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Experimental Investigation On Strength And Resistance To Corrosion In RC Beams Enhanced By Nanomaterials

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Abstract - *This research examines how the mechanical characteristics and corrosion resistance of reinforced concrete (RC) beams are affected by the addition of nano-silica. Cement was used to partly replace nano-silica in five different mix proportions that were examined: 0% (C1), 5% (C2), 10% (C3), 15% (C4), and 20% (C5). All mixes had the same quantities of fine and coarse aggregate. Compressive strength, durability, and corrosion resistance were the main experimental metrics employed to evaluate the impact of nano-silica. According to the findings, the ideal amount of nanosilica improves strength and durability, whereas too much replacement may result in performance trade-offs. This research sheds light on environmentally friendly concrete alternatives that have longer structural life spans.*
Keywords *- mechanical properties, corrosion resistance, and nanosilica*

1. INTRODUCTION

Because of its great durability and compressive strength, reinforced concrete (RC) is one of the most used building materials. Corrosion of embedded reinforcement, which results in structural degradation and a shorter service life, is still a major problem. In order to improve the durability and mechanical performance of concrete, recent research has concentrated on advanced material modifications, including the incorporation of nanomaterials [1]. Of these nanomaterials, nano-silica (NS) has drawn the most attention because of its capacity to improve interfacial transition zones (ITZ), improve hydration, and refine microstructure in concrete [2].Because of its large surface area and pozzolanic activity, nano-silica is used as a filler to increase the strength, durability, and resistance of concrete against chloride penetration. According to studies, nano-silica improves the link strength between aggregates and cement paste, decreases porosity, and speeds up the cement's hydration process [3]. Furthermore, by creating a thick and impermeable microstructure that inhibits the passage of hostile ions, the addition of nano-silica greatly increases corrosion resistance [4].The potential of nano-silica to improve the corrosion resistance of RC structures has been shown in a number of experimental studies. For example, [5] found that a 10% substitution of nano-silica for cement greatly decreased the migration of chloride ions, improving durability. A different research by [6] discovered that the ideal amount of nano-silica increased resistance to sulfate and acid assaults in addition to compressive strength. However, an ideal dose is required for real-world applications since an excessive amount of nano-silica (over 15–20%) may cause early-age shrinkage and decreased workability [7]. Few studies have examined the impact of nano-silica on the mechanical characteristics and corrosion resistance of reinforced concrete beams in real-world settings, despite the material's apparent advantages. Research is still ongoing to determine the best dose and long-term effects (Author, Year). The purpose of this research is to assess how different replacement amounts of nano-silica (0%, 5%, 10%, 15%, and 20%) affect the mechanical characteristics and corrosion resistance of RC beams. The main goals are:

- to evaluate the durability and compressive strength of concrete that has been treated with nanosilica.
- to evaluate reinforced concrete's gains in corrosion resistance.
- to ascertain the ideal amount of nanosilica for the longest possible structural life.

The materials and methods section, which covers the mix design, specimen preparation, and testing protocols, is how the research is organized. The experimental findings, which demonstrate how nano-silica affects strength, durability, and corrosion resistance, as well as a comparison with previous studies, are followed by conclusions and suggestions.

2. MATERIALS AND METHODS

2.1 Materials Used

Ordinary Portland cement (OPC), water, fine and coarse aggregate, and nano-silica are the materials employed in this study. The mix proportions were created in order to investigate how replacing nano-silica affects the mechanical characteristics and resistance to corrosion of reinforced concrete (RC) beams.

2.1.1 Cement

Because of its excellent early strength and durability properties, grade 53 Ordinary Portland Cement (OPC) was utilized in this investigation. Prior to usage, the cement was tested for specific gravity, fineness, and setting time to ensure it met IS 12269:2013 requirements.

2.1.2 Nano-Silica

Concrete's hydration process and microstructural refinement are improved by nano-silica, a high-reactivity pozzolanic substance with ultrafine particle size. With a mean particle size of less than 50 nm, the nano-silica used in this investigation ensured efficient dispersion inside the cement matrix.

2.1.3 Fine Aggregate

River sand that was readily accessible in the area was used as fine aggregate. Good workability and strength were guaranteed by the sand's cleanliness, grade, and absence of organic contaminants.

Table 1. Utilized Materials' Properties

Material	**Property**	**Value**
Cement (OPC 53 grade)	Specific Gravity	3.15
	Fineness	3.5 %
	Initial Setting Time	30 min
	Final Setting Time	600 min
Nano-Silica	Particle Size	<50 nm
	Surface Area	200-300 m^2/g
Fine Aggregate	Specific Gravity	2.65
	Fineness Modulus	2.8
Coarse Aggregate (Crushed Granite, 20 mm)	Specific Gravity	2.75
	Water Absorption	0.5 %
Water	pH Value	>6

2.1.4 Coarse Aggregate

As coarse aggregate, crushed granite aggregate with a nominal size of 20 mm was used. The aggregate was tested for impact value, crushing strength, and water absorption, and it met IS 2386:1963 requirements.

2.1.5 Water

For mixing and curing, portable drinking water that complied with IS 456:2000 criteria was used. To ensure that there were no contaminants that may compromise hydration, the pH level was kept above 6.

2.2 Mix Proportioning and Specimen Preparation

At 0%, 5%, 10%, 15%, and 20%, nano-silica was used to partly replace cement in five different concrete mix proportions. In accordance with normal protocols, each mix was batched, mixed, cast, and cured. Details on the mix representation and percentage are given below:

Mix No.	**Mix Representation**			
	Nano Silica (%)	**Cement** (%)	**Fine Aggregate** (%)	**Coarse Aggregate** (%)
C1	0	100	100	100
C2	5	95	100	100
C3	10	90	100	100
C4	15	85	100	100
C5	20	80	100	100

2.2.1 Mixing and Casting

To guarantee even dispersion of the nano-silica, the components were precisely weighed and dry mixed. Water and nano-silica were pre-mixed separately before being added to the concrete mix in order to avoid agglomeration. After that, the new mixture was poured into conventional molds to evaluate its corrosion resistance, durability, and compressive strength.

2.2.2 Curing Process

After a day, the specimens were demolded and placed in curing tanks with potable water that was kept at 27 ± 2°C for 7, 14, and 28 days.

2.3 Compressive Strength Test

Using cured concrete cubes (150 mm × 150 mm × 150 mm), the compressive strength of concrete with nanosilica was measured. Prior to testing, the specimens were dried, and then axial stress was gradually applied using a Universal Testing Machine (UTM) at a rate of 140 kg/cm² per minute until failure. Following a 24-hour casting process, the specimens were demolded and submerged for 7, 14, and 28 days in curing tanks with potable water maintained at 27 ± 2°C.

2.4 Rapid Chloride Penetration Test (RCPT)

By measuring the permeability of chloride ions, the Rapid Chloride Penetration Test (RCPT) was used to evaluate the corrosion resistance of concrete. After 28 days of curing, cylindrical specimens (100 mm × 200 mm) were cut into 50 mm thick discs, dried, and conditioned before being put into RCPT test cells. Each specimen was subjected to a 0.3N NaOH solution on one side and a 3% NaCl solution on the other. For six hours, a steady 60V voltage was placed across the specimen; a lower charge passing indicates greater corrosion resistance. Based on the test findings, the impact of nano-silica on resistance to chloride penetration was examined.

2.5 Water Absorption Test

Concrete's porosity and permeability were assessed using the Water Absorption Test. After being weighted (W_1), oven-dried concrete cylinders were submerged in water for a whole day. Following the immersion time, the specimens were reweighed (W_2) after the surface water was removed. Higher durability was evidenced by lower water absorption values, indicating that nano-silica improved the concrete's overall density and reduced porosity.

2.6 Electrochemical Corrosion Test

The corrosion potential of reinforcement in concrete beams containing nanosilica was assessed using the Electrochemical Corrosion Test. To speed up the corrosion process, Prismatic concrete beams (100 mm × 100 mm × 500 mm) strengthened with steel bars were partly submerged in a 3.5% NaCl solution after 28 days of curing. A saturated calomel electrode (SCE) was used to measure the half-cell potential of the steel reinforcement after a continuous voltage of 12V was supplied to start the corrosion. The best nano-silica content for optimum corrosion protection was determined after the impact of nano-silica on lowering corrosion potential was investigated.

3. RESULTS AND DISCUSSION

3.1 SEM Analysis

The microstructural properties of concrete mixtures containing nanosilica were investigated using Scanning Electron Microscopy (SEM). According to the research, the control mix (C1) had a loosely packed, comparatively porous microstructure, which suggested a larger void content and a lower density. The pozzolanic interaction between nano-silica and calcium hydroxide, which led to further C-S-H gel formation, made the microstructure denser and more refined as the nano-silica concentration rose to 10% (C3). This resulted in better mechanical qualities, decreased porosity, and increased compactness. However, the SEM images revealed aggregation of nano-silica particles at higher levels of replacement (C4 and C5), which resulted in the creation of microcracks and an increase in voids. The homogenous particle distribution was upset by the severe clustering, which had an adverse effect on permeability and workability. These findings support the results of the mechanical and durability tests, demonstrating that although excessive nano-silica incorporation (≥15%) might impair concrete performance, C3 (10%) nano-silica offers the best microstructure with increased strength and durability.

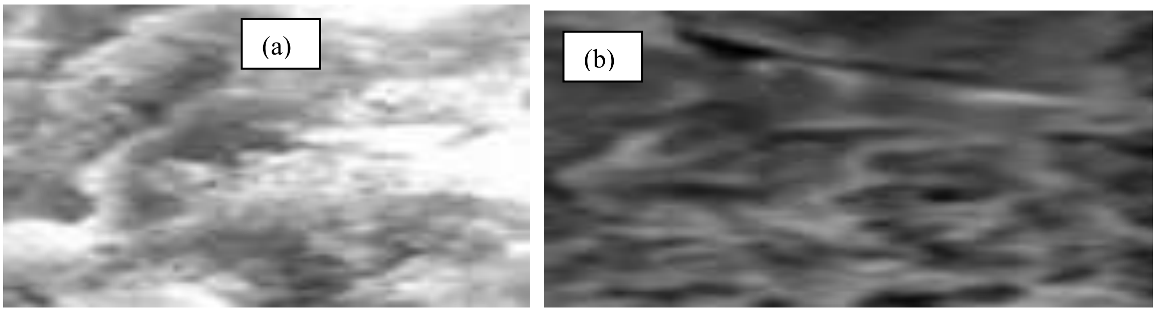

Figure 1. SEMinvestigation of (a) 0 % nano silica and (b) 20 % nano silica

3.2 Mechanical Properties

3.2.1 Compressive Strength Analysis

The purpose of the compressive strength study was to assess how the addition of nano-silica affected the concrete's strength at seven, fourteen, and twenty-eight days of curing. The results show that up to 10% replacement (C3), where the maximum strength was recorded, the inclusion of nano-silica greatly increased the compressive strength. The pozzolanic reaction of nano-silica, which improves the bonding between cement particles and refines the pore structure, is responsible for this improvement. C3's compressive strength at 7 days was 30.5 MPa, much greater than that of control mix C1 (25.4 MPa). Nevertheless, mixes C4 and C5 showed a progressive deterioration in strength after 10% replacement, most likely as a result of agglomeration effects and higher water consumption, which decreased the concrete's workability. At 28 days, C3's compressive strength was 20.7% more than C1's, indicating that the ideal degree of nano-silica incorporation for strength augmentation is 10%. The strength decrease in C4 and C5 indicates that too much nano-silica might upset the mix balance, resulting in increased porosity and ineffective hydration.

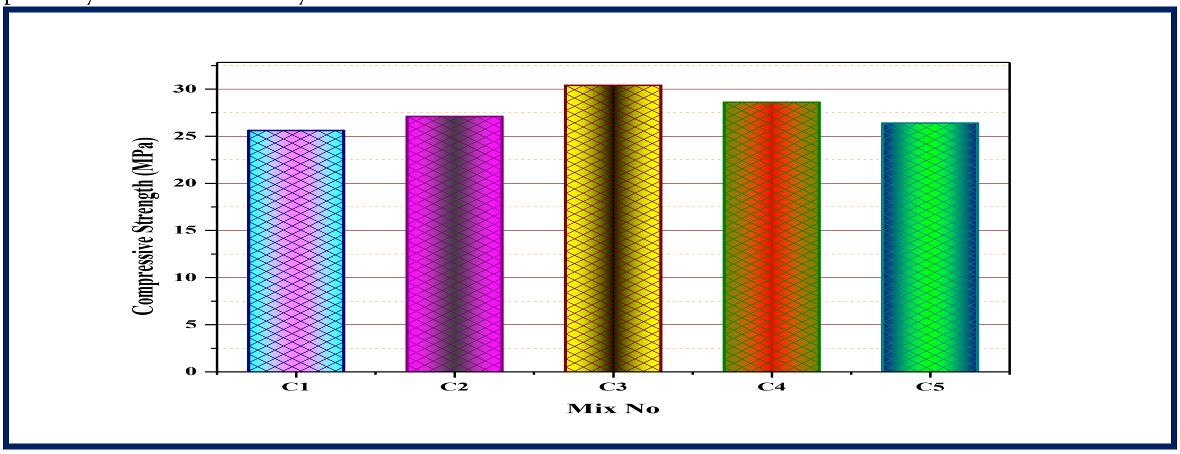

Figure 2. Compressive Strength of various specimens by after 7 Days

3.2.1 Rapid Chloride Penetration Test (RCPT) Analysis

The permeability of chloride ions in concrete, which has a direct effect on the corrosion resistance of reinforced buildings, was assessed using the Rapid Chloride Penetration Test (RCPT). The results showed that the charge flowing through the concrete dropped up to 10% replacement (C3) as the nano-silica concentration rose, suggesting improved resistance to chloride penetration. In contrast to the control mix (C1), which had the maximum permeability at 4200 Coulombs, C3 showed the lowest charge passed (1900 Coulombs), indicating improved durability and corrosion resistance. This notable 54.8% decrease in permeability demonstrates how well nano-silica refines the microstructure of concrete, resulting in better densification and less porosity.

Nevertheless, a little increase in permeability was seen after 10% nano-silica substitution (C4 and C5), with C4 and C5 recording 2500 and 3100 Coulombs, respectively. Excessive nano-silica clustering is the cause of this rise, which may result in increased porosity, microcrack development, and poor particle dispersion. Therefore, although a modest quantity of nano-silica improves durability, too much might negatively impact the performance of concrete. The best mixture for minimizing chloride permeability and, therefore, the danger of corrosion of steel reinforcement was found to be C3. According to the results, a 10% nano-silica incorporation successfully increases the durability of concrete, while greater concentrations (≥15%) may weaken the microstructure and result in increased permeability and worse long-term performance.

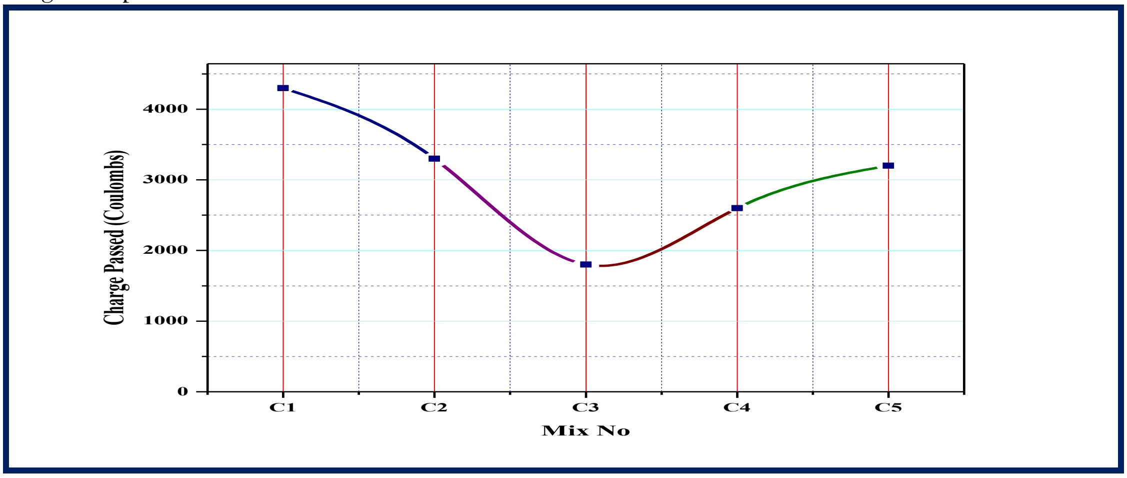

Figure 3. Chloride Permeability of different Compositions of the specimens

3.2.2 Water Absorption Test

Concrete's porosity and permeability two important characteristics affecting its durability—were assessed using the Water Absorption Test. Up to 10% replacement (C3), the findings indicated a declining trend in water absorption as the nano-silica concentration increased; beyond that, absorption levels started to increase. With a 5.8% water absorption rate, the control mix (C1) showed the highest porosity and lowest density. Water absorption dropped to 4.5% with the addition of 5% nano-silica (C2), indicating better particle packing and fewer empty areas. The combination with the greatest density and lowest permeability was C3 (10% nano-silica), which showed the lowest absorption at 3.2%. The pozzolanic reaction of nano-silica, which improves the overall compactness of the concrete matrix and refines the pore structure, is responsible for this improvement.

The water absorption started to rise after 10% replacement, with C4 (15% nano-silica) recording 4.0% and C5 (20% nano-silica) reaching 4.9%. This pattern implies that a high nano-silica concentration causes more voids to emerge, most likely as a result of poor particle agglomeration and dispersion. Such clustering may cause the concrete mix to become less homogeneous, which would increase its permeability and lessen the durability-enhancing effects of nano-silica. Overall, the results show that the best dosage for reducing water absorption and enhancing concrete's density and durability is 10% nano-silica replacement (C3). However, by generating voids, an excessive amount of nano-silica (C4 and C5) may negate these advantages, resulting in increased water absorption and decreased long-term performance.

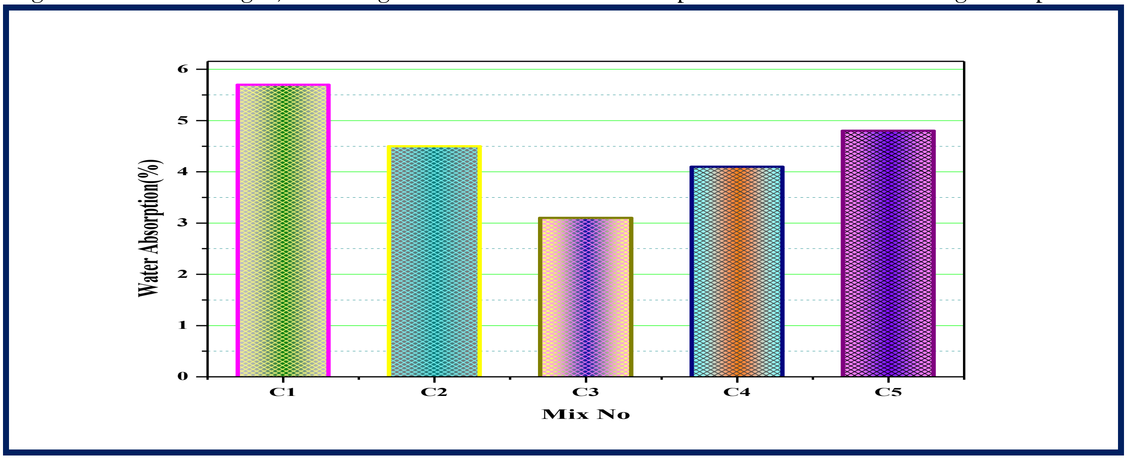

Figure 3. Percentage of Water Absorption in various compositions of the specimens

3.2.3 Electrochemical Corrosion Test

By comparing the corrosion potential of reinforced concrete beams to a standard reference electrode (SCE), the Electrochemical Corrosion Test was performed to evaluate the corrosion resistance of the beams. The findings show a distinct pattern wherein the addition of nano-silica enhanced corrosion resistance up to 10% replacement (C3), beyond which the corrosion potential marginally increased, indicating possible hazards related to an excessive amount of nano-silica. With a potential of -410 mV, the control mix (C1) showed the highest corrosion probability, suggesting a significant risk of corrosion of the reinforcement because of higher permeability and increased penetration of chloride ions. The corrosion potential increased to -330 mV with the addition of 5% nano-silica (C2), falling inside the moderate risk category and indicating better durability and decreased permeability. With a corrosion potential of -220 mV, which indicates a low chance of corrosion, C3 (10% nano-silica) showed the greatest improvement. The improved microstructure and decreased chloride permeability brought about by the pozzolanic reaction and densification effects of nano-silica are responsible for this improvement.

The corrosion potential, however, started to rise once again at greater nano-silica replacement levels (C4 and C5), with C4 recording -290 mV (moderate danger) and C5 reaching -350 mV (high risk). According to this pattern, an overabundance of nano-silica might cause particle agglomeration, which would result in uneven dispersion and void formation in the concrete matrix. These microstructural flaws may cause permeability to rise, making it easier for corrosive substances like moisture and chlorides to enter and decreasing the concrete's capacity to protect. Overall, the findings demonstrate that the best replacement level for reducing corrosion risk and greatly extending the lifespan of reinforcement is 10% nano-silica (C3). Beyond this point, however, the advantages of nano-silica decrease and corrosion susceptibility rises as a result of microvoid development and decreased compactness. This research emphasizes how crucial it is to balance strength, durability, and corrosion resistance in reinforced concrete buildings by maximizing the nano-silica content.

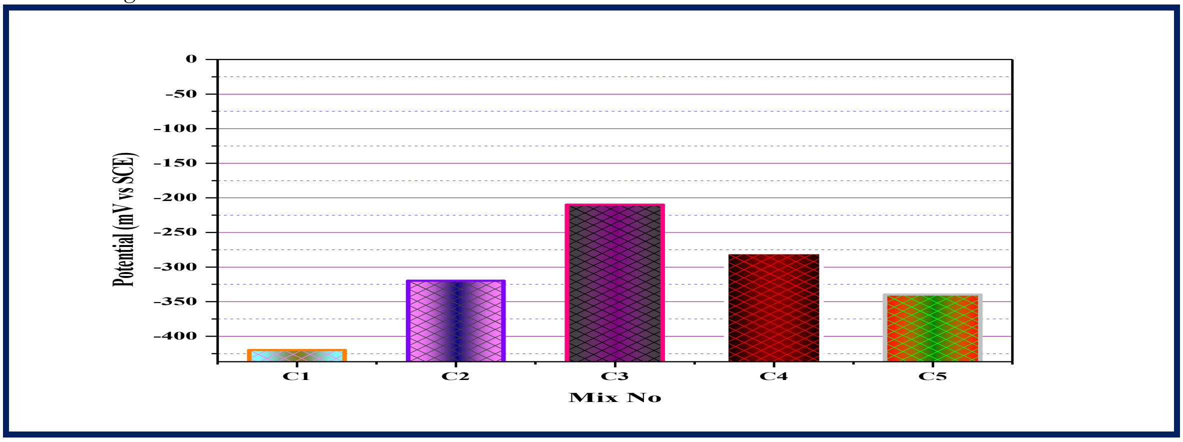

Figure 4. Corrosion Probability of the experimental specimens

4. Comparative Analysis

10% is the ideal amount of nano-silica substitution for reinforced concrete, according to a thorough analysis of mechanical and durability criteria (C3). C3 continuously shown improved results across all performance variables, including corrosion resistance, water absorption, compressive strength, and chloride permeability (RCPT), demonstrating its efficacy in improving concrete qualities. The pozzolanic reaction of nano-silica, which improves the bonding between cementitious elements and refines the concrete microstructure, is responsible for the strength gains in compressive strength, which was greatest for C3. The lowest compressive strength, on the other hand, was found in C5 (20%) nano-silica. This is probably because of severe nano-silica agglomeration, which reduces workability and particle dispersion, which leads to the production of microcracks and poorer structural integrity.

The findings of the Rapid Chloride Penetration Test (RCPT), which showed a chloride permeability that was 54.8% lower than that of the control mix (C1), further supported the higher durability of C3. This decrease is directly linked to the concrete matrix's densification by nano-silica, which reduces pore size and limits chloride ion penetration. In contrast, C1 was the least resilient mix in terms of resistance to chloride incursion due to its maximum permeability. Likewise, studies of water absorption showed that C3 had the lowest absorption rate (3.2%), indicating that it was more compact and had less porosity. By limiting moisture intrusion, which may cause long-term deterioration, lower water absorption increases the durability of concrete. C1 was more prone to degradation because it had the lowest barrier to water penetration and the greatest absorption rate (5.8%). Furthermore, C4 and C5 exhibited higher absorption than C3, suggesting that too much nano-silica might cause voids and impair the efficiency of particle packing.The electrochemical corrosion test showed that C3 had the lowest corrosion potential (-220 mV), which greatly increased the durability of reinforcement in terms of corrosion resistance. The reason for this improvement is that concrete with an optimum nano-silica concentration has less permeability, which reduces the entry of moisture and aggressive agents like chlorides. However, the greatest corrosion potential (-410 mV) was shown by C1, suggesting a considerable danger of reinforcement degradation. Excessive replacement (C4 and C5) enhanced corrosion susceptibility, perhaps because of microstructural flaws and increased permeability at larger doses, but moderate amounts of nano-silica improved corrosion resistance.

Table 3. Comparative analysis of the observations of the specimens

Performance Factor	Best Mix	Worst Mix	Observations
Compressive Strength	C3 (10%)	C5 (20%)	Peak strength at 10% replacement.
RCPT (Durability)	C3 (10%)	C1 (0%)	C3 had 54.8% lower chloride permeability than C1.
Water Absorption	C3 (10%)	C1 (0%)	C3 had the lowest absorption (3.2%), reducing permeability.
Corrosion Resistance	C3 (10%)	C1 (0%)	C3 exhibited the least corrosion potential (-220 mV).
Compressive Strength	C3 (10%)	C5 (20%)	Peak strength at 10% replacement.

5. CONCLUSION

According to the research, adding up to 10% nano-silica to reinforced concrete greatly increases its strength and longevity. Agglomeration effects and increasing porosity cause performance to deteriorate beyond this replacement level. The best combination among the studied mixtures was C3 (10% nano-silica), which showed a 20.7% increase in compressive strength over the control mix (C1), a 54.8% decrease in chloride permeability, and a 45% decrease in water absorption rate. Furthermore, C3 showed the lowest corrosion potential (-220 mV), which increased the lifespan of the reinforcement. These results suggest that the ideal dose of 10% nano-silica be applied to concrete in order to increase its mechanical strength, durability, and resistance to corrosion. Long-term durability may be adversely affected by workability problems and increased permeability caused by high nano-silica inclusion (≥15%).

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