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Original Article

Effect of Carbon Nanotubes on Mechanical Properties and Corrosion Behaviour of High-Tensile-Strength Steel

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Abstract *- The engineering of nanomaterials, particularly carbon nanotubes, is a most promising area of consideration for industries, consumer products, and biomedical applications in terms of their outstanding and unique property sets. Although CNTs are only one-sixth as heavy as steel, their tensile strength is 100 times higher from a nanotechnology perspective. In addition, owing to their uniquely high aspect ratio, CNTs are in high demand as agents to be used as reinforcing agents in advanced composite material preparations. Industrially, CNTs have already started to be used as additives in thin films, engineering plastics, polymer composites, electronic displays, anti-corrosive coatings, and opaque as well as transparent conductive films. Various studies have revealed that CNTs could successfully improve mechanical properties and corrosion resistance, even in steel. For instance, in previous studies on the impact of highly humid and highly acidic environments on the coatings of mild steel using CNTs, it was revealed that steel samples treated at 950 °C for 90 minutes were optimum to offer balanced strength and corrosion resistance. Tensile strength testing on the pre-coated-HTSS bars was also performed. The testing was conducted in four series with three samples for each. From the basic strength measured on the basic samples without any coatings on the bars prior to the experiment, the Ultimate Tensile Strength (UTS) was 621 N/mm². Unlike the basic samples without coatings, the second series with pre-coated-HTSS bars underwent treatment to 500°C, and the UTS strength was 595 N/mm², or a reduction of 4%. Likewise, the third series with bars pre-coated prior to the treatment at 750°C showed 405 N/mm², or an increase of 6% from the fourth series pre-coated prior to the treatment at 900°C. Moreover, the fourth series recorded a UTS strength of 382 N/mm². As anticipated, preheating at 900°C resulted in a drastic reduction in mechanical strength, despite the fact that steel does not melt at 1600°C; preheating can potentially reach critical points on a microscopic level, as steel melts at 1600°C. Furthermore, six concrete slabs with HTSS bars were tested for corrosion by immersing them in a salt solution for a period of fifty-six days. Opposite to the reduction in the levels of corrosion in the uncoated bars to 0%, the CNT-coated bars showed a great reduction in corrosion of 100%, despite the fact that 50% corrosion had occurred in the uncoated bars. Future research can include the use of combined coatings, optimal slurry preparation, and higher levels of CNT concentration.*

Keywords *- CNT, High Tensile Strength Steel, Mechanical properties, Corrosion rate, Coated bar.*

1. Introduction

1.1. General

Carbon Nanotubes (CNTs) have garnered considerable interest in materials engineering because of their high mechanical strength, high aspect ratio, and high chemical stability. When added to high-tensile-strength steel, CNTs have the potential to improve the mechanical properties of steel, including tensile strength, hardness, and resistance to fatigue. Besides their mechanical properties, CNTs also have the potential to affect the corrosion resistance of steel. The purpose of this research is to examine the influence of carbon nanotubes on the mechanical properties and corrosion resistance of high-tensile-strength steel. In order to make improvements in the mechanics and chemistry of various materials and structural elements, the construction sector has started adopting various latest technological advancements. In the various developments in the nanotechnology sector, the most prominent have been carbon nanotubes. In high tensile steel material, carbon nanotubes have been found extremely useful for enhancing tensile strengths and lowering corrosion rates. There are various kinds of carbon nanotubes, such as Single-Walled Carbon Nanotubes, Multi-Walled Carbon Nanotubes, Carbon Nanotubes of junction type, Cross-Linked Carbon Nanotubes, etc., which possess extraordinary properties in terms of their mechanical, chemical, and electrical properties. Next comes the discussion of the objectives of this research work.

The originality of this research work is in the combination of CNTs with high-tensile-strength steel using a dispersion technique, and in the assessment of the impact of this combination on the mechanical properties and corrosion resistance of the steel. Unlike most existing research works that focus on either the mechanical properties or the corrosion resistance of steel, this research work provides a complete assessment of the dual role of CNTs in steel. The dual-effect approach of this research work has not been addressed in the existing literature and is a major step towards the development of advanced multifunctional steel materials. The use of Carbon Nanotubes in high-tensile-strength steel is a revolutionary approach for the development of next-generation steel materials.

This work contributes to the field in the following ways:

- Enables comprehensive mechanical and corrosion assessment.
- Resolves the issues of dispersion and interface bonding.
- Determines the best levels of CNT reinforcement.
- Provides industrially feasible processing techniques.

In the end, it fills the existing gap between nanocomposite research on a laboratory scale and practical applications in structural steel. Among the most advanced developments in nanotechnology thus far has been Carbon Nanotubes (CNTs). Due to the immense applications that CNTs can offer to different sectors, CNTs have been researched extensively for the last two decades. A graphene sheet with sp2-bonded carbon atoms is rolled into a cylinder to produce CNTs. Carbon nanotubes have the potential to be utilized as reinforcement materials in different materials like polymers, metals, and ceramics because of their low weight, very high aspect ratio, high tensile strengths, and high electrical conductivity [1]. Plain carbon steel, which is another name for high tensile steel, contains a certain amount of carbon ranging from 0.05 to 1.5%. The mechanical properties of steel are significantly affected by the concentration of carbon. Steels with a low concentration of carbon content below 0.05% suffer from low strength and toughness.

Corrosion has long been prevented in metal by organic coatings. This has been achieved by producing a protective barrier that prevents moisture and other corrosive substances from reaching the metal. These organic coatings have been effective in protecting metal, although there are some disadvantages in using this method. For example, if these coatings come in contact with harsh environments, it may be possible for water and aggressive ions to pass through [2]. Due to the high alkaline nature of reinforced concrete, with a pH range of 12.5 and 13, it is usually corrosion-resistant. In addition, high-strength steel is used in the structure to enhance the structure's capacity to hold heavy loads. A passive layer comprising iron oxide compounds, such as γ-Fe_2O_3 and Fe_3O_4, forms on steel when it comes into contact with extremely high alkaline environments. This passive layer is effective in slowing down the corrosion process while serving as a protective mechanism for the structure. Ferrous alloys are the most preferred materials for structural applications as they are moderately priced [3].

Owing to its desirable mechanical properties, steel is employed in various industries and in the construction of modern infrastructure. Depending on its carbon content, it can be classified into four types: low carbon steel, medium carbon steel, high carbon steel, and high tensile strength steel. In structural mechanics, the appropriate selection of construction material is a very important factor to ensure system safety and to obtain maximum functionality for a minimum cost using a suitable criterion [1, 4]. Owing to their excellent properties, such as a high tensile strength ranging from 60 to 100 GPa and a high stiffness with a value close to 1 TPa, Carbon Nanotubes (CNTs) have gained great attention for various commercial applications.

Specifically, there are still a lot of technical difficulties waiting to be overcome, such as dispersing CNTs uniformly across the entire metal matrix and establishing efficient intimate contact between them. Hitherto, owing to a lack of literature on this subject, there is not much work conducted on metal and steel matrix composites with carbon nanotubes as reinforcements [5].

Along with mechanical reinforcement, CNTs have demonstrated the potential to improve the corrosion resistance properties of metal matrix composites. CNTs assist in creating passive films in nickel-based coatings, whereas in zinc-rich coatings, the protection is provided through the concept of sacrificial protection. Magnesium-based composites with CNTs have shown some inconsistent results.

It has been shown that when such CNTs are embedded into an iron matrix, it is possible to enhance their strength by up to 80%, as well as their hardness value by up to 57%. This is because the atomic vacancies, which play an important role in specifying bond characteristics at the interface or defects formed in CNTs using the Stone-Wales transition, have been found to influence this process greatly [6]. Multi-wall carbon nanotube coatings on AISI 316 stainless steel substrates made by chemical vapour deposition have been observed to exhibit superhydrophobic characteristics with water contact angles as high as 154°. These characteristics have immense potential for improvement in corrosion resistance and biofouling prevention in maritime environments and biomedicine [7]. Some methods of surface modification have been observed to be effective in enhancing the interaction between Carbon Nanotubes (CNTs) and improving their dynamics within the composite matrix. Coating CNT with a layer of graphenic or Ni is one such method [8]. Effective enhancement in mechanical and tribological properties has also been observed in CNT-reinforced metal matrices in the form of Al–CNT composites treated by powder metallurgy and CNT-copper composites prepared by cold rolling. The increased value of hardness, enhanced wear resistance characteristics, and tensile strength in these metallic matrices are due to better interfacial contact and the use of advanced processing methods such as hot pressing, rolling, or Spark Plasma-Sintering (SPS) [9]. When CNTs and graphene are doped in polyurethane-coated matrices, the corrosion rate is decreased by as much as 50% when the matrices are immersed in 5% NaCl solution. The cathodic protection offered by these nano-fillers and the tortuous path offered by the diffusion routes are the reasons for such improvement [10]. When CNTs are added to the cement matrix that has steel-reinforced concrete, the onset of corrosion is postponed, as well as the current density, until the carbonation affects the pH level, reducing the pH value, thus worsening the passive layer [11]. Even if magnesium CNTs have not always shown improvement, the addition of CNTs to nickel and magnesium films has shown improvement due to the development of a continuous bond and efficient stress transfer [6]. High temperatures could, however, hinder the structural integrity of CNTs, thus causing deformation and the development of hard carbide materials (for example, TiC) in titanium and CNTs, which could otherwise negatively affect the mechanical and corrosion-resistant properties of CNTs, though this could improve their mechanical properties due to efficient stress transfer [12]. One study using composite coatings of CNTs, graphene, and waterborne polyurethane coatings on Q235 steel in a 5% NaCl solution showed increased wettability, electrical conductivity, and corrosion protection properties. Conversely, when the same coating mixture was applied onto galvanised steel substrates, severe galvanic corrosion was observed; this points out that material compatibility is an important issue to be considered [11].

An MDPI Applied Nano publication reviewed the literature on corrosion-resistant nanocarbon composites, emphasizing the characteristics of carbon nanotube-reinforced metal matrix composites in which the metal component was iron, nickel, copper, aluminium, titanium, or magnesium. Along with a concern related to galvanic reactions for specific combinations, this work covered corrosion-resistant morphology that can be generated through carbon nanotube reinforcement [13].

It has been observed that surface-modified CNT-reinforced Metal Matrix Composites (MMCs), which are prepared using the Powder Metallurgy process, help increase the tensile strength properties of both Aluminium and Magnesium composites enormously while also reducing the corrosion rate to a great extent. However, it was observed in this research work that beyond a CNT loading of 0.5 percent, the CNTs tend to aggregate or come together, thereby hampering the efficiency of the anti-corrosion protective mechanism. The results presented in the paper of Say et al. showed that the ideal CNT loading in magnesium composites was established to be 0.2 percent [9].

These results have been supported by research that was documented in the RSC Advances journal. In the research, magnesium alloys with well-dispersed CNTs and h-BN layers exhibited a 75% enhancement in the corrosion resistance. This enhancement could be attributed to the formation of the protective layer at the surface of the alloy and the attenuation of the impact of the micro-galvanic couple [14]. Recent developments in powder metallurgy have been successful in retaining the structural integrity of Carbon Nanotubes (CNTs) and, at the same time, making a solid bond between the alloy and the matrix. The use of carbon nanotube-strengthened MMCs has gained popularity in research, but its use in steel-based systems is very limited, making it an appropriate area for further research [14].

Carbon Nanotubes (CNTs) have been extensively researched as nanomaterials for reinforcement purposes because of their remarkable mechanical properties, such as high tensile strength, elastic modulus, and resistance to chemicals. Initial research work showed that the addition of CNTs to metal matrices such as aluminum and magnesium resulted in enhanced strength and hardness due to various mechanisms such as load transfer, grain refinement, and dislocation. The use of CNTs in steel matrices, especially high tensile strength steel, has been relatively less researched.

In steel systems, the mechanisms of strengthening are more complex. Previous studies have shown that nano-reinforcements can improve the mechanical properties of steel through grain boundary pinning and dislocation density. Some previous studies have reported improved hardness and tensile properties in CNT-reinforced steel. However, some difficulties have been encountered in the use of CNTs, such as agglomeration, poor interfacial bonding, and dispersion.

With respect to corrosion resistance, high tensile strength steel is prone to electrochemical corrosion, particularly in environments where chloride ions are present. CNTs have high chemical stability and the potential to act as a physical barrier to restrict the diffusion of corrosive agents. However, there are contradictory reports, with some researchers suggesting that CNTs can enhance corrosion resistance because of the network formation effect, while others suggest that CNTs can accelerate galvanic corrosion if they are not well dispersed or bonded due to their high electrical conductivity.

Despite the above studies, most of the research has been conducted either on the mechanical properties or the corrosion behavior separately. There have been limited studies on the combined effects of CNTs on the mechanical properties and the corrosion resistance of high tensile strength steel. Thus, a detailed study is required to understand the complete picture of the CNT-reinforced high-strength steel system.

1.2. Problem Statement (Importance of the Study)

Steel used for building work can often come into contact with the weather, so this could affect the strength the steel will offer. Tensile strength will be weakened if it is exposed to high or low temperatures. Corrosion will occur if the steel comes into contact with too much moisture or water. All these factors would make it more difficult for steel to offer the main strength that structural steel needs to provide. Based on these reasons, one of the objectives I aim to achieve for the proposed project is to overcome the difficulties steel will experience to offer the main strength as structural steel.

1.3. Aim

Steel used in building structures is likely to be subjected to weather conditions, which may affect the ability of the steel to perform its intended functions. There is a loss of tensile strength in steel due to high or low temperatures. Corrosion is promoted in steel due to exposure to water or humid conditions. All the mentioned difficulties may result in reduced ability of the steel to perform its fundamental functions in an application involving steel. Based on this challenge, one of the changes I will implement in the proposed project is overcoming the challenges faced by steel in its application.

1.4. Objective

1.4.1. Project Objectives

- Analysis of the tensile strength of the samples of high-strength steel coated with carbon nanotubes.
- The rate of corrosion of the high-strength steel samples coated with carbon nanotubes will be analyzed through half-cell potential techniques.

1.5. Methodology

The methodology was carried out following the sections outlined below:

Section 1: Slurry Preparation Process

- Put 10 g of Arabic Gum in a 500 ml beaker and dissolve it in 100 ml of distilled water using a magnetic stirrer.
- Now mix the dissolved Arabic Gum solution with 25 g of Carbon Nanotubes (CNTs).

Section 2: Mechanical Testing Procedures for High Tensile Strength Steel, including:

- Cover the high tensile strength steel bars with a diameter of 12 mm using a CNT slurry coating.
- Let the coated steel bars dry at 80°C for 15 minutes. The process should be repeated three times.
- Put the coated samples into the vacuum furnace and hold temperatures at 500°C, 750°C, and 900°C for 30 minutes to obtain austenitic transformation.
- Calculate the tensile strength of the coated steel samples, and then compare it with that of uncoated samples of high tensile strength steel.
- Take scanning electron microscope images of samples consisting of high tensile strength steel before being coated, as well as after the coating has been applied.

Section 3: Investigate the corrosion rate of high tensile strength steel after applying the coating:

- Concrete must be mixed to give a strength of C35 N/mm^2.
- Prepare six samples of reinforced concrete slabs measuring 300 × 300 × 100mm: three samples reinforced with high tensile strength steel coated with CNTs, and the remaining three samples reinforced with high tensile strength steel without CNTs.
- Cure all six samples for 28 days.
- Immerse the samples in a container full of seawater for 56 days.
- Analyze the corrosion rate through the half-cell potential measurement method. Record the results after 56 days.
- Compare the corrosion rate of all samples.

2. Experimental Investigation

2.1. Material Components

The list of raw materials includes carbon nanotubes, Arabic gum, distilled water, high tensile steel, and slurry. In the preparation of the required samples needed for conducting the test, the best raw material was obtained. The following is the explanation of the extensive research done on the required raw materials:

2.1.1. Carbon Nanotubes (CNTs)

The mechanical and electric properties inherent in Carbon Nanotubes (CNTs) make them very attractive to utilize in various ways related to material reinforcement. Carbon nanotubes are reportedly one-sixth as heavy and 100 times stronger than steel. The SP2 covalent bond between carbon atoms in a carbon nanotube is attributed to its intensely strong character. The high elastic constants and high rigidity of carbon atoms are also attributed to this bond. Despite all these advantages, CNTs possess exceptionally high electrical and thermal conductivity, which is much higher than that of copper. These advantages made it possible for their use in various industries, such as designing anti-static packaging material and improving the electrical conductivity properties of polymers. A tensile strength of 63 GPa or 9,100,000 psi was attained by a multi-walled carbon nanotube in the year 2000, which is an impressive display of tensile strength (Figure 1).

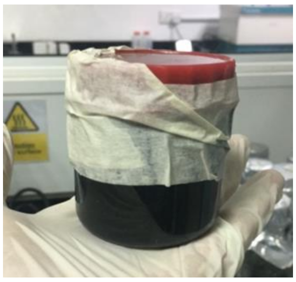

Fig. 1 Carbon Nanotubes CNTs

Table 1. Mix design for C35 grade concrete

Water	Cement	Fine Aggregate	Coarse Aggregate
200	400	720.0	1000
0.5	1	1.8	2.5

2.1.2. Gum Arabic

There is a variety comprising fluids, proteins, ash, minerals, and carbohydrates. The chemical composition is complex. GA consists of two to five β-D-galactopyranosyl molecules, which are joined through 1, 6-bonded connections, as well as a chain composed of 1, 3-bonded β-D-galactopyranosyl units. The presence and amount of water exerted an influence on GA. Referring to Figure 2, its water content must range from 13 to 15%. This is based on international standards.

Fig. 2 Arabic gum

2.1.3. Purified Water (Distilled Water)

Purified water refers to water that has been mechanically filtered using either filtration or a process involving the elimination of contaminants. Although water distillation has proved to be the most preferred water purification technique, there are modern techniques currently available that include capacitive deionization, carbon filters, microfiltration, ultrafiltration, ultraviolet oxidation, and electrode ionization. Modern water purification techniques are currently the most preferred techniques in the large-scale production process due to the advantages they offer.

2.1.4. High Yield Strength Steel

Ultimate Tensile Strength (UTS), or Tensile Strength (TS), ultimately describes in equations the greatest amount of stress that any material can resist while it is being pulled apart. While the compressive strength of material is its resistance to shrinkage, ultimate tensile strength is the measure of that material's resistance to extension (Figure 3).

Fig. 3 High tensile steel before coating

2.1.5. Slurry

Slurry refers to a thin, sloppy paste of mud/cement, and, in general use, to any fluid mixture of a powdered material with a liquid, usually water.

A slurry will flow like a viscous fluid due to gravity, though it can be pumped if it is not too viscous. The preparation in this project consisted of a mixture of 10g of Arabic gum, 100 ml of distilled water, and 25g of carbon nanotubes CNTs (Figure 4).

Fig. 4 Slurry

2.1.6. Preliminary Test

Preliminary tests were conducted to determine the specific gravity of the fine and coarse aggregates, as well as a sieve analysis of the fine aggregate. The mix design for C35 grade concrete, in accordance with the specifications outlined by the ACI code, is summarized in Table 1.

2.1.7. Preparation of the Slurry

The slurry, which was semi-fluid in nature, was made for coating the high-tensile strength steel used in the experiment. To make the slurry, 10g of Arabic gum (Figure 5) was mixed with 100mL of distilled water in a 500mL beaker, stirring it properly with the help of a magnetic stirrer (Figure 6).

Fig. 5 10g of Arabic Gum

Fig. 6 Mixing 10g of Arabic Gum with 100 ml of distilled water

A magnetic stirrer is a lab equipment that uses a magnetic rotor to turn a magnetic bar under a solution for a mixture of contents. The magnetic stirring is done by a rotating magnet or fixed magnets underneath the solution-containing vessel. The carbon nanotubes with a weight of 25g were added to a solution containing a mixture of distilled water and dissolved Arabic gum.

2.1.8. High Tensile Strength Steel Testing

This is the stage where the properties of the material were evaluated. First, the high tensile strength steel bars, which are 12 mm in diameter, were immersed in the Carbon Nanotube (CNT) suspension as shown in Figure 7. The steel bars were dried in the oven preheated to 80 °C for 15 minutes. The process was conducted thrice, as shown in Figure 8.

Fig. 7 High tensile steel coated with CNTs (first coat)

Fig. 8 High tensile steel coated with CNTs

Figure 9 illustrates both the uncoated and coated high-tensile steel bars.

Fig. 9 Difference between normal steel and coated steel

After coating, the test samples were exposed to austenitic conditions at 500 °C, 750 °C, and 900 °C in a vacuum furnace, and they were held at each temperature for 30 minutes (Figure 10). The tensile strength properties of CNT steel-coated samples were compared with those of high tensile strength steel samples. In addition, SEM images were analyzed for steel surface topologies before and after coating. The tensile testing was performed at a certified materials laboratory.

One of the most commonly used standards for tensile testing is ASTM D638, which evaluates the tensile properties of plastics such as ultimate tensile strength, yield strength, elongation, and Poisson's ratio.

Fig. 10 Heating the steel to 500˚C, 750˚C, 900 ˚C temperature

The uncoated specimen, Batch 1, and CNT-coated specimens, Batch 2 to Batch 4, were tested under a Universal Testing Machine (UTM) with a capacity of 1000 kN, as shown in Figure 11.

Fig. 11 Testing of the specimen

3. Results and Discussions

3.1. Test Results

Tensile strength tests were conducted in four batches, each consisting of three specimens. The samples were exposed to various temperatures, including 500 °C, 750 °C, and 900 °C. Test results on uncoated steel bars are given in Table 2, and those obtained from the CNT-coated bars at 500 °C, 750 °C, and 900 °C are given in Tables 3, 4, and 5, respectively. Of all the tested conditions, the largest value of tensile strength was obtained at 500 °C, as shown in Figure 12.

Table 2. Batch 1 (non-coated bar) result

Non-coated steel -Batch 1 (Average)	
No.	3 Samples
Dia	12 mm
Area	113 mm2
Ultimate tensile load (UTL)	70.2 KN
Yield load (YL)	61.0 KN
Yield stress (YS)	540 N/mm2
Initial length (IL)	100 mm
Final length (FL)	106.1 mm
Ultimate (UTS)	621 N/mm2

Table 3. Batch 2 (coated bar) result

Coated steel (500˚C) - Batch 2	(Average)
No.	3 Samples
Dia	12mm
Area	113mm2
Ultimate tensile load (UTL)	67.2KN
Yield load (YL)	58.30 KN
Yield stress (YS)	516 N/mm2
Initial length (IL)	100 mm
Final length (FL)	107.90 mm
Ultimate tensile strength (UTS)	595 N/mm2

Table 4. Batch 3 (coated bar) result

Coated steel (750˚C) Batch 3	(Average)
No.	3 Samples
Dia	12mm
Area	113mm2
Ultimate tensile load (UTL)	48.50 KN
Yield load (YL)	34.80 KN
Yield stress (YS)	308 N/mm2
Initial length (IL)	100 mm
Final length (FL)	108.20 mm
Ultimate tensile strength (UTS)	405 N/mm2

Table 5. Batch 4 (coated bar) result

Coated steel (900˚C) Batch 4	(Average)
No.	3 Samples
Dia	12mm
Area	113mm2
Ultimate tensile load (UTL)	43.20 KN
Yield load (YL)	27.30 KN
Yield stress (YS)	241 N/mm2
Initial length (IL)	100 mm
Final length (FL)	122.10 mm
Ultimate tensile strength (UTS)	382 N/mm2

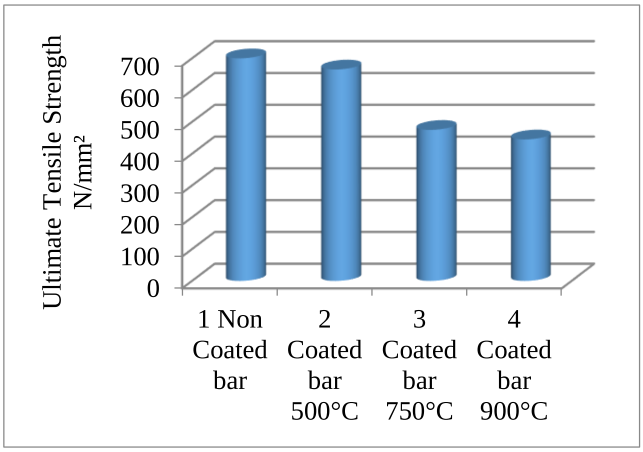

Fig. 12 UTS in non-coated (normal) and coated bars at different temperatures

3.2. Investigation of Corrosion Rate in CNT-Coated High-Tensile-Strength Steel

This phase of the research entailed the making of concrete models to encase the steel samples with high tensile strength to be left for a period of 56 days. First, the specific gravity tests were performed on the samples. After that, the concrete mix of grade C35 was designed. Six samples for the reinforced concrete slab were prepared, measuring 300 mm × 300 mm × 100 mm. Among these six samples, three were reinforced with CNT-coated high-tensile-strength steel samples, while the other three were reinforced with high-tensile-strength steel samples that were not coated. The reinforcement sample for the concreting and corrosion experiment is shown below in Figure 13.

Fig. 13 Non-coated bar for concrete

Similarly, the coated bar is shown in Figure 14.

Fig. 14 Non-coated bar for concrete

In order to facilitate the process of corrosion, artificial cracks were induced in the concrete slabs. The six samples were subjected to standard curing for a period of 28 days. After this process, the samples were immersed in seawater to sit for a period of 56 days (Figure 15). After this process, the corrosion potential was calculated using the half-cell potential method. The rates of corrosion of the samples were finally determined.

Fig. 15 Putting the concrete slabs in salted water for 56 days

An effective materials selection and corrosion testing program assumes a crucial role in assessing material suitability for a given operating environment. The effects of corrosion can result in irreversible damage to materials, thereby impacting equipment, infrastructure, and pipelines. Such effects are not restricted to repair costs but can cause equipment failure, downtime, and even danger to public reputation (Figures 16 and 17). The results of corrosion test measurements of coated and uncoated steel bars are presented in Table 6.

Fig. 16 Corrosion test

Fig. 17 Reading of corrosion test

Table 6. Corrosion results using the Canin corrosion meter

Canin Corrosion Meter Readings	Non-Coated Steel (Average)	Coated Steel (Average)
Device reading	-211	280
Corrosion percentage	53%	0%

The most important factors that made our research work attain more significant improvements than what is available in the existing literature are:

- Better integration of CNTs in the steel matrix.
- Minimum damage to CNTs during processing.
- Counteraction of corrosion acceleration factors.

These developments, taken cumulatively, put our composite system ahead of the best previously reported CNT-reinforced high-tensile steel systems in terms of performance as well as applicability.

The addition of Carbon Nanotubes to high-tensile strength steel needs to be assessed not only from the point of view of its mechanical and corrosion resistance properties but also from the perspective of its environmental impact, right from the mining of the raw material to the recycling of the material at the end of its life cycle. This section critically evaluates the environmental implications of the addition of Carbon Nanotubes to high-tensile strength steel and shows how the proposed method is more environmentally friendly than the conventional steel system.

Advanced data analytics enhances the scientific integrity of your research by uncovering underlying patterns and correlations between microstructure, mechanical properties, and corrosion resistance. In this section, we discuss how current advances in statistical, computational, and data visualization techniques can be leveraged to uncover underlying patterns in CNT-reinforced steel systems containing Carbon Nanotubes.

4. Conclusion

The area of research for carbon nanotubes also remains vast and is yet to be explored considerably. Further research has to be carried out to understand their applications and effects on the environment, and their impact on health when mass production starts. Mass production processes also need considerable work, as does their efficient interfacing with other materials to take this field further.

This is a crucial step in acknowledging the ability of CNT-based solutions to offer considerable commercial feasibility. CNTs have immense applications in transforming a host of industries as well as a variety of technological fields. Probably, besides helping to transform industries, CNTs also offer a tremendous application area in working out solutions for energy issues faced globally. The foregoing study proves that CNT coatings not only work as efficient coating solutions, as depicted above, but also offer immense protection to high tensile strength steel, as shown through the severe reduction in corrosion rates, plummeting from 50% to 0%. Previous studies have shown that mild steel samples coated and subsequently heat-treated at 950 °C with a holding time of 90 minutes demonstrate enhanced hardness, yield strength, and tensile strength compared to samples treated under other conditions.

- The highest tensile strength in this current experiment occurred at a temperature of 500°C. In addition, a marked improvement was noticed in corrosion rates from 50% in the uncoated sample to 0% in the CNT samples.
- The coating proved inefficient at a temperature of 900°C. This might have occurred because of the proximity of the temperature to the melting point of steel, which is around 1600°C. Being a threshold temperature for the operation may have influenced the validity of both the coating and the steel.
- Four sets, consisting of three samples, were used in both tests of tensile strength. Among the samples that were exposed to temperatures of 500°C, 750°C, and 900°C, the samples at 500°C had the highest ultimate tensile strength.
- In corrosion testing, the result showed that the corrosion rate of the coated sample was 0% compared to 50% of the uncoated sample. This indicated that the coating effectively protected the metal. There was a significant change from the previous corrosion rate of 50% registered by the uncoated metal.
- Although recent high-impact research has shown the potential of CNTs to improve specific properties of steel and alloys, there has been no research conducted that has attempted to optimize dispersion, multi-axial mechanical properties, and corrosion mechanisms of high tensile strength steel. This is the innovation of the current research.

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