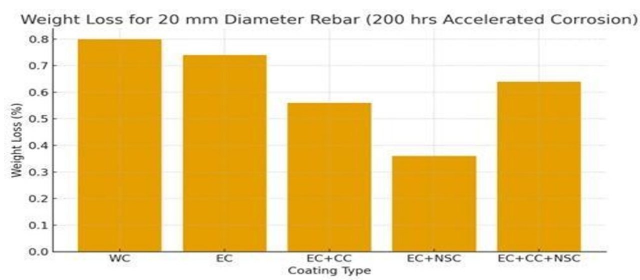

Fig 13. Comparison Of Various Coatings For 20mm Dia Rods.

4.2.4 A comparison of how well coatings work on rebars that are 12 mm, 16 mm, and 20 mm thick.

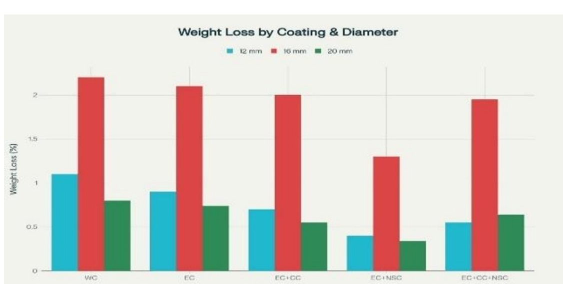

Fig 14. A graph that shows how much weight loss there is for 12 mm, 16 mm, and 20 mm rebar under different coating conditions

A combined analysis of weight loss for different coatings on 12 mm, 16 mm, and 20 mm rebars shows that epoxy–nano silica coatings always offer the best corrosion resistance. The hybrid epoxy–cement–nano silica system also works well, but its effectiveness depends on the size of the bar. All coated bars work better than uncoated steel, which shows how important nano-silica is for improving durability in corrosive conditions.

5 Conclusion

This study set out to evaluate the effectiveness of nanostructured coating systems specifically epoxy, cement, and nano-silica combinations in enhancing the corrosion resistance of steel reinforcement bars. The results of the accelerated corrosion testing show that the work's goals have been met. The first thing we did was compare four coating systems: EC, EC+CC, EC+NSC, and EC+CC+NSC. We found that adding nano-silica to the mix made the coating work much better by making the microstructure more stable, increasing adhesion, and making it less permeable to chloride ions. The epoxy-nano-silica coating (EC + NSC) kept the most weight from being lost for all bar diameters, which was the point of the test to find the best protective layer. The hybrid epoxy-cement-nano-silica system (EC + CC + NSC) also made the coating less likely to rust than other coatings, which was one of the goals of looking into multi-component nanostructured coatings. Nano-silica makes coatings much more durable and slows down the rate of corrosion. It does this by making adhesion and barrier properties better, which fixes the problems with older methods. In general, nanostructured coatings, especially those that use nano-silica, are very good at protecting steel reinforcement in harsh environments for a long time.

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