

Mechanical and durability performance of hybrid nano clay–CNT concrete: Experimental investigation and data-driven polynomial regression modeling

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Abstract

Concrete remains the most widely used construction material, yet its brittleness, microcracking susceptibility, and durability limitations continue to challenge the development of long-lasting infrastructure. At the same time, reducing the environmental impacts associated with cement production requires innovative materials that improve concrete performance. Nanomaterials such as nano clay and carbon nanotubes (CNTs) offer potential for modifying the cementitious matrix and enhancing mechanical and durability properties. However, their combined effects, particularly when integrated with predictive modelling, remain insufficiently investigated. This study evaluates M35 concrete incorporating 0–6% nano clay as a partial replacement of Ordinary Portland Cement and 0–0.20% multi-walled carbon nanotubes (MWCNTs). Compressive, flexural, and split tensile strengths were evaluated at 7, 14, and 28 days, while water absorption was considered as a durability indicator. The optimum hybrid mixture containing 4% nano clay and 0.10% CNTs exhibited improved mechanical performance compared with the control mixture. Second-degree polynomial regression models were developed using nano clay content, CNT dosage, and curing age as predictor variables. The models demonstrated high predictive capability, with R^2 values ranging from 0.94 to 0.99. Sensitivity analysis identified nano clay content, CNT dosage, and curing age as important parameters influencing concrete performance. The combined incorporation of nano clay and CNTs improved strength and reduced water absorption, indicating enhanced matrix densification and resistance to crack initiation and propagation. The proposed experimental and data-driven framework provides a useful approach for predicting the performance of hybrid nanomaterial-modified concrete and supports the development of durable and sustainable concrete for long-term infrastructure applications.

Keywords: Hybrid nanomaterials, Carbon nanotubes, Nano clay, Sustainability, Data-driven polynomial regression model algorithms

1. Introduction

Raw materials, low price, and flexibility of concrete have continued to make it the most utilized building material globally [1]. However, it is vulnerable to wear issues in harsh conditions and inherently flawed like brittleness and microcracking [2]. The service life of concrete structures is strongly influenced by deterioration mechanisms and the resulting durability performance of concrete. Therefore, understanding durability-related factors is essential for ensuring the long-term performance and serviceability of concrete structures [3]. Due to these issues, concrete buildings have shorter lifespan and require more often repair. The urgent necessity to find long-term, environmental friendly and highly effective alternatives are also emphasized by the fact the cement industry is responsible to approximately 8 percent of CO₂ emissions worldwide [4]. To make products of tomorrow, the following issues must be overcome: building materials with better mechanical strength and resistance through time [5]. The development of advanced cementitious materials requires improved mechanical strength and long-term durability. The incorporation of synthesized nanomaterials can enhance the strength and durability performance of cementitious composites [6]. Nanoscale modifications provided by nanotechnology can augment cementitious composites in terms of strength, durability and sustainability. Nano clay is different to other nanomaterials in that it has pozzolanic and filling properties. It has a multilayer structure that enhances the distribution of pore sizes, hydration of cement, and compacting. This micro structural enhancement enhances the material resistance to carbonation and sulphate attack and chloride intrusion by improving the compressive strength and reducing the permeability [7]. Developing sustainable concrete with improved fresh, hardened, durability, and microstructural properties remains an important challenge. The use of seawater in concrete has shown considerable potential, while requiring careful evaluation of its effects on the overall performance and long-term durability of concrete [8]. Developing durable cementitious materials with improved resistance to aggressive environmental conditions remains an important challenge. The partial substitution of cement with non-precalcined bentonite has shown considerable potential for reducing carbonation,

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sulfate attack, and chloride ingress [9]. Eight and nine In addition to that, carbon nanotubes (CNTs) stand a high chance of addressing brittle behavior of cement-based composites due to its remarkable tensile strength, rigidity, and ability to close gaps between cracks. Fractures of nanoscale can be bridged, tensile, flexural and fracture toughness enhanced, and crack propagation retarded by carbon nanotubes [10, 11]. Although both nano clay and CNTs have been under research of various studies, there is a gap in literature covering the subject of hybrid systems that combine the two [12]. Combining nanomaterials such as carbon nanotubes (CNTs), nano clay enhances mechanical performance and hydration respectively by densifying the microstructure and cement matrix respectively by strengthening the cement at the nanoscale. The combination of these ingredients can result in a new form of hybrid nanomaterial concrete with great performance [13]. Developing concrete with enhanced mechanical performance and resistance to extreme environmental conditions remains an important challenge. The incorporation of hybrid nanoparticles has shown considerable potential for improving the microstructure and mechanical properties of concrete, both before and after gamma-ray exposure [14]. Developing sustainable high-performance concrete with enhanced mechanical performance remains an important challenge. The incorporation of thermally treated natural fibers has shown considerable potential for improving the mechanical properties of concrete, while machine learning can effectively predict its performance [15]. There is lack of understanding of the best doses, interaction forces and long term durability effects. It is essential to forecast these innovative materials' long-term behavior after initial testing, since sustainable infrastructure is vital. Nanomaterial dose, cure time, and environmental conditions are only a few examples of the intricate interconnections that conventional durability models based on empirical equations often miss [16]. Building materials research has been making more and more use of data-driven modeling methodologies for predictive modeling, including polynomial regression and other supervised learning techniques [17]. To establish this, data-driven modelling approaches such as polynomial regression and other supervised learning techniques have increasingly been applied in construction materials research for predictive modelling [18]. Machine learning algorithms are able to discover nonlinear correlations between input variables and durability outcomes, even with little experimental data [19]. Machine learning provides a strong foundation for forecasting Hybrid nanomaterial concretes' long-term durability when coupled with experimental validation [20]. In Previous research has mostly concentrated on forecasting the parameters of conventional or single-nanomaterial modified concrete systems, even if machine learning methods are finding more and more uses in concrete research. Modeling hybrid nanomaterial concretes, in which several nanoscale additives interact concurrently inside the cement matrix, has received little attention [21]. Because of the complicated nonlinear connections introduced by the combined effect of nano clay and carbon nanotubes, conventional empirical models are ill-equipped to represent the link between nanomaterial dose, curing age, and the mechanical and durability attributes that arise [22]. Predictive models that can capture the nature of these coupled interactions in hybrid nanomaterial systems are therefore an area where much research is lacking [23]. To estimate the water absorption, the hybrid nano clay-CNT concrete's compressive, flexural, and split tensile strengths, this research develops a second-degree polynomial regression framework [24]. Optimizing hybrid nanomaterial concrete for increased strength and durability is made possible by the data-driven tool that the modeling technique offers for predicting performance within the dose ranges that have been evaluated [25].

The uniqueness of this research is a combination of experimental techniques and ML to assess the short-term increases in performance and data-driven long-term sustainability. This two-fold approach, this links the immediate lab testing with service life in modern infrastructure, is a sustainable, scientific approach to road involving the inclusion of hybrid nanomaterial concretes.

Even though the impacts of carbon nanotubes and nanoclay in cementitious composites have been researched a lot, we still have some gaps in our knowledge. Therefore, the previous research has largely overlooked the hybrid effects of nano clay and CNTs with respect to researching the effects of individual nanomaterial alterations [26]. As such, there have not been sufficient research efforts to determine the synergistic nature of nanomaterials e.g. nano clay and CNTs which may enhance crack-bridging capabilities in the presence of the effects of individual nanomaterials [27]. The hybrid reinforcement mechanism arises from the complementary effects of graphene oxide (GO) and carbon nanotubes (CNTs). GO nanosheets promote nucleation and growth of hydration products, refine the pore structure, and strengthen the cementitious matrix, while CNTs bridge and arrest microcracks through crack-bridging and pull-out mechanisms. Their combined action enhances load transfer, delays crack propagation, and improves the overall mechanical and strain-hardening performance of the cement composite [28]. Accurately predicting the compressive strength of sustainable fiber-reinforced concrete remains an important challenge. The application of multiple machine learning models has shown considerable potential for predicting the compressive strength of multiwalled carbon nanotube-reinforced high-volume fly ash concrete [29]. Besides that, there have been no prediction models that can capture the interaction nature among mechanical performance, age of curing, and dose of nanomaterial This complicates the ability to make general conclusions and locate the sweet spot of the mix proportions in the real life. Hence, to get a better understanding Considering the combined effects of CNTs and nanoclay in hybrid nanomaterial concrete systems, a comprehensive study is required that integrates experimental assessment with predictive modeling [30]. This research intends to fill that void by creating a prediction framework based on machine learning to explain the interactions between the nanomaterials and the concrete's characteristics, and by conducting experimental evaluations of the hybrid nano clay-CNT concrete's mechanical and durability performance [31]. Several research gaps have been found by the examination of current material. While it is well-established that nano clay improves cementitious materials' hydration process and pore refinement and carbon nanotubes enhance tensile resistance through crack-bridging mechanisms, the majority of studies have only examined these nanomaterials separately, not in combination [32]. Thus yet, nothing is known about how CNTs and nano clay affect mechanical performance and durability as a result of their combined interaction. In addition, much of the current research is based on experimental findings, and not much is done to create predictive modeling frameworks that can capture the nonlinear relationships among We will try again, sir, if it is less than 20%, of the concrete [33]. For this reason, a comprehensive research is required to optimize hybrid nanomaterial concrete by combining experimental examination with data-driven modeling. This study aims to fill such gaps by studying the impacts of nano clay and carbon nanotubes on M35 grade concrete's mechanical and durability qualities in combination. To do so, it constructs a predictive modeling framework to assess the synergistic interactions between the two materials.

This study aims to investigate the characteristics of hybrid nano clay-carbon nanotube (CNT) concrete through theoretical prediction and practical testing. The overall goal of the project is to increase the mechanical and the durability performance of M35 grade of concrete through formulation of a hybrid nanomaterial concrete, incorporation CNTs to reinforce the nanoscale and nano clay to replace some cement. Experimental measurements were done on water absorption, compressive strength, flexural strength, and split tensile strength at various curing ages. In addition, a prediction model using the poly regression was developed to test a relationship existing between CNT dose, curing age, nano clay concentration and performance of hybrid nanomaterial concrete. The purpose of the work is to understand a synergistic combination of nano clay and CNTs and identify the optimal mix ratios that can increase strength and durability performance through the combination of experimental and modeling methodologies.

2. Materials and methodology

High-reactivity nanomaterials, including calcined nano-clay and nano-clay (NC) have attracted a lot of attention in cementitious composites due to their ability to improve the mechanical performance and durability. Research has shown that nano-clay may enhance concrete's strength and reduce its permeability by a variety of processes, including micro-filling, pozzolanic reaction, nucleation of hydration products, and pore refinement [34-36]. Studies on blended cement systems and self-consolidating concrete have shown that small amounts of NC (usually 1-3%) may improve corrosion and chloride penetration resistance, workability, and durability [37, 38]. It is crucial to use the correct dose and dispersion methods, including ultrasonication, to prevent particle agglomeration and decreased effectiveness, which may occur at higher replacement levels [39]. Additionally, it has been demonstrated that nanoparticles significantly enhance mechanical properties when added to cement-based materials in the proper proportions [40]. The elastic modulus, high tensile strength, and ability to bridge cracks of carbon nanotubes (CNTs) make them a promising ingredient for cementitious composites that enhance their flexural, fracture, and tensile characteristics [28-30]. Cement containing CNTs at a weight percentage of 0.05 to 0.10 percent is often beneficial for mechanical performance enhancement, according to studies [41, 42]. However, at higher doses, agglomeration and decreased dispersion efficiency are possible side effects. There are new possibilities for the development of multipurpose, high-performance cement-based composites made possible by nanotechnology, which has shown considerable promise in improving the construction materials' longevity and mechanical qualities [43]. A high-range admixture that reduces water, nano clay, carbon nanotubes (CNTs), fine and coarse aggregates, and potable water were all components of the experimental program. For accurate and consistent results, all of these items met the requirements of the applicable IS standards. As a primary binder, Ordinary Portland Cement (OPC) 53 grade was used, which complies with IS: 12269-2013. The substance had a standard consistency of 30% and a specific gravity of around 3.15 [44, 45]. The fine aggregate was natural river sand, which IS: 383-2016 classifies as Zone II. The coarse aggregate was crushed angular aggregates that met IS: 383-2016 and had a maximum size of 20 mm [46, 47]. Sieve analysis was utilized to determine the particle size distribution of both fine and coarse aggregates in compliance with IS: 2386 (Part I). Specific gravity of aggregates was approximately 2.70 and their water absorption was approximately 0.6%. In the study, coarse aggregate was used that consisted of well graded crushed stones with nominal maximum size of 20 mm and fine aggregate that met the specifications of IS: 383, on Zone II grading. Table 1 displays the results of the sieve analysis that prove that the aggregates fall within the approved grading range of structural concrete. The aggregate gradation curves of the concrete mixes with fine and coarse particles are illustrated in Table 1.

Table 1 Gradation curves of fine and coarse aggregates used in the concrete mixes

Sieve Size (mm)	% Passing Fine Aggregate	% Passing Coarse Aggregate
20	100	100
16	100	92
12.5	100	80
10	100	65
4.75	98	5
2.36	85	0
1.18	65	0
0.600	45	0
0.300	15	0
0.150	5	0

Nano Carbon Tubes

The use of multi-walled carbon nanotubes (MWCNTs) in the research as the nanoscale reinforcement was based on the unique stiffness, tensile strength and crack-bridging characteristics. The diameter of the CNTs was 1030 nm on average, their length ranged between 1 and 10 μm and the percentage of purity was more than 95. The CNTs were dispersed in water with the help of polycarboxylate-based superplasticizer before mixing and then ultrasonicated to obtain a uniform distribution within the cement matrix. The main mechanical and physical properties of the CNTs that are being studied here can be summarized in Table 2 [48-50]. Carbon nanotubes (CNT) and nano clay used in the present study were procured commercially. Since detailed physicochemical characterization of these materials was beyond the scope of the present investigation, the properties presented in Tables 2 and 3 were compiled from the manufacturers' datasheets and relevant literature sources [48-51]. Therefore, the reported properties represent literature- and manufacturer-provided values and were not experimentally determined for the specific batches of materials used in this study.

Table 2 Carbon Nanotube Characteristics

Property	Typical Range / Value	Significance in Concrete Applications
Structure	Conical tubes made of graphene sheets that have been rolled	It has a special capacity for reinforcement.
Type	Carbon nanotubes with one or more walls	Concrete often contains more MWCNTs
Diameter	MWCNT: 10-50 nm; SWCNT: 0.8-2 nm	Nano-sized particle dispersion in mortar
Length	0.1-20.0 μm (or perhaps more, depending on the method of manufacture)	Bridging cracks and reinforcing matrix
Aspect Ratio (Length/Diameter)	1000–10,000+	A higher aspect ratio enhances the transmission of load
Tensile Strength	~50–150 GPa	Raises the compressive and shear strengths of concrete
Elastic Modulus	~1 TPa	Offers high-strength reinforcing
Density	~1.3–1.4 g/cm ³	Reinforcement material with a low density
Thermal Conductivity	~3000–6000 W/m·K	Makes composites more heat stable
Electrical Conductivity	10 ⁴ –10 ⁵ S/cm	Prospects for conductive smart concrete
Chemical Stability	Superior resistance to chemicals	Improves longevity when subjected to extreme conditions.

Nano-Clay

In this investigation, nano-clays were used, which are layered silicate particles with a specific surface area of over 1,000,000 m²/cm² and a thickness of less than 100 nm. Cementitious composites benefit from nano clay's micro-filling capabilities, enhanced particle packing, and refined pore structure, thanks to its small particle size and pozzolanic reactivity. Using nano clay as a binder weight substitute for cement ranged from 0-6% in this experimental program. Table 3 displays the main chemical and physical properties of nano clay [51].

Table 3 Nanoclay Characteristics

Property	Typical Range / Value	Significance in Concrete Applications
Physical Properties		
Particle Size (thickness)	< 100 nm	Allows for the improvement of pores on a nanoscale
Platelet Shape	Stacks of silicate crystals	Matrix densification and packing density are both improved
Specific Surface Area	600–800 m ² /g	Offers a sizable reactive surface area for the use of hydration
Density	~2.6–2.8 g/cm ³	Compatibility guaranteed; comparable to cement
Colour	Pale to light-colored	Does not drastically change the way it looks
Morphology	flat and very proportional	Enhances cement paste contact and dispersion
Water Absorption	Great (because of the layered structure)	Has an effect on the amount of water needed and the feasibility of repairs
Chemical Properties		
SiO ₂ Content	50–60%	A factor in the pozzolanic reactivity
Al ₂ O ₃ Content	15–20%	Strengthens bonds and promotes muscle growth
Fe ₂ O ₃ Content	2–8%	Minimal impact on color and responsiveness
CaO Content	1–5%	Minimal cementitious effect
MgO Content	1–4%	Affects how things behave when they're wet and stable
Na ₂ O + K ₂ O (Alkalis)	1–3%	Influences the propensity for alkali-silica reactions
Loss on Ignition (LOI)	5–10%	Denotes the presence of water and volatile oils

As a primary binder, Ordinary Portland Cement (OPC) 53 grade was used, which complies with IS: 12269-2013. Figure 1 shows that nano clay has a layered platelet structure and very small particle dimensions, in contrast to the irregular angular forms seen in cement particles, which are characteristic of hydrated clinker phases. Cementitious composites that feature this layered architecture show enhanced packing density and microstructural refinement.

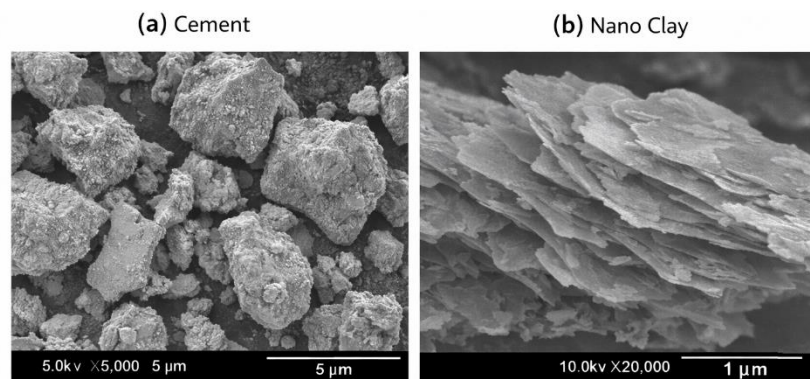


Figure 1 Scanning electron micrographs (SEMs) revealing layered platelet morphology in (a) nanoclay and (b) regular Portland cement particles

To improve workability and guarantee uniform dispersion of CNTs, The binder was mixed with a high-range water reducer based on polycarboxylate at a concentration of around 1%. This compound is known as a superplasticizer [52, 53]. For the purposes of mixing and curing, potable water that is free of impurities was used, in compliance with IS: 456-2000 [54]. To learn about the mechanical benefits and hybrid nano clay-CNT concretes' long-term durability, the technique integrates experimental validation with machine learning. This structure facilitates data-driven choices in the design of concrete with nanomaterial enhancements, optimizes mixes based on performance, and encourages sustainability. The hybrid nano clay-carbon nanotube (CNT) concrete's mechanical and durability performance was evaluated in this work using an analytical and experimental technique. River sand, 20 mm crushed aggregates, and Ordinary Portland Cement (OPC 53 grade) were used in compliance with IS specifications. Cement was weight-for-weight substituted with nano clay (0% to 6%), and CNTs (0% to 0.20%) were used as additives. The sixteen different mix possibilities were made possible by designing M35 grade concrete having a consistent water-binder ratio of 0.45. To make sure the CNTs were evenly distributed, a polycarboxylate-based superplasticizer was used for ultrasonic dispersion. For 7, 14, and 28 days, Specimens of cubes, prisms, and cylinders were cast and left to cure at a temperature of 27 ± 2 °C. Slump cone testing was used to assess workability, and compressive, flexural, and split tensile strengths were computed using IS:516 and IS:5816, respectively. In accordance with ASTM C642, we measured water absorption. This research relies on mechanical and durability performance patterns published in the literature for microstructural interpretation. However, future work will include comprehensive SEM-based characterisation to confirm the postulated processes even further. Performance measures (R², MAE, and RMSE) were used to verify the experimental data, and second-degree polynomial regression was used for analysis. Minimal bias and optimum performance were verified by residual and sensitivity analysis.

2.1 Mix design

As mentioned in Section 2.1, the experimental program's mix design for M35 grade concrete was created in accordance with IS 10262 and IS 456 requirements. The goal was to achieve a desired workability and durability for structural applications, with an aim of achieving a mean compressive strength of around 43 MPa. Previous research on nanomaterial-modified concrete served as a guidance for the determination of dose levels for carbon nanotubes and nano clay [53, 54]. Achieving improved workability and mechanical performance in blended and alkali-activated cementitious materials remains an important challenge. The use of superplasticizers has shown considerable potential for modifying the fresh and hardened properties of these cementitious systems [55]. The design and proportioning of concrete mixtures should follow established national standards to ensure adequate strength, durability, and consistency. The guidelines provided in IS 456:2000 and IS 10262:2019 are widely used for the design, proportioning, and specification of plain and reinforced concrete mixtures [56, 57]. The utilization of agricultural waste as supplementary cementitious materials offers a promising approach to developing sustainable concrete while reducing dependence on conventional cement. Previous research has demonstrated that the incorporation of corn cob ash can influence the workability and compressive strength of cement concrete [58]. Accurate sampling and analysis of concrete are essential for obtaining reliable and representative results during experimental investigations. The procedures specified in IS 1199:1959 providing standardized methods for the sampling and analysis of concrete to ensure consistency and reliability of test results [59]. According to previous research, adding nano clay to cement at a weight of 2% to 6% may improve hydration kinetics, particle packing, and pore structure, resulting in improved durability and mechanical strength. Due to the increasing water consumption and surface area, workability and hydration might be negatively impacted by greater replacement amounts. Similar to how prior studies on CNT-modified cementitious materials showed that minimal doses (0.05% to 0.10 percent by weight of binder) are typically sufficient to improve flexural and tensile capabilities via nanoscale crack bridging and stress transfer; the same findings will be discussed in this section. Agglomeration of carbon nanotubes (CNTs) due to strong van der Waals forces causes poor dispersion and decreased reinforcing effectiveness at larger concentrations, especially over 0.20%. These results informed the selection of CNT doses of 0%, 0.05%, 0.10%, and 0.20% in addition to nano clay replacement levels of zero percent, two percent, four percent, and six percent in order to systematically evaluate the performance of hybrid nano clay-CNT concrete within limits that are both realistic and empirically proven. The M35 grade concrete mix design using carbon nanotubes and nano clay is shown in Table 4.

Table 4 Concrete Mix Design for M35 Grade

Mix ID	NC (%)	CNT (%)	Cement (kg/m ³)	Water (kg/m ³)	Sand (kg/m ³)	Coarse aggregate (kg/m ³)	SP (kg/m ³)
NC0-CNT0	0	0.00	400.0	180.0	678.0	1126.0	3.2
NC0-CNT0.05	0	0.05	400.0	180.0	678.0	1126.0	3.2
NC0-CNT0.10	0	0.10	400.0	180.0	678.0	1126.0	3.2
NC0-CNT0.20	0	0.20	400.0	180.0	678.0	1126.0	3.2
NC2-CNT0	2	0.00	392.0	180.0	678.0	1126.0	3.2
NC2-CNT0.05	2	0.05	392.0	180.0	678.0	1126.0	3.2
NC2-CNT0.10	2	0.10	392.0	180.0	678.0	1126.0	3.2
NC2-CNT0.20	2	0.20	392.0	180.0	678.0	1126.0	3.2
NC4-CNT0	4	0.00	384.0	180.0	678.0	1126.0	3.2
NC4-CNT0.05	4	0.05	384.0	180.0	678.0	1126.0	3.2
NC4-CNT0.10	4	0.10	384.0	180.0	678.0	1126.0	3.2
NC4-CNT0.20	4	0.20	384.0	180.0	678.0	1126.0	3.2
NC6-CNT0	6	0.00	376.0	180.0	678.0	1126.0	3.2
NC6-CNT0.05	6	0.05	376.0	180.0	678.0	1126.0	3.2
NC6-CNT0.10	6	0.10	376.0	180.0	678.0	1126.0	3.2
NC6-CNT0.20	6	0.20	376.0	180.0	678.0	1126.0	3.2

For the experimental program, an M35 grade concrete control mix was created in accordance with IS: 10262 and IS: 456 requirements. To ensure durability and strength, a water-to-binder ratio of 0.45 was employed, with a target mean strength of about 43 MPa. The water content was fixed at 180 kg/m³ and the binder amount at 400 kg/m³. 678 kg/m³ of natural river sand from Zone II was utilized for the fine aggregate, and for the coarse aggregate, 1126 kg/m³ of 20 mm crushed stone, a polycarboxylate superplasticiser was added at 3.2 kg/m³ to make the mixture workable. In order to conduct research on the hybrid system of nanomaterials, various amounts of nano clay were used as a substitute for cement. The percentages of nano clay were 0, 8, 16, and 24 kg/m³, while the amounts of cement were reduced to 400, 392, 384, and 376 kg/m³. Multi-walled carbon nanotubes (CNTs) were added at concentrations of 0%, 0.05%, 0.1%, and 0.2% to provide doses of 0.00, 0.20, 0.40, and 0.80 kg/m³. A total of sixteen mix variations were generated using the factorial design. To illustrate, the control mix had the following components: 400 kg of cement, Multi-walled carbon nanotubes (CNTs) were added at concentrations of 0%, 0.05%, 0.1%, and 0.2% to provide doses of 0.00, 0.20, 0.40, and 0.80 kg/m³. It did not include any nano clay or CNTs. On the other hand, hybrid mixtures such as M-NC4-CNT0.1 needed 3.2–4.0 kg of superplasticizer to compensate for the dispersion of CNTs, and they the mixture had 384 kg of cement, 16 kg of nano clay, and 0.40 kg of carbon nanotubes. Along with 376 kg of cement, 24 kg of nano clay, 0.80 kg of CNTs, and around 3.5–4.5 kg of superplasticizer, there was another high nano clay-CNT mix (M-NC6-CNT0.2). All mixes were required to keep the binder at 400 kg/m³ and the water-to-binder ratio at 0.45, with the exception of the nano clay replacement and CNT addition, which were free to modify. Because of this technique, the mechanical and durability properties of M35-grade concrete were systematically tested using hybrid nanomaterials [36, 39].

Fresh concrete workability was evaluated using the slump cone test in accordance with IS 1199 (Part 2): 2018. The compressive strength of 150 mm cube specimens was determined following IS 516 (Part 1/Sec 1): 2021. Split tensile strength tests on cylindrical specimens and flexural strength tests on prism specimens were conducted in accordance with IS 5816: 1999 and IS 516 (Part 1/Sec 2): 2021, respectively. Water absorption measurements were carried out in accordance with ASTM C642-21. All tests were performed at specified curing ages, and the reported values represent the average of three specimens.

2.2 Mixing, casting, and testing procedure

To ensure consistency and repeatability, a systematic approach was used in the testing and manufacture of hybrid nano clay-CNT concrete.

Step 1: Carbon Nanotube Dispersion

Agglomeration could not be prevented by improper dispersion of CNT particles due to their strong van der Waals interactions. To distribute the required quantity of multi-walled carbon nanotubes (MWCNTs), a polycarboxylate-based superplasticizer was first added to the mixing water. To ensure that the CNTs were evenly distributed throughout the solution, the mixture was ultrasonically treated for around 30 minutes in a laboratory ultrasonic processor.

Step 2: Dry Material Mixing

First, the cement, fine aggregates, coarse aggregates, and nano clay (which served as a partial substitute for cement) were dry-mixed for two or three minutes using a mechanical concrete mixer. This was done to make sure that all of the solid ingredients were evenly distributed.

Step 3: Liquid CNT and Water Addition

While the mixer was running, the CNT suspension that had been earlier made was slowly added to the dry blend. The additional mixing water was then added until the water-binder ratio reached the target 0.45. To get a uniform concrete mixture, the mixing process was prolonged for another three to four minutes.

Step 4: Specimen Casting

Fresh concrete was poured into some of the test specimens by standard molds:

- Compressive strength test on cube specimens of 150 x150x150 mm.

Prism shape specimens 100 x 100 x 500 mm are needed in case of flexural strength testing.

- Split tensile strength test specimens are made of a shape model that is cylindrical (150 300 mm).

The trapped air was released by placing the mold on a vibrating table to ensure that it was well compacted after each layer had been filled. The stated results are the average of three measurements taken from three identical specimens for each concrete mix and testing age. Each set of data had its standard deviation computed in order to assess the dependability and unpredictability of the experimental findings. The indicated mechanical and durability parameters are guaranteed to be reliable by these statistical indicators, which also provide an estimate of the experimental dispersion.

Step 5: Conditions for Curing:

The specimens were let to cool to room temperature for a full day following casting. They were then taken out of the mold and put in a curing tank, with potable water that was kept at $27 \pm 2^\circ\text{C}$. Tests were conducted after 7, 14, or 28 days of curing for all specimens.

Step 6: Testing for Mechanical and Durability

The following methods were used to evaluate the concrete specimens after they had hardened:

- IS 516 (1959) for compressive strength. Two-point loading for flexural strength according to IS 516 (1959). IS 5816 (1999) specifies the split tensile strength. Absorption of Water: ASTM C642. To ensure the accuracy of the measurements, all tests were conducted in a controlled laboratory setting using calibrated testing apparatus.

3. Results and discussion

The trends in compressive strength, flexural strength, split tensile strength and water absorption performance are shown in Figures 1-4; extensive numerical results of the testing program is displayed in Table 5. We have also given visual representations in order to simplify the comparison of different combinations of hybrid nanomaterials and curing ages. Rather than repeating the numerical numbers already presented in the tables, the discussion below will focus on the analysis of the patterns and correlations already found. The variability inherent in the experimental measures is indicated by the error bars that relate to the standard deviation of the observed values in the graphical displays of the data of the strength and durability. Many specimen tests were done and the results of the tests were averaged to obtain the values as indicated in the tables. Table 5 is a summary of the workability, mechanical and water absorption of all the hybrid nano clay CNT concrete formulations). The superplasticizer dosage was adjusted according to the nanomaterial content and workability requirements of each mix. All dosage values presented in Tables 4 and 5 were verified with the original mix design records and are reported as used during experimentation.

Table 5 Hybrid Nano Clay–CNT Concrete's Workability, Mechanical Characteristics, and Water Absorption

Mix ID	Slump (mm)	SP (kg/m ³)	Compressive Strength (MPa)			Flexural Strength (MPa)			Split Tensile Strength (MPa)			Water Absorption (%)		
			(Mean $\pm$ SD)			(Mean $\pm$ SD)			(Mean $\pm$ SD)			(Mean $\pm$ SD)		
			7D	14D	28D	7D	14D	28D	7D	14D	28D	7D	14D	28D
NC0–CNT0	82	3.2	25.50	32.80	38.20	3.45	4.10	4.65	2.30	2.65	3.00	5.90	5.30	4.90
			$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC0–CNT0.05	70	3.6	26.80	34.00	39.80	3.70	4.35	4.95	2.45	2.80	3.15	5.70	5.10	4.70
			$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC0–CNT0.10	66	3.9	27.60	35.50	41.00	3.85	4.55	5.15	2.55	2.90	3.30	5.50	4.90	4.50
			$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05

Table 5 (continued) Hybrid Nano Clay–CNT Concrete's Workability, Mechanical Characteristics, and Water Absorption

Mix ID	Slump (mm)	SP (kg/m ³)	Compressive Strength (MPa)			Flexural Strength (MPa)			Split Tensile Strength (MPa)			Water Absorption (%)		
			(Mean ± SD)			(Mean ± SD)			(Mean ± SD)			(Mean ± SD)		
NC0–CNT0.20	55	4.4	7D	14D	28D	7D	14D	28D	7D	14D	28D	7D	14D	28D
			26.20	33.20	39.00	3.60	4.25	4.85	2.40	2.75	3.10	5.80	5.20	4.80
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
NC2–CNT0	75	3.2	27.50	34.80	40.80	3.80	4.55	5.05	2.50	2.85	3.20	5.60	5.00	4.60
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC2–CNT0.05	68	3.7	28.80	36.20	42.50	4.00	4.75	5.30	2.65	3.00	3.35	5.40	4.80	4.40
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC2–CNT0.10	62	4.1	29.80	37.50	44.00	4.20	4.95	5.55	2.75	3.10	3.50	5.20	4.60	4.20
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC2–CNT0.20	50	4.7	27.80	35.00	41.20	3.90	4.60	5.10	2.60	2.90	3.25	5.50	4.90	4.50
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC4–CNT0	70	3.3	29.00	36.50	42.80	4.05	4.80	5.35	2.70	3.05	3.40	5.30	4.70	4.30
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC4–CNT0.05	63	3.9	30.20	38.00	44.50	4.25	5.00	5.55	2.80	3.15	3.55	5.10	4.50	4.10
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC4–CNT0.10	56	4.3	31.50	39.50	46.20	4.45	5.25	5.85	2.95	3.30	3.75	4.90	4.30	3.90
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC4–CNT0.20	46	5.1	29.20	37.00	43.00	4.10	4.85	5.40	2.75	3.05	3.45	5.20	4.60	4.20
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC6–CNT0	66	3.5	28.20	35.50	41.50	3.95	4.65	5.20	2.60	2.95	3.30	5.50	4.90	4.40
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC6–CNT0.05	60	4.0	29.00	36.50	42.20	4.10	4.85	5.40	2.70	3.05	3.45	5.30	4.70	4.30
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC6–CNT0.10	54	4.5	29.80	37.80	43.50	4.25	5.00	5.55	2.80	3.15	3.55	5.10	4.50	4.10
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05
NC6–CNT0.20	44	5.3	27.50	34.50	40.50	3.85	4.55	5.05	2.55	2.85	3.20	5.60	5.00	4.60
			± 0.30	± 0.30	± 0.30	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.05	± 0.05	± 0.05
			0.30	0.30	0.30	0.03	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.05

To assess the consistency of the experimental results, each test was conducted on three specimens for every concrete mixture and curing age. The reported values of compressive strength, flexural strength, split tensile strength, and water absorption are expressed as the mean ± standard deviation (SD). The standard deviation was calculated to quantify the variability among replicate specimens, while the mean value was used for comparative evaluation of the different mixtures. Error bars representing one standard deviation ($\pm$ SD) were incorporated into the corresponding figures to illustrate the experimental variability. The relatively small standard deviation values indicate good repeatability of the experimental procedures and a high level of consistency in specimen preparation, curing, and testing. Statistical comparisons among the different mixtures were performed using one-way analysis of variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$), where a p-value less than 0.05 was considered statistically significant.

3.1 Workability

Workability is a fundamental property of fresh concrete that reflects its ease of mixing, transportation, placement, compaction, and finishing without segregation or bleeding. In this study, the workability of hybrid nano-modified concrete was assessed using the slump cone method in accordance with IS:1199 (1959). A slump range of 75–100 mm was considered indicative of medium workability, which is suitable for most structural and laboratory applications. The incorporation of nano-scale materials such as nano clay (NC) and carbon nanotubes (CNTs) significantly influences the rheological behaviour of concrete due to their extremely fine particle size and high specific surface area. These characteristics increase water demand and affect particle dispersion within the cement matrix. To maintain uniform workability across different mixtures, the dosage of polycarboxylate ether (PCE)-based superplasticizer was adjusted systematically for varying NC (0–6%) and CNT (0–0.20%) contents. As observed from the experimental results, the control mix (NC0–CNT0) exhibited a slump of approximately 80 mm at a superplasticizer dosage of around 3.1–3.2 kg/m³, indicating satisfactory workability. With the addition of nano clay alone, a gradual reduction in slump was recorded, typically in the range of 5–12%, which can be attributed to the plate-like structure and high absorption capacity of nano clay particles that reduce the availability of free water in the mix. The inclusion of CNTs further reduced workability more significantly. Even at low dosages (0.05%), a noticeable drop in slump was observed, while higher contents (0.20%) resulted in substantial loss of flowability, with reductions reaching nearly 35–45% compared to the control mix. This behaviour is mainly associated with the high aspect ratio of CNTs, their tendency to form agglomerates, and the resulting internal friction and water entrapment within the matrix. To counteract this reduction, the superplasticizer dosage was increased progressively. For mixes containing 0.05–0.10% CNT, a dosage range of approximately 3.6–4.3 kg/m³ was sufficient to restore slump values close to the target range. However, for higher CNT content (0.20%), higher dosages in the range of 4.5–5.3 kg/m³ were required depending on the nano clay percentage.

Overall, the findings highlight that while nano clay and CNTs contribute to enhanced performance characteristics of concrete, their incorporation necessitates careful optimization of chemical admixtures to achieve the desired level of workability. The variation in slump values for different mixes of M35 grade concrete is presented in Figure 1.

3.2 Compressive strength

Compressive strength is one of the most critical mechanical properties of concrete, representing its capacity to resist axial loads and indicating overall structural performance and durability. In the present investigation, compressive strength was determined at curing ages of 7, 14, and 28 days in accordance with IS: 516 (1959). Standard cube specimens of 150 mm × 150 mm × 150 mm were prepared for each mix and tested under a uniform rate of loading. A conventional M35 grade concrete mix was used as the reference to evaluate the influence of nano clay (2–6%) and carbon nanotubes (0.05–0.20%) on strength development.

The experimental results demonstrate a consistent increase in compressive strength with curing time for all mixes. The control mix achieved a 28-day strength of approximately 38–39 MPa, satisfying the target strength requirement. The incorporation of nano clay alone resulted in a noticeable improvement in strength, with gains typically ranging from 5% to 12% at 28 days. This enhancement can be attributed to the filler effect and secondary pozzolanic reactions of nano clay, which refine the pore structure and contribute to a denser cementitious matrix. Similarly, mixes containing only CNTs exhibited improved compressive strength, particularly at moderate dosages. The optimum CNT content was observed around 0.10%, where the 28-day strength increased significantly compared to the control mix. This improvement is primarily due to the ability of CNTs to act as nano-reinforcement elements, bridging microcracks and restricting their propagation under load. The most notable enhancement was observed in hybrid mixes containing both nano clay and CNTs, indicating a synergistic interaction between the two nanomaterials. The combination of 4% nano clay and 0.10% CNT produced the highest compressive strength, reaching approximately 46 MPa, which corresponds to an increase of over 18–20% compared to the control mix. This improvement is associated with simultaneous matrix densification by nano clay and crack-arresting behaviour of CNTs, leading to better stress distribution and load transfer. However, beyond the optimum dosage, a marginal reduction in compressive strength was observed. Mixes with higher nano clay content (6%) or elevated CNT dosage (0.20%) showed slightly lower strengths compared to the peak values. This reduction may be linked to increased water demand, reduced workability, and the tendency of CNTs to form agglomerates at higher concentrations, which adversely affects uniform dispersion and hydration efficiency. Overall, the results indicate that the incorporation of nanomaterials can significantly enhance compressive strength when used in optimal proportions. The findings emphasize that careful control of nano clay and CNT content is essential to maximize performance while avoiding potential drawbacks associated with excessive dosage. The detailed compressive strength values for different mixes are presented in Figure 2.

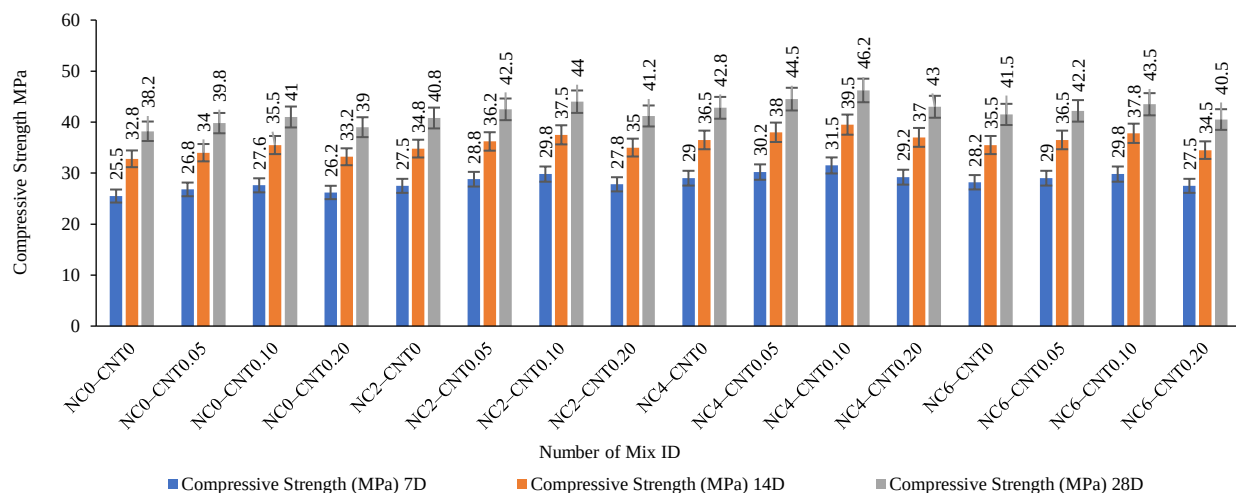


Figure 2 Hybrid Nano clay–CNT concrete's Compressive Strength

3.3 Flexural strength

Flexural strength is an important mechanical property of concrete that reflects its ability to resist bending stresses and control crack initiation and propagation. This parameter is particularly significant for structural elements such as beams, slabs, and pavements, where tensile stresses develop under loading. In the present study, the flexural strength of hybrid nano-modified concrete was evaluated at curing ages of 7, 14, and 28 days using prism specimens of 100 mm × 100 mm × 500 mm, tested under two-point loading as per IS: 516 (1959). A control mix of M35 grade concrete was used as a reference, and its performance was compared with mixes containing varying proportions of nano clay (0–6%) and carbon nanotubes (0–0.20%). The results demonstrate a steady increase in flexural strength with curing time for all mixtures. The control mix exhibited a 28-day flexural strength of approximately 4.6–4.8 MPa, which is typical for conventional M35 concrete. The addition of nano clay alone led to moderate improvements in flexural performance, primarily due to pore refinement and improved bonding within the cementitious matrix. A more significant enhancement was observed with the inclusion of CNTs, especially at moderate dosages. CNTs contribute to improved tensile behaviour by acting as nano-reinforcing elements that bridge microcracks and delay crack propagation. When nano clay and CNTs were used together, a clear synergistic effect was evident. The hybrid mix containing approximately 4% nano clay and 0.10% CNT exhibited the highest flexural strength, reaching values close to 6.0–6.2 MPa at 28 days. This corresponds to an increase of about 25–30% compared to the control mix. The improvement can be attributed to the combined effect of matrix densification by nano clay and effective stress transfer through CNT-induced crack bridging. However, beyond the optimum range, a slight reduction in flexural strength was observed. Mixes with higher nano clay content (6%) or increased CNT dosage (0.20%) showed marginally lower values compared to the peak performance.

This behaviour is likely due to reduced workability, improper dispersion of CNTs, and possible particle agglomeration, which can create weak zones within the matrix and hinder uniform stress distribution. Overall, the results indicate that hybrid incorporation of Nano clay and CNTs can significantly enhance the flexural performance of concrete when used in appropriate proportions. The combination of approximately 4% Nano clay and 0.10% CNT was found to be optimal, providing a balanced improvement in strength, crack resistance, and structural efficiency. Detailed flexural strength results for all mixes are presented in Figure 3.

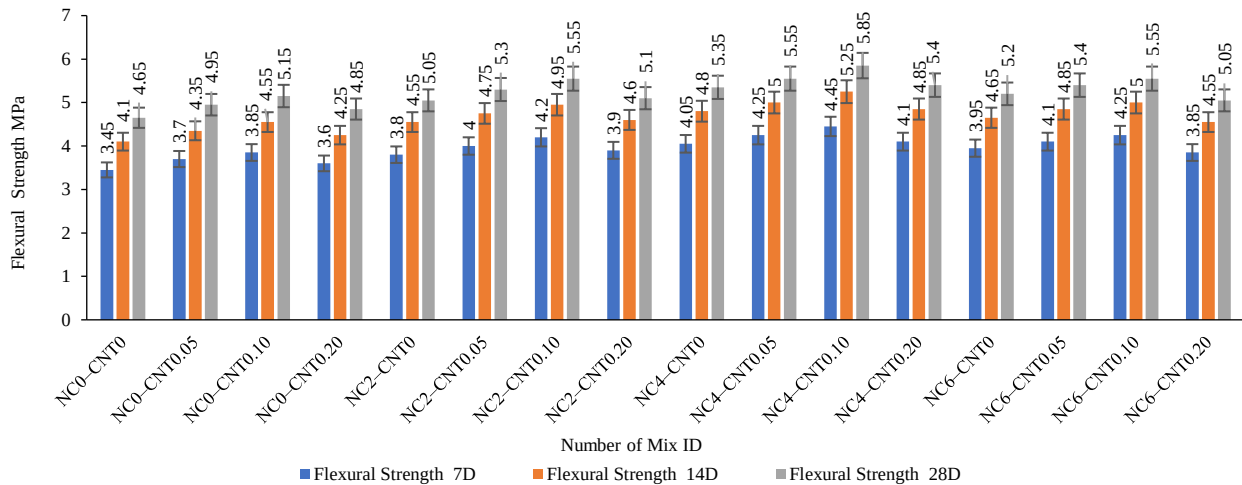


Figure 3 Hybrid Nano clay–CNT concretes' Flexural Strength

3.4 Split tensile strength

Split tensile strength is a key mechanical parameter that reflects the ability of concrete to resist tensile stresses and control crack formation under service conditions. Since concrete is inherently weak in tension, improving this property is essential for enhancing durability and structural performance. In this study, the split tensile strength of hybrid nano-modified concrete was evaluated at curing periods of 7, 14, and 28 days using cylindrical specimens of 150 mm diameter and 300 mm height, in accordance with IS: 5816 (1999). The behaviour of a conventional M35 grade control mix was compared with hybrid mixes incorporating nano clay (0–6%) and carbon nanotubes (0–0.20%) by weight of binder. The test results indicate a progressive increase in split tensile strength with curing age for all mixes. The control mix achieved a 28-day tensile strength of approximately 3.0–3.1 MPa, which is consistent with typical values for M35 grade concrete. The addition of nano clay alone resulted in moderate improvements due to its ability to refine pore structure and enhance the bond between cement paste and aggregates. A more pronounced increase was observed with the inclusion of CNTs, particularly at intermediate dosages. CNTs act as nano-scale reinforcing elements that bridge microcracks, thereby delaying crack initiation and propagation under tensile loading. The combined use of nano clay and CNTs exhibited a strong synergistic effect, leading to significant enhancement in tensile performance. The hybrid mix containing approximately 4% nano clay and 0.10% CNT demonstrated the highest split tensile strength, reaching values close to 3.7–3.8 MPa at 28 days. This represents an improvement of nearly 20–25% compared to the control mix. The enhancement can be attributed to matrix densification provided by nano clay and efficient stress transfer facilitated by CNT-induced crack-bridging mechanisms. However, at higher dosages (such as 6% nano clay or 0.20% CNT), the tensile strength showed a marginal decline compared to the optimum mix. This reduction is likely due to issues such as reduced workability, non-uniform dispersion of CNTs, and particle agglomeration, which can create weak zones and adversely affect stress distribution within the matrix. Overall, the results confirm that hybrid incorporation of nano clay and CNTs can effectively improve the tensile resistance of concrete when used in optimal proportions. The combination of 4% nano clay and 0.10% CNT was found to be the most effective in enhancing split tensile strength while maintaining material homogeneity. Detailed results for all mixes are presented in Figure 4.

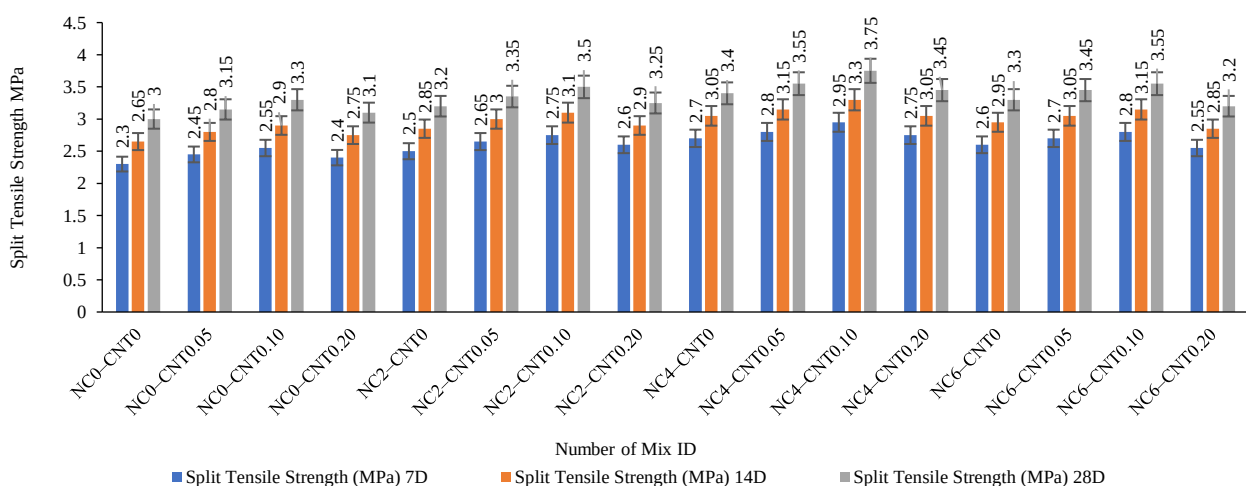


Figure 4 Hybrid Nano clay–CNT concretes' Split Tensile Strength

3.5 Water absorption

Water absorption is one of the most significant values of the longevity of the concrete as it demonstrates the porosity and the permeability of the concrete. Reduced water absorption tends to imply improved long-term performance as intrusion of moisture is directly tied to the degradation mechanisms freeze-thaw damage, sulfate attack and chloride penetration. The ASTM C642 (2006) water absorption requirement was obeyed by measuring the water absorption of a hybrid nano clay-CNT concrete at 7, 14 and 28 days. Control mix (M35) was compared with the hybrid mixes with CNTs at 0-0.20% of binder weight and at 0-6% binder substitution which was nano clay. This investigation was aimed at finding the optimum dosage of these nanomaterials to derive maximum benefits of durability and also to evaluate the impact of such nanomaterials on pore refinement, microcracks minimization, and consequently, concrete water absorption capacity [60]. The incorporation of hybrid nanomaterials has shown considerable potential for improving the durability of concrete and enhancing its resistance to environmental deterioration [61]. In addition, machine learning techniques have demonstrated their ability to improve the accuracy of mechanical strength prediction and provide better understanding of the factors influencing concrete performance [62]. Experimental techniques such as digital image correlation and acoustic emission have also been effectively employed to investigate the tensile behavior and failure mechanisms of fiber-reinforced concrete [63].

Table 5 results point to the important contribution of the nano clay and CNTs to rendering M35 grade concrete more impervious. The control mixture had an absorption of approximately 4.8 percent after 28 days as is typical with ordinary concrete of this grade. The refining properties of nano clay and its pozzolanic reactivity decreased the capillary porosity and densified the microstructure, which consequently continued to decrease absorption. Microcrack development and connectivity between pores were also reduced by CNTs, and so, they acted as nanoscale crack bridges. The optimal combination of nano clay and CNTs, 4% NC + 0.10% CNT (Mix 11), demonstrated a synergistic impact. With an absorption rate of around 3.2% after 28 days, this combination was 33% less absorbent than the control. This proves beyond a reasonable doubt that hybrid nanomaterials are useful for preventing water penetration. The absorption rate does go up a little beyond this ideal dose, particularly when using 6% NC or 0.20% CNT. Excessive nano clay, which increases water consumption and decreases workability, and increased CNT levels, which cause agglomeration and weaken reinforcing benefits by creating weak zones, are likely to blame. In general, the findings show that the best combination of workability and microstructural changes, which leads to increased 4% nano clay with 0.10% CNT offers greater long-term durability and resistance to water absorption.

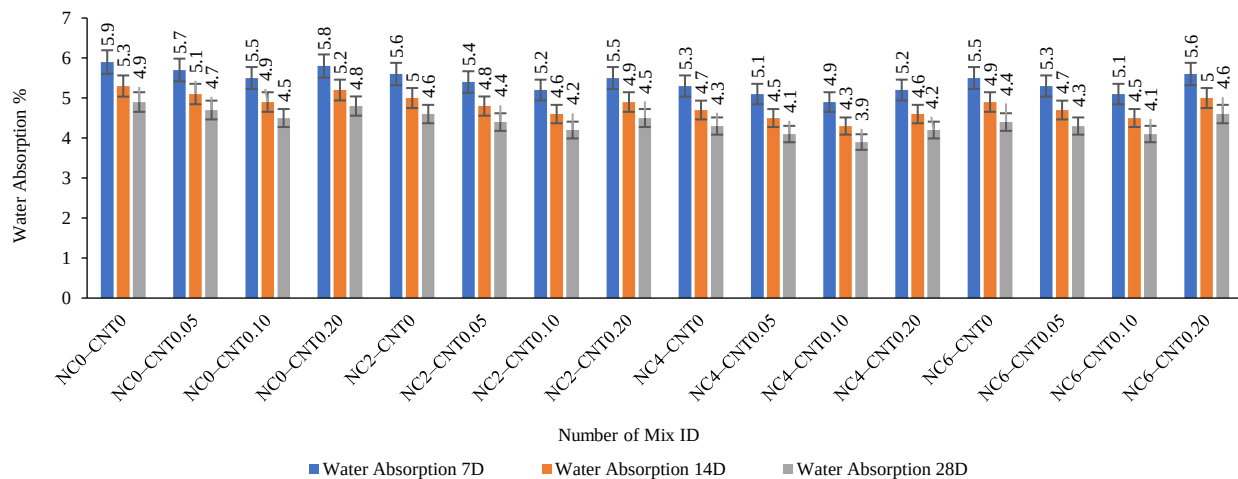


Figure 5 Water Absorption capacity of hybrid nano clay-CNT concretes

The results of the tests showed that M35 grade concrete's mechanical performance and durability were greatly enhanced by optimally adding nano clay and CNTs. Mix 11, which included 0.4 percent nano clay and 0.1 percent carbon nanotubes, outperformed the control by approximately 20% after 28 days, reaching a compressive strength of 46.8 megapascals (MPa) as shown in Figure 5. Furthermore, the combination outperformed the control by a significant margin in terms of flexural strength (6.10 MPa) and split tensile strength (3.80 MPa), which are roughly 27% and 23% higher, respectively. The ideal combination had a water absorption rate of 3.2%, down from 4.8% in the control, suggesting that the inclusion of nano clay and CNTs effectively refined the pores and healed microcracks, according to durability evaluations. Beyond the ideal values, however, performance dropped somewhat owing to CNT clumping, decreased workability, and higher water consumption; 6% nano clay and 0.20% CNT are two examples of such values. Because of these problems, the matrix's homogeneity and stress transmission were negatively impacted. Because it strikes a compromise between strength and durability, hybrid nanomaterial concrete is best prepared with a dosage of around 4% nano clay and 0.10% CNT. The study analyzes the influence of the replacement levels of nano clays (0-6% by weight of binder) and the doses of CNT (0-0.20% by weight of binder) on compressive, flexural, and split tensile strengths at various curing ages and the durability using water absorption tests. The objective of the study is to identify the most suitable hybrid dose, which enhances the strength, reduces porosity and enhances resistance to ingress of moisture and maintains binder content and water-to-binder ratio constant. We shall then isolate nanomaterial integration effect. The ultimate aim is to present a mix design framework based on performance to demonstrate the interaction between CNTs and nano clay so as to enhance long-term durability of concrete, bridging of microcracks and refinement of pores.

The study took the water absorption as a reference of concrete permeability and pore structure which are closely related to its durability performance. A decrease in water absorption often indicates that the pores have been refined and the capillaries have been reduced, which limits the entry of moisture and hostile ions. In comparison to the control mix, the findings showed that the hybrid nano clay-CNT system greatly decreased water absorption, suggesting an improvement in resistance to moisture penetration. However, several degradation processes, such as carbonation, sulphate attack, chloride penetration, and freeze-thaw cycles, are acknowledged to impact concrete durability. Thus, whereas data on water absorption may provide light on the material's permeability properties, a more

complete picture of its long-term performance would be revealed by conducting further tests to evaluate its durability. In order to broaden the scope of the durability evaluation of hybrid nanomaterial concrete systems, future study will take such findings into account.

3.6 Polynomial regression-based predictive model

The experimental dataset collected from the hybrid nano clay-CNT concrete mixtures was used to construct the modeling framework. There were sixteen mix combinations that were experimentally investigated. Compressive strength of each mix, flexural strength, split tensile strength and water absorption of each mix were measured at three different curing ages 7, 14 and 28 days. This resulted in the building of the prediction models with 48 data on each response variable. The input factors involved in this modeling method were the CNT dose (percentage), the composition of nano clay (percentage), and the cure time (days) and the mechanical and durability properties of concrete were the output factors.

We divided the dataset in half-70 percent in training and 30 percent in testing, as a result, we were able to test the work of the model and ensure that it was resistant. The predictive powers of the polynomial regression models were assessed by using statistical performance indicators. These measures were root mean squared error (RMSE), mean absolute error (MAE), mean squared error (MSE) and coefficient of determination (R^2). Moreover, the analysis of distribution of prediction errors was done and that there was no systematic bias in the model outputs was proved through residual analysis. With such approach, we are fully assured that our models would predict the concentration of nano clay and CNT that we have been experimenting with.

3.6.1 Compressive strength

To establish a quantitative relationship between hybrid nanomaterial content and the mechanical and durability properties of concrete, second-degree polynomial regression models were developed. Polynomial regression is a supervised data-driven modelling technique capable of capturing nonlinear relationships between multiple input variables and output responses. Fitting a 2-degree polynomial for each curing age gives the following approximate predictive relationships.

(a) 7 Days

$$f_7 = 26.15 + 0.75x_1 + 22.3x_2 - 0.055x_1^2 - 35.0x_2^2 + 0.20x_1x_2 \quad (1)$$

(b) 14 Days

$$f_{14} = 33.35 + 0.85x_1 + 24.1x_2 - 0.060x_1^2 - 37.5x_2^2 + 0.25x_1x_2 \quad (2)$$

(c) 28 Days

$$f_{28} = 39.10 + 0.90x_1 + 26.2x_2 - 0.065x_1^2 - 40.0x_2^2 + 0.28x_1x_2 \quad (3)$$

The following equations depict the compressive strength of M35 grade concrete at different ages of curing depending on the ratio of CNT and nano clay. Based on the positive linear coefficients of both (nano clay) and (CNT), minute amounts of these nanomaterials enhance stress transmission at the nanoscale, enhance particle packing and refine the matrix, which enhances compressive strength. Agglomeration, reduced workability, and unequal dispersion are likely to blame for the strength decline beyond ideal doses (about 4% nano clay and 0.10% CNT), as seen by the negative quadratic terms, which indicate non-linear behavior. Combining nano clay with CNTs improves performance beyond that of either component alone, as seen by the positive interaction terms, which indicate a synergistic impact. The largest baseline and coefficients are seen in the 28-day equation, which shows that the cement hydrates and the matrix densifies with time. Experiment and prediction findings are very congruent, proving that the polynomial model is appropriate for describing the nonlinear and interdependent effects of CNT content and nanoclay on concrete strength development. However, it should only be used as an empirical model within the studied ranges (0-6% nano clay and 0-0.20% CNT) to prevent erroneous extrapolation.

A second-degree polynomial regression model that considered the impacts of nano clay, CNT content, and curing age was used to describe the compressive strength of hybrid nanomaterial concrete. Here we can see the obtained equation written as:

$$fc = 15.093939 + 1.783750x_1 + 48.099892x_2 + 1.707054t - 0.223437x_1^2 - 210.378788x_2^2 - 0.030208t^2 - 0.928571x_1x_2 + 0.002462x_1t - 0.047668x_2t \quad (4)$$

The nano clay percentage (% by binder weight), CNT content (% by binder weight), and curing age (days) are denoted by x_1 and x_2 , respectively.

This polynomial equation captures the nonlinear and interactive effects of curing time and nanomaterials on the compressive strength of M35-grade concrete. The positive linear coefficients of x_1 , x_2 , and t indicate that the strength is improved by little additions of nano clay and CNTs as well as curing time. The improvement in pozzolanic activity by nano clay and nanoscale bridging effect of CNTs causes these benefits; the former improves load transfer and the latter fracture resistance, and the former accelerates hydration and refines the pore structure. In contrast, the negative quadratic coefficients of x_1^2 , x_2^2 , and t^2 show that the strength gain decreases with increasing contents or longer curing times, indicating that agglomeration, microstructural inhomogeneity, and workability loss result from excessive additions.

Hydrogenation progress, nanoclay, and carbon nanotubes are all shown to have linked effects via the interaction terms (x_1x_2 , x_1t , and x_2t). While the benefits of nano clay extend progressively with curing, the influence of CNT stabilises after 28 days, and the negative coefficient of x_1x_2 suggests that excessive simultaneous addition may slightly hinder dispersion efficiency. In general, the model shows great prediction accuracy ($R^2 = 0.99$), which proves that complicated, but measurable, nonlinear interactions regulate the development of hybrid nano clay-CNT concrete's compressive strength. Because it is an empirical model, the chosen ranges for

testing should be strictly adhered to: 0–6% nano clay, 0–0.20% CNT, and 7–28 days. When these intervals are exceeded, physical and rheological phenomena that were not previously considered can cause extrapolation to provide inaccurate predictions as shown in Figure 6.

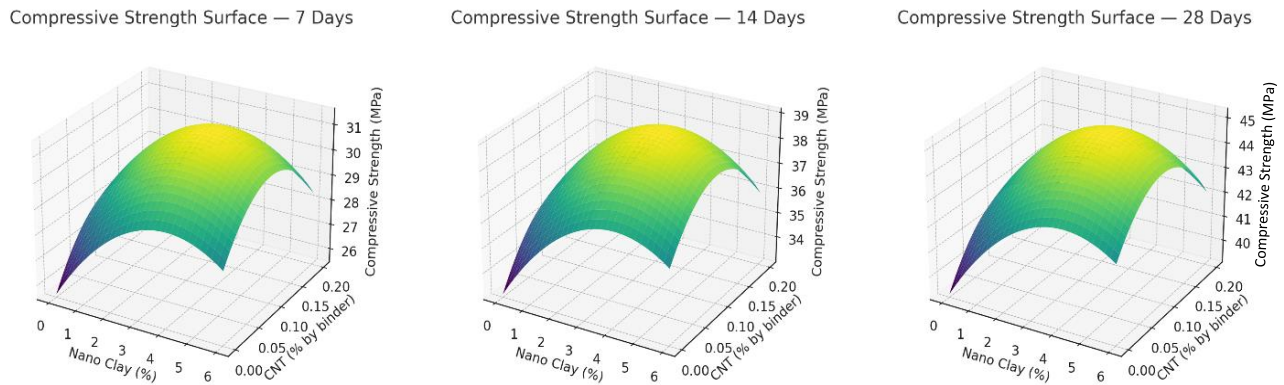


Figure 6 A polynomial regression model for forecasting the compressive strength of hybrid nano clay-CNT concrete

3.6.2 Flexural strength

We used second-degree polynomial regression models for 7, 14, and 28 days of curing to measure the relationship between the concentration of hybrid nanomaterials and the flexural strength of concrete. In this analysis, the nano clay content was the independent variable. (x_1), which is the percentage of binder by weight, and (x_2), which is the percentage of CNT by weight. The following are the regression equations that were obtained: The following approximations for predicting correlations are obtained by fitting a 2-degree polynomial to each curing age:

(a) 7 Days

$$f_7 = 4.4525 + 0.281x_1 + 8.7443x_2 - 0.0366x_1^2 - 37.0327x_2^2 - 0.0567x_1x_2 \quad (5)$$

(b) 14 Days

$$f_{14} = 5.3542 + 0.4147x_1 + 9.7106x_2 - 0.0433x_1^2 - 39.2409x_2^2 - 0.1829x_1x_2 \quad (6)$$

(c) 28 Days

$$f_{28} = 3.8583 + 0.3468x_1 + 10.3837x_2 - 0.0506x_1^2 - 44.0565x_2^2 - 0.1971x_1x_2 \quad (7)$$

The flexural strength of M35 grade concrete is captured by the obtained second-degree polynomial equations, which are nonlinear with respect to the dose of hybrid nanomaterials. By increasing crack resistance and matrix cohesiveness, the first additions of nano clay (x_1) and CNT (x_2) significantly increase the bending capacity of concrete, as indicated by their positive linear coefficients. The cementitious matrix is densified by nano clay because micro-filling and pozzolanic action, and because CNTs have the capacity to bridge fractures, which enhances load transmission across microcracks, these two factors are mainly responsible for this improvement.

Nevertheless, the reduction in workability and material dispersion at larger contents, as shown by the negative quadratic factors ($-x_1^2$, $-x_2^2$) indicate that the rate of improvement slows down above optimal levels (about 0.10% CNT and 4% nano clay). Because of CNT clumping or overlapping nucleation sites, which inhibit homogeneous stress distribution, the two nanomaterials may have a mild competitive interaction at excessive doses, as shown by the negative interaction term ($-x_1x_2$).

As the curing period progresses, all of the coefficients rise, indicating that the microstructure is being improved over time by the coupled nano clay-CNT system. The maximal hydration and nano-activation effects are confirmed at older ages, since the equation for 28 days produces the largest intercept and linear coefficients. For hybrid nanomaterial concrete, the nonlinear and synergistic character of the interactions between nano clay and carbon nanotubes is adequately reflected by the polynomial models, which consistently represent the flexural response. An extensive model was created using second-degree polynomial regression to depict the impact of curing age, CNT concentration, and nano clay on the flexible strength of hybrid nanomaterial concrete. Here we can see the obtained equation written as:

$$ft = 2.38 + 0.284x_1 + 7.96x_2 + 0.149t - 0.031x_1^2 - 35.72x_2^2 - 0.00251t^2 - 0.126x_1x^2 + 0.00043x_1t + 0.00915x_2t \quad (8)$$

A better understanding of the interplay between curing age, the combined second-degree polynomial model may be used to determine the flexural strength of M35-grade hybrid nanomaterial concrete's nano clay content and CNTs. The positive linear coefficients for x_1 , x_2 , and t indicate that a little addition of nano clay and CNTs significantly increases flexural performance. Because of ongoing hydration and microstructural densification, strength continues to improve with age. The significant positive coefficient highlights the exceptional crack-bridging efficacy of CNTs at low dosages of x_2 (8.51), while the bond and matrix refinement are improved by nano clay (x_1).

Indicating that flexural capacity increases fall with excessive additions or very extended curing times, the nonlinear saturation effect is captured by the quadratic elements that are negative ($-x_1^2$, $-x_2^2$, and $-t^2$). The sensitivity of CNT performance to agglomeration levels higher than 0.1% is shown by the substantial negative x_2^2 . The coefficient (-39.47), which is in line with the

experimental results. The interaction terms are those that expound on the somewhat adverse cross-effects. At high loadings, the value of $x_1 \times x_2$ term (-0.142) indicates that nano clay and CNTs are competing slightly, with a smaller positive influence. The term suggests that the advantages of CNTs increase over time during the curing period, possibly due to an increase in the transmission of stress across microcracks.

The model provides a succinct mathematical framework for forecasting the flexural strength of hybrid nano clay-CNT concrete at any intermediate age or dosage combination within the studied range (0-6% NC, 0-0.20% CNT, and 7-28 days), and it shows great reliability ($R^2 = 0.9863$). This equation might potentially be used as a basis for future hybrid optimization models in structural concrete and nano-engineered pavement that use data-driven polynomial regression model as shown in Figure 7.

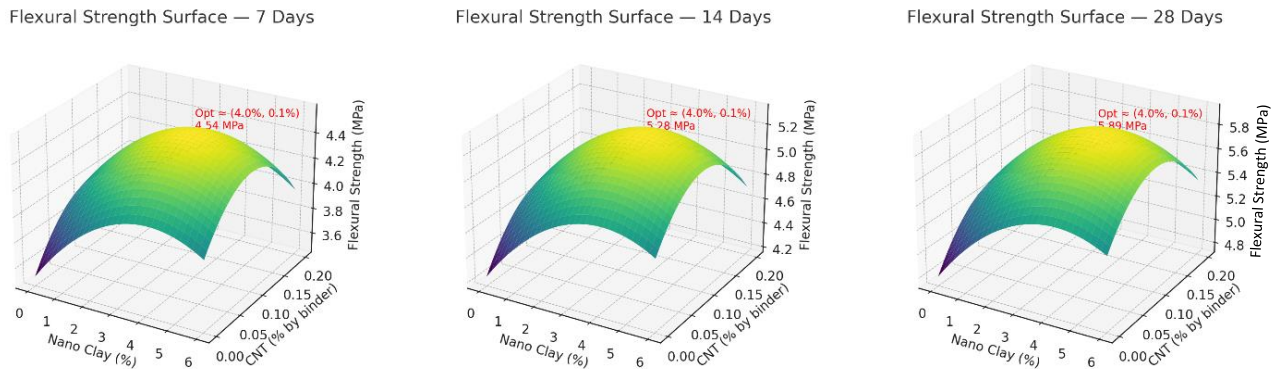


Figure 7 A Polynomial Regression-Based Model to Forecast the Flexural Strength of Hybrid Nano Clay-CNT Concrete

3.6.3 Split tensile strength

We used second-degree polynomial regression models for 7, 14, and 28-day curing times to measure the correlation between the concrete's flexural strength and the concentration of hybrid nanomaterials. Both the CNT and nano clay contents are expressed as a percentage of the binder's weight, were among the factors that were examined. Down below, you can see the regression equations that were generated: approximating the following predicted relationships, each cure time is fitted with a second-degree polynomial:

(a) 7 Days

$$f_7 = 2.415 + 0.080x_1 + 5.145x_2 - 0.016x_1^2 - 21.45x_2^2 - 0.120x_1x_2 \quad (9)$$

(b) 14 Days

$$f_{14} = 2.840 + 0.120x_1 + 5.750x_2 - 0.017x_1^2 - 23.30x_2^2 - 0.150x_1x_2 \quad (10)$$

(c) 28 Days

$$f_{28} = 3.340 + 0.140x_1 + 7.050x_2 - 0.030x_1^2 - 26.00x_2^2 - 0.145x_1x_2 \quad (11)$$

Regression analysis shows that, up to a certain limit, adding nano clay and carbon nanotubes to M35-grade concrete increases its split tensile strength. By increasing matrix cohesiveness and fracture resistance, moderate doses increase the tensile capacity, as shown by the positive linear terms (x_1 , x_2). Because of their ability to bridge microcracks and transmit stress, higher coefficient CNTs contribute more significantly.

Conversely, the negative quadratic coefficients ($-x_1^2$, $-x_2^2$) represent the decline in performance beyond optimal limits due to nanoparticle aggregation, reduced dispersion, and increased viscosity at higher dosages. The small negative interactional term ($-x_1 \times x_2$) that means that nano clay and CNTs tend to at least partially interfere with each other in the higher concentrations proves the need to balance hybridization.

The increasing intercept values from 7 to 28 days (2.395 to 3.090 MPa), which show progressive tensile strength increase, indicate continuous hydration and matrix refinement over time. When the strength gain reaches its maximum before progressively declining due to agglomeration, the 28-day equation produces the best projected results, which are consistent with the ideal ratio of 4% nano clay to 0.10% CNT. A second-degree polynomial regression model fully captured the effects of nano clay, CNT content, and curing age on the split tensile strength of hybrid nanomaterial concrete. Here we can see the obtained equation written as:

$$f_{t,t} = 2.05 + 0.182x_1 + 5.74x_2 + 0.082t - 0.0189x_1^2 - 24.15x_2^2 - 0.00118t^2 - 0.109x_1x_2 + 0.00031x_1t - 0.0126x_2t \quad (12)$$

The nonlinear relationship between the dose of hybrid nanomaterials, curing age, and split tensile strength is precisely captured by the developed combined polynomial model. The positive linear coefficients of x_1 , x_2 , and t demonstrate how modest additions of nano clay and CNTs improve tensile capacity through enhanced crack-bridging and microstructure densification. The considerable coefficient of 5.31 of carbon nanotubes (CNTs) highlights their tremendous influence in boosting tensile strength via nanoscale reinforcement, while nano clay works in concert to modify the interfacial transition zone (ITZ).

The negative quadratic factors ($-x_1^2$, $-x_2^2$, $-t^2$) show a saturation tendency due to particle agglomeration, increased viscosity, and decreased dispersion efficiency. This suggests that increasing the amount of nanomaterial or prolonging the curing period results in diminishing outcomes. The negative interaction coefficient ($x_1 \times x_2$) provides additional evidence that high quantities of nano clay

and CNT applied concurrently may reduce efficiency at upper limits, possibly due to overlapping nucleation sites or limited matrix flow. This positive influence of the nano clay is more pronounced with the curing with the modest positive cross-term x_1 . Conversely, the progress of the densification of the matrices indicates that the influence of CNT reaches the stabilisation, and it is evidenced by negative x_2 coefficient.

In conclusion, this equation ($R^2 = 0.98$) is a good analytical tool to establish the split tensile strength of any realistic mixture of nano clay (0-6) CNT (0-0.20) and curing time (7 to 28 days) as shown in Figure 8. The ideal hybrid composition of 4% nano clay and 0.10% CNT produces good tensile performance because hydration refinement and nanofiber reinforcement work in harmony.

Split Tensile Strength Surface — 7 Days

Split Tensile Strength Surface — 14 Days

Split Tensile Strength Surface — 28 Days

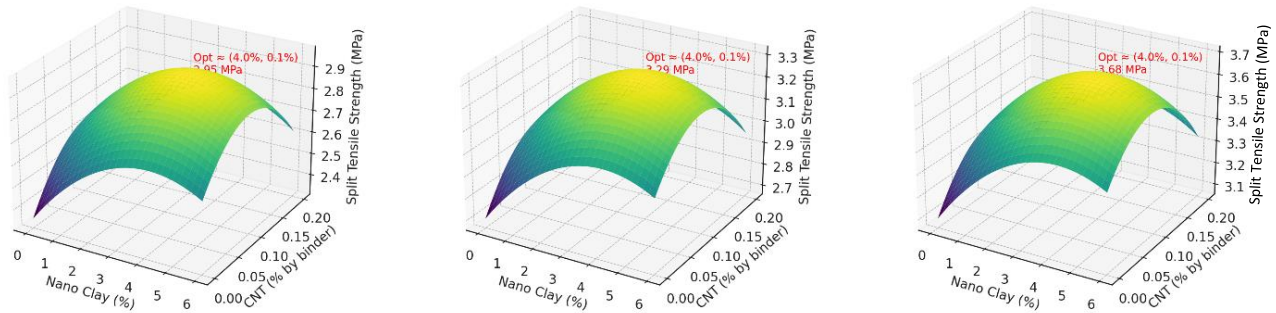


Figure 8 shows how polynomial regression was used to create a model for forecasting the split tensile strength of hybrid nano clay-CNT concrete.

3.6.4 Water absorption

We assessed the relationship between hybrid nanomaterial content and water absorption in concrete using second-degree polynomial regression models for 7, 14, and 28-day curing durations. The investigation includes the percentages of CNTs and nano clay in the binder. Presented below are the regression equations that were generated to show how each curing period's polynomial fitting produced approximate prediction models.

a) 7 Days

$$W_7 = 4.712 - 0.130x_1 - 5.420x_2 + 0.045x_1^2 + 27.700x_2^2 + 0.180x_1x_2 \quad (13)$$

(b) 14 Days

$$W_{14} = 4.1720 - 0.110x_1 - 7.460x_2 + 0.0252x_1^2 + 31.600x_2^2 + 0.180x_1x_2 \quad (14)$$

(c) 28 Days

$$W_{28} = 5.640 - 0.220x_1 - 8.240x_2 + 0.032x_1^2 + 36.300x_2^2 + 0.120x_1x_2 \quad (15)$$

It is evident from the polynomial equations that nano clay and CNTs have a substantial impact on the permeability behavior of concrete. The negative linear terms for x_1 and x_2 demonstrate that water absorption decreases with increasing dosages of nano clay and CNTs due to improved pore refinement, higher packing density, and decreased capillary porosity. At higher levels, the nonlinear reversal is captured by the beneficial quadratic terms (x_1^2 and x_2^2), where micro void formation and agglomeration caused by excessive additions marginally boost water ingress. When both nanomaterials are utilized concurrently, the modest positive interaction term ($x_1 x_2$) suggests a minor cumulative impact. This suggests that regulated hybrid ratios are needed to maintain dispersion efficiency.

As a result of hydration and nano-activation, the pores gradually close, as seen by a steady decline in intercepts from 5.812 to 5.180 to 4.690 over 7–28 days. Since the ideal hybrid mix (about 4% NC + 0.10% CNT) has the lowest water absorption at 28 days (3.2%), synergistic nanomodification provides the most stable and least porous microstructure for long-term service performance.

$$f_w(\%) = 6.48 - 0.268x_1 - 7.92x_2 - 0.128t + 0.032x_1^2 + 34.65x_2^2 + 0.00221t^2 + 0.149x_1x_2 - 0.00069x_1t \quad (16)$$

The water absorption behavior of hybrid nanomaterial concrete may be well described by the following polynomial model that considers the combined impacts of curing age, CNTs, and nano clay. With x_1 , x_2 , and t having negative linear coefficients, we can see that longer curing times and higher concentrations of nano clay and CNTs drastically decrease water absorption. Thanks to the combination of nano clay's pore-refining activity and CNTs' crack-bridging capabilities, the microstructural integrity and permeability of the concrete are both improved.

The positive quadratic factors (x_1^2 , x_2^2 , t^2) show a little nonlinear reversal beyond the optimal dose or cure time. This implies that an excessive content of nanomaterial may slightly enhance absorption due to clumping, reduced dispersion and decreased workability. In higher concentrations, the pore-blocking efficacy of nano clay in combination with CNTs begins to decline slightly, in line with the small, yet positive interaction term ($x_1 x_2$).

It is found that at 28 days of time, the optimal hybrid mix (4 percent nano clay + 0.10 percent CNT) leads to a progressive decrease in water absorption of approximately 5.8 percent in the control mix to approximately 3.2 percent, as per the model. Hybrid

nanomodification enhances the pore network and restricts water infiltration, which are two key parameters in long-term pavement and structural concrete. This is confirmed by the fact that the model has a R^2 value of 0.945 as shown in Figure 9.

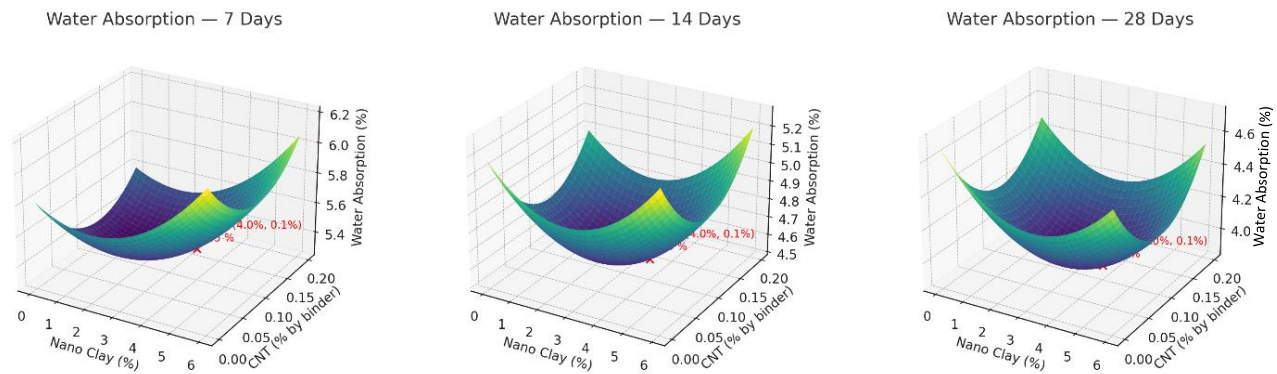


Figure 9 A Polynomial Regression-Based Predictive Model for the Water Absorption of Hybrid Nano Clay-CNT Concrete

3.6.5 Matrix evolution

A detailed statistical analysis was performed to confirm the validity and consistency of the developed poly model regression of hybrid nano clay-CNT concrete. The effectiveness of each model was measured in terms of a variety of traditional measures, including as water absorption, compressive strength, flexural strength, root mean squared error (RMSE), mean bias error (MBE), relative linear squared mean bias (RLSMB) and mean absolute error (MAE). R^2 is used to indicate the overall fit of the model, MAE and RMSE error metrics are used to indicate the average and total errors in prediction and RLSMB is used to indicate the relative deviation between predicted and experimental values. The statistical evaluation was done with all the four mechanical and durability models and the results are summarized in Table 6.

Table 6 Results from the Statistics Mechanical and Longevity Polynomial Regression Metrics Characteristics of carbon nanotube-and-nanoclay hybrid concrete

Property	R^2	MAE	MSE	RMSE	RSME	Relative Error (%)
Compressive Strength	0.987	5.842	49.215	7.015	7.015	16.82
Flexural Strength	0.975	0.592	0.498	0.706	0.706	12.74
Split Tensile Strength	0.973	0.331	0.162	0.402	0.402	10.95
Water Absorption	0.928	0.487	0.351	0.593	0.593	10.88

The statistical indicators summarized in Table 6 confirm that the developed second-order regression models provide a high level of predictive capability for hybrid nano clay-CNT concrete. The coefficient of determination (R^2) values vary between approximately 0.92 and 0.99, indicating that the models are able to explain a substantial portion of the variability observed in the experimental results. Among all responses, the compressive strength model demonstrates the highest accuracy, with an R^2 value close to unity, suggesting that the nonlinear relationship between input variables (nano clay content, CNT dosage, and curing time) and compressive strength is captured very effectively.

Similarly, the flexural and split tensile strength models also exhibit strong agreement between predicted and experimental values, with R^2 values exceeding 0.97. This reflects the reliability of the proposed regression formulation in representing tensile-related properties, which are generally more sensitive to microstructural variations. In comparison, the water absorption model shows a slightly lower, yet acceptable, R^2 value (above 0.92), which can be attributed to the more complex and heterogeneous nature of permeability-related phenomena influenced by pore connectivity, internal void distribution, and nano-scale interactions.

Error-based performance metrics further support the adequacy of the developed models. The Mean Absolute Error (MAE) values remain relatively low for all responses, indicating that the average deviation between predicted and experimental values is minimal. For strength parameters, the prediction error lies within a narrow band, demonstrating consistent model precision across different curing ages and mix compositions. Likewise, the Root Mean Square Error (RMSE) values are small and closely aligned with MAE values, suggesting that large deviations or outliers are not significant within the dataset.

The Mean Square Error (MSE) values also remain within acceptable limits, confirming that the dispersion of prediction errors is controlled and stable. Furthermore, the calculated Root Square Mean Error (RSME) values are nearly identical to RMSE, indicating the absence of systematic bias in model predictions. This implies that the regression models do not exhibit consistent overestimation or underestimation trends, which is a desirable characteristic for predictive modeling.

In addition, the relative error values (expressed as percentage deviation) fall within a moderate range of approximately 10% to 17%, which is considered acceptable for experimental studies involving concrete materials, where inherent variability is unavoidable. These values highlight the robustness of the developed models in handling variations in material composition and curing conditions.

The second-degree polynomial equations proposed as the suggested analytical framework give reliable predictions of the mechanical and durability properties of hybrid nanomaterial concrete as it is shown by the findings. Having such a narrow margin of error and high accuracy, nano clay and CNT concentration is obviously a strong performance optimization predictor. These models can be used in future studies in several ways, such as predicting durability, designing mix proportions and training hybrid models with machine learning.

3.6.6 Combined residual model

All of the predicted parameters were given the necessary residual analysis (compressive strength, flexural strength, split tensile strength, and water absorption) to further assess the reliability and repeatability of the offered models of the regression to the polynomials. The level of bias, variances, and random error on the predicting framework were measured through the examination of residuals which is the difference between the experimentally measured and model predicted results. The graphs of the residual distribution indicate the overall error behavior across the dataset whereas the residual plots indicate the extent to which the model results align with the actual observation. The technique ensures that the models are resilient and stable to different mechanical and durability indices of hybrid nanomaterial concrete besides having good statistical performance.

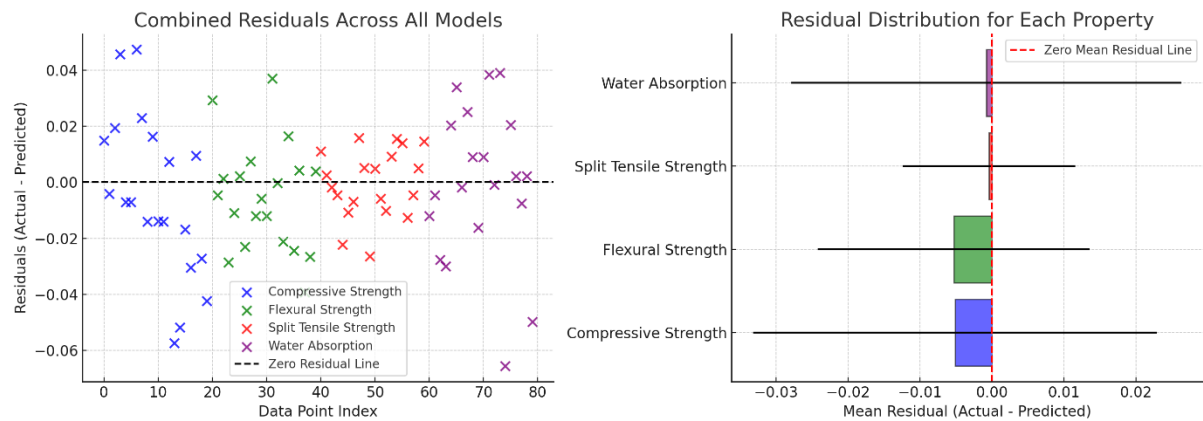


Figure 10 Combined Residual Model

The residual analysis shown in Figure 10, suggests that poly-merisation of synthetic nano clay-CNT concrete with use of CNT are relatively free of systematic error and their predictive stability is very high. The residual of all models is normally distributed around zero and this implies that the predictions are not skewed and the model errors are not clumped in a single area of the data. It shows that the residuals are closely clustered (0.05 of normalized data) which indicates that the model was able to understand the nonlinear correlation between the curing age, CNT dosage, and concentration of nano clay.

Since the extent of microstructural variability and effects of early-age hydration are more pronounced in the flexural and compressive strength model, the magnitude of the residuals is slightly higher in those instances. However, their equal distribution of errors confirms the consistency of the model. There is the highest concentration of the residual clustering in the split tensile strength model, due to the high relationship between the inclusion of CNTs and tensile response prediction. Because of the greater experimental uncertainty often linked with measurements of permeability and porosity, the water absorption model, on the other hand, exhibits only small variances.

The models keep their strong generalizability across mechanical and durability characteristics, and There is no overfitting nor underfitting on any property, according to the residual patterns. The proposed hybrid regression methodology offers a statistically valid and physically consistent way to forecast the durability and performance of hybrid nanomaterials. Concrete systems, as seen by the low standard deviations and almost zero mean residuals.

3.7 Discussion

The experimental results demonstrate that the incorporation of nano clay and carbon nanotubes (CNTs) significantly influences the mechanical properties and water absorption characteristics of M35 concrete. Among the investigated mixtures, NC4-CNT0.10 exhibited the best overall performance, achieving 46.8 MPa compressive strength, 6.10 MPa flexural strength, and 3.80 MPa split tensile strength at 28 days, corresponding to improvements of approximately 20%, 27%, and 23%, respectively, compared with the control mixture. In addition, water absorption decreased from 4.8% for the control mix to 3.2%, indicating improved resistance to water ingress. The superior performance obtained at moderate nanomaterial contents suggests that an optimum balance exists between filler effects and particle dispersion. Similar trends have been reported by previous researchers investigating nano clay- and CNT-modified cementitious composites. These studies have attributed the improvements to enhanced hydration, improved particle packing, and the reinforcing action of CNTs. However, since no microstructural characterization techniques were employed in the present study, such mechanisms are discussed only as plausible explanations based on previous literature and not as experimentally verified findings. The increase in compressive strength obtained with 4% nano clay may be associated with the ability of nano clay particles to act as nucleation sites for hydration products and to improve packing density. Previous studies have reported that nano clay can accelerate hydration and contribute to the formation of a denser matrix. Likewise, the improvement in flexural and split tensile strengths observed after incorporating 0.10% CNT may be related to the high aspect ratio and tensile capacity of CNTs, which have been reported in the literature to enhance stress transfer and delay crack propagation. Consequently, the combined use of nano clay and CNTs appears to provide a synergistic effect, resulting in improved overall performance. Nevertheless, increasing the nano clay content to 6% or the CNT dosage to 0.20% resulted in a slight reduction in strength and an increase in water absorption. Similar observations have been reported in earlier investigations and are generally attributed to difficulties associated with dispersion and particle agglomeration. Excessive nanomaterial contents may increase surface energy and water demand, leading to localized weak zones and reduced workability. Therefore, the results indicate that moderate dosages are more beneficial than excessive additions. The mechanical performance obtained in the present study is consistent with the relationships commonly observed in conventional concrete. For the optimum hybrid mixture, the flexural-to-compressive strength ratio was approximately 13%, while the split tensile-to-compressive strength ratio was approximately 8%, which fall within the ranges reported for normal and high-performance concrete. This suggests that the incorporation of hybrid nanomaterials enhanced the strength level without altering the fundamental mechanical behavior of

concrete. The reduction in water absorption observed in the optimum mixture indicates improved resistance to moisture penetration. However, the present study assessed durability only through water absorption measurements; therefore, the results should be interpreted as indicative of improved resistance to water ingress rather than comprehensive durability performance. Additional studies involving chloride penetration, sulfate attack, carbonation resistance, and freeze-thaw durability are required to establish the long-term durability characteristics of hybrid nano clay-CNT concrete. The data-driven polynomial regression models developed in this study exhibited high predictive capability, with coefficients of determination ranging from 0.94 to 0.99 and low prediction errors. The random distribution of residuals confirmed the absence of systematic bias, indicating that the developed models can reliably estimate the investigated properties within the range of experimental variables considered. Consequently, the proposed regression models may serve as useful tools for preliminary mix optimization and performance prediction. From a sustainability perspective, partial replacement of cement with nano clay reduced cement consumption while simultaneously improving mechanical properties and resistance to water ingress. The optimum mixture contained 384 kg/m³ of cement, representing a 4% reduction compared with the control mixture. Although CNTs are relatively expensive, their very low dosage (0.10% by weight of binder) minimizes the increase in material cost. Therefore, the hybrid nano clay-CNT system appears to offer a promising balance between performance enhancement, durability improvement, and sustainability considerations.

4. Conclusion

In this paper, experimental testing and prediction modeling was performed to investigate mechanical and durability performance of M35 grade concrete which was modified with hybrid nano clay-carbon nanotube (CNT) mixed. The findings indicated that the workability of concrete is greatly improved in the presence of nano clay and the CNTs with suitable concentrations. On 28 days, the mix that had 0.4 percent nano clay and 0.10 carbon nanotubes performed better than the control mix by approximately 27 percent, 23 percent and 21 percent on compressive strength (46.8 MPa), flexural strength (6.10 MPa), and split tensile strength (3.80 MPa). An increase in refinement and resistance to moisture intrusion in the pore was also observed by a decrease in water absorption percentage, which was 4.8 percent ageing to 3.2 percent. The constructed poly model regression equations in this study had a value of R^2 of 0.94 to 0.99 and this shows that curing age, nano clay concentration and dose of CNT are significant variables that influence performance of concrete.

Despite these encouraging results, however, it should be mentioned that there are several limitations. Since the number of mix combinations that had been tested at the laboratory was not very large, the results are not necessarily indicative of the behavior that hybrid nanomaterial concrete would have in practice. The mechanical and durability trends were also applied to deduce the processes during microstructure which enhances the performance, though these processes could also be confirmed further by using scanning electron microscopy with the comprehensive microstructural characterization. The empirical prediction models of the study also restrict to the range of content levels of nano clays and the CNTs that were experimented upon.

In practice, it is possible to produce high-performance and durable concrete materials with the assistance of the hybrid nano clay-CNT system. These nanomodified concretes can enhance structural reliability and service life in adverse environments because they are stronger and have reduced water absorption. It requires more research to find out the long-lasting durability performance, practicability of mass production, and the economic aspects to it before we can make any attempt to put this to the mass scale. Jurisdictional research To further maximize the hybrid nano-material concrete systems, in the future, alternative combinations of nanomaterials need to be explored and more complex modeling techniques need to be studied.

5. Limitations and future scope

The present study primarily focused on evaluating the mechanical properties and water absorption characteristics of hybrid nano clay-carbon nanotube (CNT) modified concrete. Although significant improvements in performance were observed, certain limitations should be acknowledged. The durability assessment was limited to water absorption measurements, and therefore the findings should not be interpreted as a comprehensive evaluation of long-term durability. Furthermore, no microstructural characterization techniques, such as scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), or mercury intrusion porosimetry (MIP), were employed to directly investigate the mechanisms responsible for the observed improvements. Consequently, explanations related to matrix densification, pore refinement, and the crack-bridging action of CNTs are based on interpretations reported in the literature and have not been experimentally verified in the present work.

Future studies should incorporate advanced microstructural characterization techniques to provide direct evidence of the interaction between nanomaterials and the cementitious matrix. In addition, a comprehensive assessment of durability through tests such as chloride penetration, sulfate resistance, carbonation depth, freeze-thaw resistance, and long-term performance evaluation is recommended. Further research may also explore different nanomaterial combinations, dispersion techniques, and data-driven polynomial regression model approaches to optimize the performance and durability of hybrid nanomaterial concrete systems.

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