Assessing Disaster Resilience of Concrete with Titanium Dioxide Nanoparticles

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Abstract

In recent decades, the occurrence of extreme events has intensified across diverse regions of the world, inflicting substantial impacts on economies, safety, and the quality of life of affected populations. This reality underscores the urgent requirement for innovative solutions to mitigate such damages. Within this framework, nanotechnology has emerged as a promising paradigm, with nanoadditives distinguished as effective agents for enhancing the durability, impermeability, and mechanical strength of construction materials. Nanoparticles such as titanium dioxide (TiO_2), carbon nanotubes (CNTs), silica, clay, and copper (Cu) have been associated with improvements in durability, strength-to-weight ratio, stability, and seismic resilience. The integration of these nanomaterials fosters densification of the concrete matrix by reducing voids and capillaries, thereby enhancing waterproofing and hindering the infiltration of deleterious substances. The present study offers an experimental investigation complemented by a comprehensive literature review, including water-absorption simulations and assessments of surface integrity in both treated and untreated materials. The objective is to evaluate the contributions of nanoadditives to safety, durability, and sustainability in the face of challenges posed by climate change. Results indicate that a 1% addition of nanoTiO_2 yields the highest mechanical strength, while higher concentrations tend to reduce benefits due to particle agglomeration. This finding underscores the importance of optimizing nanoparticle content to enhance concrete resilience against natural disasters, contributing to sustainable construction practices. The comparison with copper-based additives reveals that, despite some relative strength gain over time, copper formulations fall short in mechanical performance, highlighting nanoTiO_2 as a more promising agent for improving concrete durability in disaster-prone environments. Given the growing frequency of environmental disasters, the adaptation of civil construction through the sustainable incorporation of nanomaterials necessitates careful consideration of synthesis processes, long-term stability, and potential ecological impacts associated with nanoparticle interactions with biotic and abiotic environmental components.

Introduction

Disasters are extreme events defined by the occurrence of natural phenomena capable of posing risks to society, as illustrated by floods, landslides, earthquakes, and other such events, which may also be influenced by anthropogenic factors[1]. In the wake of the climate change that occurred in 2024, African nations such as Kenya, together with Asian countries including Indonesia and Afghanistan, experienced severe flooding, resulting in hundreds of fatalities and thousands of homeless people[2]. From 1998 to 2017, floods affected more than two billion people worldwide[3]. According to Marengo et al., between 2013 and 2022, more than 2.2 million homes in Brazil were damaged, impacting over 4.2 million individuals across 2,640 municipalities. Flooding persists owing to a combination of natural, social, and climatic drivers, and has generated losses on the order of USD 10 billion[4].

Given the increasing severity and widespread risk of these events in recent years, researchers and professionals have been seeking management strategies and new technologies aimed at fostering resilient communities, in parallel with industry advances toward greater sustainability[5,6]. Among the promising materials for civil engineering applications aimed at increasing disaster resilience are titanium dioxide nanoparticles (nanoTiO_2), which have demonstrated numerous advantages for essential construction materials, including concrete[7,8].

The use of nanomaterials in the construction industry is now widespread across a range of applications. They are employed in paints and coatings to enhance resistance to UV degradation and attack by aggressive substances. These materials contribute to greater durability, reduced permeability, improved thermal insulation, and enhanced fire resistance. For instance, when incorporated into asphalt, TiO_2 interacts with polluting gases, converting them into less harmful compounds. Applied to glass, TiO_2 can render the surface self-cleaning, as the oxide layer degrades organic molecules and facilitates the removal of inorganic dust. Ultraviolet radiation interacts with the self-cleaning glass layer, further breaking down molecules and removing organic dust. The development of new building materials is essential to render structures more resilient to environmental stresses, thereby reducing disaster impacts and enhancing safety.

Titanium dioxide, renowned for its whiteness and stability, first achieved broad public visibility in the 1970s, primarily as a pigment in concrete and other construction materials[9]. During that period, TiO_2 was employed to create high-quality, durable finishes on exterior surfaces. Beginning in the 1990s, a new direction emerged with the discovery of its photocatalytic properties, which markedly expanded TiO_2's applications within the construction sector[10].

In order to fully understand the relevance and applicability of TiO_2 in civil construction, it is essential to outline its properties and relate them to practical benefits, such as flexural, tensile, and compressive strength, along with durability indicators such as electrical resistivity, permeability, and resistance to sulfate attack, carbonation, and freeze-thaw cycles. Experimental results reported by Ali Nazari et al. indicate that concrete flexural strength increases with the addition of TiO_2 nanoparticles up to a concentration of 3.0%. Although these represent direct advantages, the photocatalytic and bactericidal properties of TiO_2 should also be considered as significant long-term economic benefits[11].

The ability of advanced materials to maintain stability in the presence of external environmental factors, including catastrophic scenarios such as weathering, climate change (e.g., increased CO_2 levels), and floods, is highly pertinent today. Nevertheless, widespread adoption is viable only if production and application are ecologically sustainable[12,13,14]. This concern is particularly salient given that cement manufacturing accounts for approximately 5%-8% of global CO_2 emissions, a substantial portion of the civil construction sector's footprint, while cement remains its mainstay and global per capita consumption stands at roughly 20 billion metric tons[15,16,17,18,19,20,21,22].

In this context, the present manuscript reports the development and application of an experimental procedure to evaluate the distinctive properties of nanoTiO_2, with emphasis on parameters such as the mechanical strength of treated concrete. The study is underpinned by a focused literature review that examines the potential benefits of these nanoparticles, regulatory considerations, sustainable production, and their relevance in the context of catastrophic scenarios.

Aspects of titanium dioxide in concrete

Titanium dioxide nanoparticles (nanoTiO_2) encompass sizes from 1 to 100 nanometers and typically assume spherical or ellipsoidal morphologies. Their nanoscale dimensions confer a markedly increased surface area, which substantially enhances their reactivity[23]. These nanoparticles have gained prominence in the realm of cement-based composites owing to their distinctive characteristics and diverse applications[24,25,26]. NanoTiO_2 has emerged as a versatile component in cementitious formulations, exhibiting properties that render it suitable for a wide range of industrial uses[11,16,18,20].

This nanomaterial is employed for several reasons, including favorable chemical properties, low toxicity, cost-effectiveness, anti-corrosive characteristics, and photocatalytic capabilities[27,28]. NanoTiO_2 can augment the resistance of concrete to handling, a factor amplified by photocatalysis that occurs under ultraviolet (UV) light. It possesses the ability to decompose organic substances - such as pollutants, dirt, and microorganisms - present within concrete[29]. Furthermore, nanoTiO_2 can generate highly reactive free radicals, endowing the surface with cleansing properties, and it also protects concrete from damage caused by atmospheric agents that accelerate wear, such as nitrogen oxides[30].

NanoTiO_2 particles can assume several crystalline forms - rutile, anatase, and brookite - each with distinct properties. Anatase and rutile are the most common polymorphs of TiO_2, while brookite's properties are not yet fully understood, which poses challenges for industrial application[31,32,33,34]. Because of TiO_2's photocatalytic properties, anatase is widely used in water and air purification systems, where it is highly effective at decomposing organic and inorganic impurities. Rutile finds extensive use in the textile, plastics, and paint industries, and the rutile form is also widely employed in sunscreens and other cosmetics due to its UV-blocking capabilities[35,36].

Titanium dioxide nanoparticles (nanoTiO_2) offer versatile applications in construction materials, such as concrete, enhancing performance and introducing new functionalities. Among their notable attributes are antimicrobial and self-cleaning properties, which hold promise for mitigating urban air pollution through the transformation of polluting gases[37,38,39]. When exposed to sunlight, nanoTiO_2 can decompose organic substances into water and carbon dioxide, with the resulting byproducts subsequently removed by water[40].

In addition, the pozzolanic activity of nanoTiO_2 at the exterior interface of concrete can augment durability, although it may be associated with increased water absorption and potential implications for workability[41]. It is also important to note that nanoTiO_2 particles may agglomerate within the cement matrix, potentially impairing performance[42,43,44]. Regarding gas degradation, concrete incorporating TiO_2, for instance, in pavement applications, has the potential to reduce tropospheric O_3 levels[45].

TiO_2's photocatalytic capabilities enable the formation of hydroxyl radicals (OH) and superoxide ions (O_2-) in the presence of water under ultraviolet irradiation. These highly reactive species oxidize and decompose dirt and inorganic contaminants. The photocatalytic action of TiO_2's also lowers the contact angle of water on surfaces, enhancing self-cleaning performance[46]. This self-cleaning property contributes to reduced airborne impurities, potentially lowering pollutant concentrations associated with greenhouse gas-driven climate risks.

NanoTiO_2 also contributes to increases in the flexural and compressive strength of materials. In terms of compressive strength, nanoTiO_2 reduces porosity, refines pore structure, densifies the matrix, and promotes hydration. However, achieving these benefits requires careful control of particle loading and effective homogenization to prevent agglomeration and the formation of weak zones that could initiate cracks[47]. TiO_2 acts as a filler that densifies the cementitious composite, thereby reducing porosity. This outcome is linked to (i) the acceleration of C-S-H gel formation, (ii) a reduction in the available space for $Ca(OH)_2$ development, yielding smaller crystallites, and (iii) the creation of a more homogeneous microstructure with reduced porosity. Appropriately calibrated additions of TiO_2 can also enhance the bending strength of cement composites[48].

NanoTiO_2 has been shown to significantly enhance the durability of cementitious composites by reducing porosity and water permeability, and by imparting protection against chemical attacks and environmental factors such as ultraviolet radiation. This benefit, however, hinges on the adequate dispersion of the nanoparticles, since their high surface energy and van der Waals interactions at the nanoscale tend to promote agglomeration[37]. When properly homogenized, the incorporation of nanoTiO_2 improves impermeability, electrical resistivity, and resistance to freeze-thaw cycles and sulfate attack, underscoring its potential for construction intended to withstand catastrophic events. Nevertheless, at high concentrations, these advantages may be diminished or even reversed[49,50].

In the context of TiO_2 applications in civil construction for extreme scenarios such as floods, storms, and temperature extremes, it is essential to balance the benefits of nanoTiO_2 with the potential risks associated with its use. For instance, the photocatalytic properties that can enhance urban air quality and assist in cleaning and waste remediation after a catastrophe must be weighed against possible inhalation hazards and lung toxicity[51,52,53].

Copper-based additives improve waterproofing and are low-cost and easily manipulated. Nanometric titanium dioxide produces water-repellent concrete and increased compressive strength. Currently used on a large scale, TiO_2 is not intended for end users but has potential for future construction. Compressive strength testing compares the results of samples with various mixtures to analyze the advantages and disadvantages of copper additives and titanium dioxide.

Concrete impregnated with nanoTiO_2 exhibits higher solar reflectance (greater albedo), contributing to milder ambient temperatures, mitigating the urban heat island effect, and, practically, reducing building temperatures and yielding energy savings. This benefit extends to reduced consumption of cleaning products[54,55].

Attributes such as opacity, durability, antibacterial potential, UV resistance, and the capacity to accommodate alternative raw materials within concrete - thereby reducing reliance on cement and aggregates - signal strong incentives for nanoTiO_2 deployment. These prospects are complemented by the potential for improvements to green roofs and surfaces that promote more efficient rainwater drainage[10,56,57,58].

On the longevity and durability of concrete incorporating nanoTiO_2, contemporary studies indicate enhanced resistance to ultraviolet radiation, as well as improved resilience against chemical attack and weathering[59]. These improvements yield direct economic benefits by reducing the frequency of repairs and replacements, thereby lowering material consumption and waste over time. Beyond these immediate financial advantages, the use of nanoTiO_2 also offers indirect savings related to the production, transportation, and disposal of concrete, contributing to a reduced carbon footprint associated with its life cycle[33,60].

Given the environmental implications of the sulfate and chloride processes used to extract ilmenite and rutile, the chloride process is regarded as the less harmful option. This route employs chlorine gas to convert rutile into $TiCl_4$, which is subsequently oxidized to TiO_2, producing fewer deleterious byproducts than the sulfate process[59]. TiO_2-containing products yield stable, non-leaching residues at the end of their life cycle, thereby presenting a lower environmental risk. This environmental profile complements the enhanced resistance and durability of materials, particularly under catastrophic conditions, underscoring the value of experimental evaluations in advancing construction technologies.

A study carried out by Mohajerani et al. demonstrates that the properties of concrete vary with the nanomaterials applied[61]. Nanoparticles of silica, titanium, carbon, iron, and aluminum are introduced to concrete to reinforce mechanical strength, promote rapid and enhanced hydration, induce a higher degree of hydration, impart self-cleaning capabilities, improve mechanical durability, prevent cracking, increase compressive strength, and boost abrasion resistance. These benefits are highly desirable in construction materials, contributing to the greater resilience of structures against natural disasters.

Therefore, the objective of this work is to validate, through the splitting tensile test on cylindrical specimens, the enhancement of mechanical strength in concrete achieved by incorporating titanium dioxide nanoparticles into the mix. This research aims to advance the development of more resilient materials, particularly in the context of natural disasters where concrete structures are subjected to extreme conditions and require superior durability and performance.

Protocol

The methodological basis employed is the Brazilian test, which determines indirect tensile (splitting) strength *via* the diametral section of vertically loaded cylindrical specimens. This procedure, developed by Professor Lobo Carneiro in 1943 for cementitious materials, involves applying two concentrated, diametrically opposed compressive forces to a cylinder, thereby generating uniform tensile stresses perpendicular to the diameter along the test section[62].

The test employed five groups, designated A, B, C, D, and E, corresponding respectively to: a control group; concrete with 1% NanoTiO2; concrete with 2% $NanoTiO_2$; concrete with 3% $NanoTiO_2$; and concrete with 3% copper-based plasticizer additive. Each group was subdivided into three curing-time subgroups: 7 days (1), 14 days (2), and 28 days (3). Thus, the study comprises a total of fifteen specimens, labeled as A1-A3, B1-B3, C1-C3, D1-D3, and E1-E3. **Figure 1** depicts the specimen used in this study.

1. Specimen preparation

1. Prepare four groups of specimens using a concrete mix of Portland CPII cement, crushed stone, medium-washed river sand, and water in the ratio 1:2:3 (cement:sand:gravel), maintaining a water/cement ratio of 0.5. For each 3.63 kg specimen, use approximately 558.46 g of cement, 1,116.92 g of sand, 1,675.38 g of gravel, and 279.23 g of water.

   NOTE: Use this formula for test specimens without any additives. For specimens with titanium dioxide, add it during the mixing of the dry ingredients (cement, sand, and gravel). Once the mixture is homogeneous, add water. For specimens with a plastic additive, dilute it in the mixing water before adding it to the mixture.

2. Homogenize all components thoroughly to obtain the most uniform mass possible, then cast the mixture into the molds. Inspect the mixture for signs of aggregate segregation, free-water accumulation, or staining from unmixed material. Ensure uniform consistency to guarantee representative results.

3. Mold the test specimens in cylindrical metal forms 10 cm in diameter and 20 cm in height. Fill the molds properly, ensuring the concrete volume reaches the designated level with uniform distribution, without excess or deficiency that could compromise the test. Completely fill the interior, preserving the mold geometry and avoiding voids.

4. Produce Sample A in accordance with ABNT NBR 6136, ABNT NBR 5738, and ABNT NBR 5739[63,64,65]. Use this sample as the negative control, devoid of any additives, to serve as the baseline for comparison with the other specimens.

5. Produce Sample B by incorporating 1% $NanoTiO_2$ (approximately 36.3 g) into the concrete mix. Exercise care during preparation, as TiO_2 tends to agglomerate; therefore, distribute the nanoparticles evenly across the mass to ensure homogeneity among sample sets.

6. Produce Sample C by incorporating 2% $NanoTiO_2$ (approximately 72.6 g) into the concrete mix. Exercise care during preparation, as TiO_2 tends to agglomerate; therefore, distribute the nanoparticles evenly across the mass to ensure homogeneity among sample sets.

7. Produce Sample D by incorporating 3% $NanoTiO_2$ (approximately 108.9 g) into the concrete mix. Exercise

care during preparation, as TiO_2 tends to agglomerate; therefore, distribute the nanoparticles evenly across the mass to ensure homogeneity among sample sets.

8. Produce Sample E by incorporating 3% copper-based plasticizer additive (approximately 108.9 g) into the concrete mix. Use this sample as the positive control to compare the effect of the plasticizer additive on concrete performance relative to the other samples.
9. Store the samples in an area with controlled conditions, without being subject to environmental influences, to await the curing time.

2. Curing process

1. Cure the specimens in a humidity-controlled area at a temperature of (23 ± 2) °C and relative humidity of at least 95% for 24 h. Then, submerge the specimens in lime-saturated water maintained at the same temperature (23 ± 2) °C for continued curing over the designated period in accordance with ABNT NBR 5738[63].
2. Measure the weight of each sample after curing; ensure that each sample mass on average 3.63 kg.
3. Specimens conditioning at room temperature (23 ± 2) °C as follows:
   7 days: samples A1, B1, C1, D1 and E1;
   14 days: samples A2, B2, C2, D2 and E2;
   28 days: samples A3, B3, C3, D3 and E3.
   NOTE: It is important to highlight that the percentages in this method are related to the mass of the test specimen, **Table 1**.

3. Compressive strength testing

NOTE: Perform the compression strength test using the Concrete Testing Machine (Press), with a nominal and calibrated range of 0-100 tons. Calibrate the equipment by indirect measurement, relating pressure to piston area, using a digital manometer and digital caliper. Zero the equipment and ensure alignment before testing.

1. Subject each specimen to an axial compression test in a universal tensile/compression testing machine.
2. Ensure the load cell capacity is compatible with the specimen dimensions and that a digital control system for monitoring and recording the applied load is in place.
3. Continue the test until failure, recording the maximum supported load.
4. Compute the compressive strength (fc) using:
   $fc = F\text{max} / A$
   where: fc = compressive strength (N/mm^2), Fmax = maximum recorded load (N), A = test specimen cross-sectional area (mm^2). 1 N/mm^2 = 1 MPa
5. Conduct the compressive-strength test by positioning each cylindrical specimen (100 mm × 200 mm) vertically at the center of the hydraulic press, ensuring proper contact with the loading plates. Ensure correct seating of the loading surfaces in accordance with ABNT NBR 5739:2018[64].
   1. Apply the axial load continuously and without impact, at a rate of 0.45 ± 0.15 MPa/s[66,67]. Repeat for the three specimen sets: control, TiO_2-doped, and copper-based additive.
6. Record all values systematically for comparison among sample sets.
7. Compare the results to assess the behavior of the samples.
8. Conclude the test.

NOTE: **Figure 2** presents the specimens subjected to the compression test after 28 days of curing. **Figure 3** displays the compressive strength values obtained for each tested sample.

4. Material residues disposal

NOTE: All waste generated during the testing process shall be disposed of in accordance with ABNT NBR 10004 and ABNT NBR 15116, as well as with the guidance of local authorities responsible for environmental protection norms and standards, including[68,69,70].

1. Separately collect concrete fragments, dust, and any materials containing TiO_2 or plasticizing additives. Prioritize the reuse or recycling of solid waste at licensed facilities for construction and demolition waste processing, in line with the technical requirements for recycled aggregates.
2. For non-recyclable waste, package the material in sealed containers to prevent the dispersion of fine particles and direct it to industrial landfills authorized by the competent environmental agency.
   NOTE: Under no circumstances should waste be released into stormwater systems, natural water bodies, or unlicensed disposal site[71].

Representative Results

The values obtained for each sample in the compressive strength test are presented in **Table 2** and **Figure 3**. **Table 2** indicates the sample identification, its curing time, and the maximum load supported in MPa. In **Figure 2**, it is possible to visualize a subset of samples after the compression test. The values recorded are presented in **Figure 3**.

Numerous studies indicate a rise in concrete strength when TiO_2 is incorporated into cementitious blends. In particular, Nazari and Riahi demonstrated that adding TiO_2 nanoparticles up to 4.0% by weight as a substitute increases compressive strength[57]; however, substitutions exceeding 5.0% by weight yield a reduction in compressive strength compared with mixtures containing 1.0%-3.0% TiO_2. The authors attributed the greater strength to the rapid consumption of crystalline $Ca(OH)_2$ during early hydration, a consequence of the high reactivity of TiO_2 nanoparticles. TiO_2 nanoparticles act as nanofillers, densifying the pore structure and mitigating detrimental porosity, thereby enhancing overall resistance.

Preliminary results from this investigation indicate an improvement in compressive strength for specimens containing TiO_2 within the concrete mix. The intended approach involves incorporation during the block manufacturing process, with the prospect of cost reductions at scale. Such an approach would render a material possessing superior characteristics and greater resilience to disasters more accessible to users. Compression tests reveal that adding TiO_2 at 1% by mass or more yields higher strength than both the control concrete and mixes containing 3% copper-based plasticizer.

Post-fracture testing, conducted in accordance with the relevant specifications, shows that specimens with defined quantities of TiO_2 exhibit superior impermeability after removal from the moisture chamber, in line with ABNT NBR 5738, and display no signs of elevated internal humidity[63,72].

Water absorption within concrete pores alters light reflection, producing observable changes in surface coloration that may serve as a non-destructive indicator for voids and overall condition. Spectral color differences correlate with void content, enabling early detection of potential ingress issues[73,74].

Conversely, concrete specimens without additives, or those containing copper-based additives, exhibited higher internal humidity and color changes consistent with greater water permeability and reduced moisture resistance. These findings underscore the effectiveness of titanium dioxide in enhancing the waterproofing properties of concrete. The photographic record of specimens subjected to 28 days of curing during compressive strength testing reveals color variations arising from both curing duration and the specific additive used. Notably, specimens labeled B3, C3, and D3 appear lighter than those labeled A3 and E3.

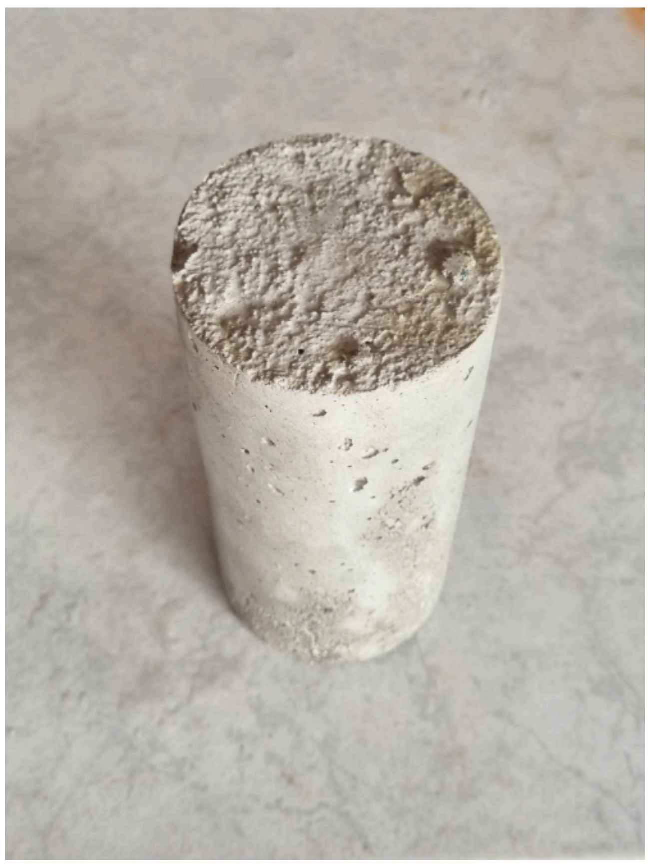

Figure 1: Cylindrical concrete test specimen molded according to ABNT NBR 5739. Please click here to view a larger version of this figure.

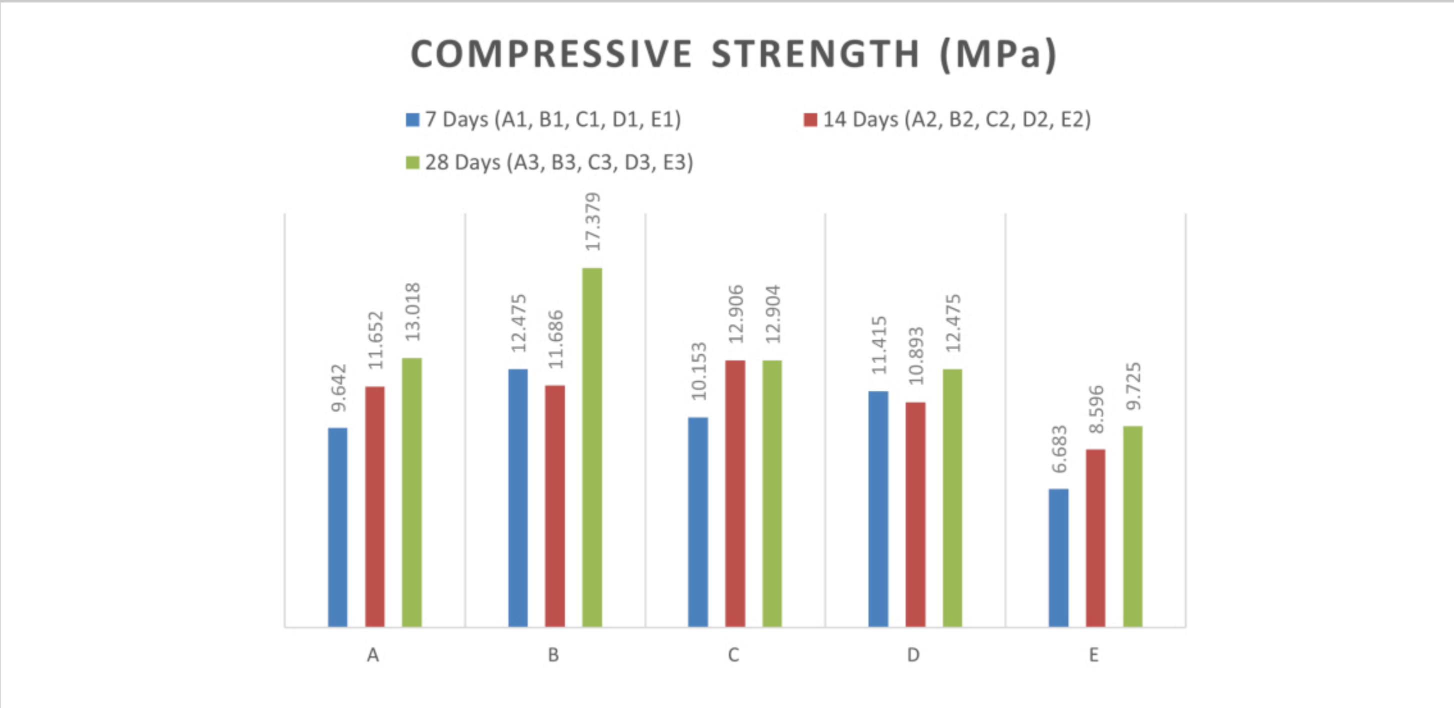

Figure 2: Samples subjected to compression test after 28 days of curing. Please click here to view a larger version of this figure.

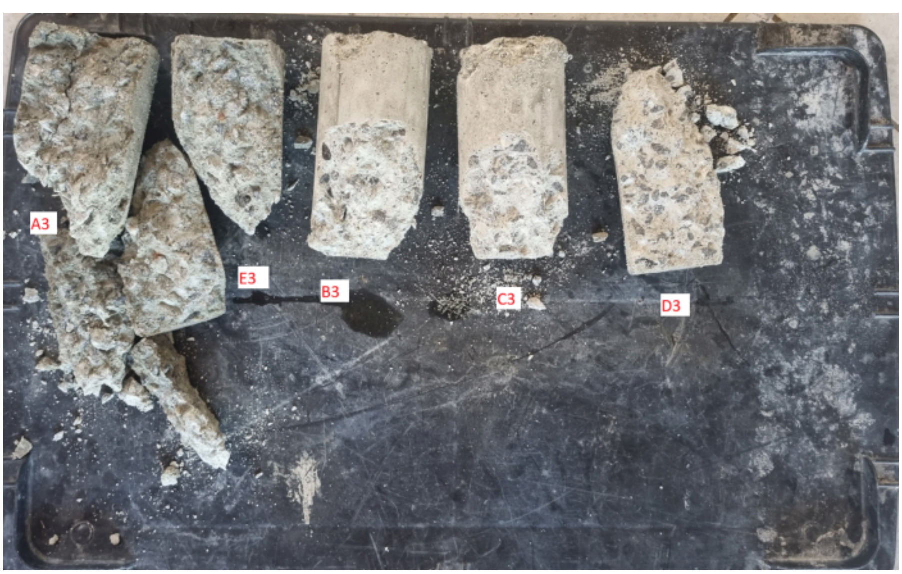

Figure 3: Compressive strength supported by each specimen (MPa). Please click here to view a larger version of this figure.

Id	Mass (kg)
A1	3,614
B1	3,920
C1	3,586
D1	3,676
E1	3,515
A2	3,594
B2	3,495
C2	3,671
D2	3,693
E2	3,640
A3	3,717
B3	2,559
C3	3,623
D3	3,639
E3	3,570

Table 1: Initial mass of the specimens.

	Compressive Strength (MPa)		
	7 Days	14 Days	28 Days
Id	(A1, B1, C1, D1, E1)	(A2, B2, C2, D2, E2)	(A3, B3, C3, D3, E3)
A	9,642	11,652	13,018
B	12,475	11,686	17,379
C	10,153	12,906	12,904
D	11,415	10,893	12,475
E	6,683	8,596	9,725

Table 2: Compressive strength for specimens (MPa).

Discussion

In the analysis of the results, which are graphically illustrated in **Figure 3**, it is evident that samples containing a copper-based plastic additive exhibited the lowest compressive strength. These values are inferior to those of the control group, which was prepared without any additive. **Figure 3** further shows that, after 28 days of curing, the specimens achieve the best performance in the compression test.

The compression tests reveal a substantial enhancement in concrete strength with the addition of nanoTiO_2, most notably at a 2% concentration, which yielded an 18.9% increase after 28 days relative to the reference sample. This improvement corroborates the findings of Nazari and Riahi (2010), who attributed the strengthened performance to the nanoparticles' nano-filler action, which reduces porosity and refines the pore structure. This effect was particularly pronounced at 14 and 28 days of curing. With regard to the copper-based additive employed in the specimens, TiO_2 outperformed it, recording on average a compressive strength approximately 3.1% higher than that achieved with the copper-based additive alone.

Based on the percentage analysis, the 1% nanoTiO_2 mixture (Group B) achieved the highest performance, reaching 17.379 MPa at 28 days, which represents a 39.3% increase compared to its own 7-day strength and 33.5% higher than the control group at the same age. The 2% mixture (Group C) showed a 27.1% gain from 7 to 28 days, while the 3% mixture (Group D) had the smallest improvement, only 9.3%, suggesting that higher nanoparticle contents may reduce benefits due to particle agglomeration. The copper-based additive group (E), although having the highest relative growth over time (+45.5%), remained 44% lower than the best-performing formulation. These results indicate that an optimal dosage exists in this study, 1% beyond which the mechanical advantages of nanoTiO_2 diminish.

A fundamental aspect in the incorporation of nanoparticles into concrete is their effective dispersion within the cementitious matrix, with research on mechanical dispersion indicating that gradual incorporation favors distribution and reduces agglomeration; however, when feasible, ultrasonic dispersion is preferable as it promotes greater homogeneity. Insufficient dispersion, combined with variations in the water-cement ratio, compromises mechanical performance, making it essential to ensure precise dosage, robust mixing, and strict control of curing conditions to guarantee the reproducibility of experimental results.

TiO_2 nanoparticles have the potential to reduce CO_2 emissions through enhanced durability and lower maintenance needs. However, its production generates significant waste and energy consumption. Sustainability depends on improved process efficiency and waste management. A comprehensive cost-benefit analysis is needed to establish industrial feasibility[75]. Regulatory authorities must establish safe usage limits and assess long-term ecological impacts. Future research should compare TiO_2 with other nanomaterials and examine its behavior under environmental processes. As climate change intensifies, smart and resilient materials, like TiO_2-enhanced concrete, will be crucial for urban infrastructure vulnerability and disaster resilience[76,77].

In conclusion, a diametrical compression test to ascertain tensile strength confirms that titanium dioxide nanoparticles are a beneficial additive for augmenting the mechanical strength of concrete. The proportion of TiO_2 incorporated into the mix does not render the final product substantially more expensive for end users. Consequently, structures constructed with concrete containing this additive exhibit enhanced strength. Additionally, TiO_2 nanoparticles occupy and fill pores within the concrete, reducing water absorption and thereby improving performance in events such as urban flooding[44].

Disclosures

The authors declare that they have no financial or material interests related to the research described in this article.

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