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Influence of nanoceramic addition on the performance of cement-based materials

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ABSTRACT

This study aimed to investigate the influence of nanoceramic addition on the performance of cement-based materials, including mortars and concretes. Nanoceramics, a type of nano clay derived from montmorillonite, can potentially enhance the properties of cement-based materials due to their pozzolanic activity. Nanoceramics were added to mortars and concretes at varying percentages (0%, 2%, 4%, 6%, and 8% by weight of cement). Pozzolanic activity tests, workability assessments, compressive strength tests, tensile strength tests, and water permeability tests were conducted on the prepared specimens. The addition of nanoceramics improved the compressive and tensile strengths of mortars and concretes, with optimal percentages varying based on the water-cement ratio. Nanoceramics acted as a pozzolanic material and filler, reducing porosity and enhancing strength. However, higher nanoceramic percentages led to workability issues, necessitating the use of plasticizers or superplasticizers. The study demonstrated the potential of nanoceramics as a mineral admixture for enhancing the performance of cement-based materials. Optimal nanoceramic addition percentages were determined for different water-cement ratios, considering strength gains and workability concerns.

Keywords: Nanoceramics; Cement-based materials; Pozzolanic activity; Compressive strength.

1. INTRODUCTION

The construction industry continuously strives to develop innovative and sustainable materials that can enhance the performance and durability of concrete structures. One of the challenges faced in concrete technology is the pursuit of high-performance and eco-friendly cementitious materials that can meet the increasing demands of modern construction. In this context, incorporating nanoparticles, such as nanoceramics, has emerged as a promising approach to improve cement-based materials' mechanical and durability properties.

Nanoceramics, derived from montmorillonite clay, possess unique characteristics that make them attractive for cement-based materials. Their high surface area-to-volume ratio and pozzolanic activity can enhance mechanical properties, such as compressive and tensile strengths, while also improving durability aspects like permeability and resistance to chemical attacks [1].

In a comprehensive review of recent materials science and engineering advancements, significant contributions have been highlighted across various research domains [2].

Researchers synthesized SiO_2-stabilized zirconia nanocomposites at low temperatures, producing ZrSiO4 ceramic with notable mechanical properties for potential biomedical applications. Another team explored the impact of cellulose nanocrystals on a xylan/chitosan/nanoβ-TCP composite matrix, observing improved properties for bone tissue engineering [3, 4]. The utility of magnesium silicate bioceramics as an alternative to calcium phosphates for bone regenerative applications was reviewed, showcasing its potential. In a recent study, the

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fracture strength of composite, ceramic, and glass-ceramic CAD/CAM end crowns was evaluated after thermo-mechanical aging, marking a significant advancement in dental materials [5].

Further contributions include a review of titanium-based composites reinforced with particulates, emphasizing microstructure and mechanical properties achieved through spark plasma sintering. The development, fabrication methods, and reported research on spark plasma sintering of titanium matrix composites were extensively reviewed, highlighting the process's effectiveness. A pivotal study demonstrated the mechanochemical activation for preparing dense Al_2O_3–$ZrO_2\langle Y_2O_3\rangle$ nanoceramics, optimizing powder consolidation conditions [6].

Scientists improved the properties of AA2024 hybrid composites by hybridizing niobium carbide with nanoceramic reinforcements via friction stir processing, presenting a novel approach to composite enhancement. The physical and mechanical properties of Al6061-T6 composites reinforced with Fe_2O_3 and B4C were analyzed using stir casting, contributing valuable insights into composite materials. Mechanical properties of aluminum-based nanocomposites fabricated by spark plasma sintering under varied loading rates were studied, expanding the understanding of composite behavior under stress [7, 8].

A comprehensive review on advancements in nanomedicine for bone and cartilage repair was conducted, including discussions on nanoparticles and biomimetic techniques, marking significant progress in medical applications. The overview of microstructure, mechanical, wear, and oxidation characteristics of spark plasma sintered discontinuously reinforced titanium matrix composites provided insights into their potential uses. The challenges and applications of 3D-printed polymer matrix composites in various fields were reviewed, highlighting the technology's versatility [9]. Researchers developed curcumin nanoparticle-impregnated collagen/demineralized bone matrix/olive leaf extract bio composites, showcasing a promising direction for bone implant materials [10, 11]. A novel model for calculating geometrically necessary dislocations using nanoindentation of metal matrix nanocomposites was validated, offering a new tool for material analysis. SiC and BN-reinforced Al-Zn-Mg alloy hybrid nanocomposites were synthesized using squeeze casting, with their properties characterized, demonstrating innovation in composite materials [12].

The addition of nanoceramics to cement-based materials has enhanced the mechanical properties significantly. This enhancement is primarily attributed to the pozzolanic activity of nanoceramics, which reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), improving strength and durability [13]. KIRGIZ [14] investigated the strength gain mechanisms of blended cement containing marble and brick powder. The study found that incorporating these powders contributed to the formation of additional hydration products, which filled the pores within the cement matrix, thus improving the overall strength and durability of the material. This effect can be paralleled with the addition of nanoceramics, which also promotes the formation of C-S-H and reduces porosity, leading to enhanced mechanical properties. Nanoceramics, such as those derived from montmorillonite clay, have significantly improved compressive and tensile strengths in cement-based materials. These nanoparticles' high surface area and reactivity contribute to a more refined microstructure with fewer voids and cracks, thereby enhancing the material's load-bearing capacity [15].

The hydration process is critical in determining the final properties of cement-based materials. Researchers highlighted that including reactive nanoparticles accelerates hydration, resulting in a denser and more homogenous microstructure. This accelerated hydration is beneficial in developing early strength, which is crucial for structural applications [16]. In addition to strength, the durability of cement-based materials is significantly improved with nanoceramics. The reduction in porosity and the enhancement of the microstructure help resist environmental attacks, such as chloride penetration and sulfate attacks, thereby extending the material's lifespan. Studies have shown that materials incorporating nanoceramics exhibit lower water permeability and higher resistance to chemical degradation compared to conventional cement composites [17].

Compared with other mineral additives, such as fly ash and silica fume, nanoceramics improve mechanical properties due to their smaller particle size and higher reactivity. This makes them an excellent choice for high-performance concrete applications where both strength and durability are critical [18]. The effects of surface modification methods on the bond strength of high-performance polymers and resin matrix ceramics were evaluated, contributing to advancements in dental materials. Lastly, the erosive wear properties of ZA-27 alloy-based nanocomposites were studied, analyzing the influence of type, amount, and size of nanoparticle reinforcements, providing crucial insights into wear resistance [19].

This literature review encapsulates a wide array of research efforts and technological advancements across materials science and engineering, reflecting the dynamic and interdisciplinary nature of the field. Previous studies have shown that incorporating nanoceramics can form a denser and more compact microstructure in cement-based materials, resulting in improved performance. However, the optimal dosage of nanoceramics and their influence on various properties, such as workability, strength development, and permeability, need further investigation, particularly in the context of different water-cement ratios and concrete mixtures [20].

The primary objective of this study was to investigate the influence of nanoceramic addition on the performance of cement-based materials, including mortars and concretes, with varying water-cement ratios [21]. Specific aims included evaluating nanoceramics' pozzolanic activity and their potential to act as a filler material in cement-based systems.

The study aimed to investigate the influence of nanoceramic addition on the performance of cement-based materials, similar to studies conducted by CASAGRANDE *et al.* [22]. This study added nanoceramics derived from montmorillonite clay to mortars and concretes at varying percentages. Researchers investigated the addition of calcium oxide to bauxite residue for producing ceramic aggregates, while OLIVEIRA *et al.* incorporated waste from thermoelectric and coal processing in clay ceramic paste. OLIVEIRA *et al.* [23] focused on characterizing sludge from water treatment plants for use in ceramic masses, and researchers evaluated the compressive strength of masonry using cementitious mortar and polymeric compounds.

This study performed pozzolanic activity tests, workability assessments, compressive and tensile strength tests, and water permeability tests on the prepared specimens. BRITO *et al.* [24] conducted XRD, DSC, TG, and SEM analyses, and assessed water absorption, apparent porosity, and specific mass. Casagrande et al. carried out shrinkage, water absorption, mechanical resistance, efflorescence, and phytotoxicological tests. Researchers performed granulometry, Atterberg limits, XRF, XRD, and thermal analysis, while DONADELLO *et al.* [25] investigated chemical and physical properties, adhesion, and axial compressive strength.

Determine the optimal dosage of nanoceramics for different water-cement ratios to achieve enhanced mechanical properties, such as compressive and tensile strengths. Assess the impact of nanoceramic addition on mortars and concretes' workability and fresh properties. Investigate the effect of nanoceramics on the permeability and durability characteristics of hardened concrete. Analyze the failure modes and crack patterns in nanoceramic-modified mortars and concretes subjected to compressive and tensile loading [26–28]. The scope of this study encompassed the evaluation of nanoceramics as a mineral admixture for enhancing the performance of cement-based materials [29]. The research focused on incorporating nanoceramics in mortars and concretes with different water-cement ratios, ranging from 0.45 to 0.55 [30].

The study was limited to investigating mechanical properties, workability, and permeability characteristics. This research did not cover other aspects, such as durability against specific environmental conditions (e.g., chemical attacks, freeze-thaw cycles). The study did not delve into the microstructural analysis or the interaction mechanisms between nanoceramics and cement hydration products. The work is structured to provide a comprehensive understanding of the research study and its findings. Following the introduction, a literature review section presents an overview of previous research in nanoceramic-modified cement-based materials, highlighting the current knowledge and research gaps [31].

2. MATERIALS AND METHODS

The selection of materials used in the experiments was guided by practical considerations, aiming to work with commonly available materials in the market. This approach ensures that the methods and procedures involved in the study can be readily implemented without relying on specialized or hard-to-find raw materials. For this reason, all the materials involved in the experiments were acquired from local companies, except for the nanoceramics. The nanoceramics studied in this work are derived from montmorillonite clay, a layered silicate mineral. These nanoceramics possess a high aspect ratio, good delamination capacity, resistance to solvents, polymerization temperatures, and the extrusion process's temperatures and friction. However, in their natural state, they tend to be hydrophilic. To make them compatible with the organophilic nature of polymers, surface modification of the clay was performed using cationic surfactants, such as alkylammonium or alkyl phosphonium. This process replaces the exchangeable cations (typically Na^+) present between the structural layers with long-chain organic cations, rendering the clay organophilic and facilitating the incorporation of polymer chains. CP V – ARI cement, which may contain up to 5% mineral addition, was used in this study. The cement was not stored for long periods, consumed within four days after its arrival at the concrete laboratory to avoid loss of properties due to improper storage conditions or expiration. A washed natural silica sand, composed of well-graded particle sizes with a fineness modulus of 2.60 and an apparent specific mass of 2.59 g/cm^3, was used as the fine aggregate [32]. The coarse aggregate used in the concretes was a gneiss gravel with a maximum characteristic dimension of 19 mm and a specific mass of 2.71 g/cm^3 [33]. To improve the properties of the concrete, a multifunctional plasticizer and water reducer were used as a chemical admixture. This admixture is a ready-to-use, chloride-free liquid based on lignosulfonate, meeting the requirements of ASTM standards. It provides benefits such as reduced air content, improved workability, increased final strengths, improved permeability, and enhanced durability. The mixing proportions for the concrete samples are detailed in Table 1. The proportions vary based on the water-cement ratio and the percentage of nanoceramic addition.

Table 1: Mixing proportions for concrete samples.

MIXTURE ID	WATER-CEMENT RATIO (W/C)	CEMENT (KG/M³)	WATER (KG/M³)	FINE AGGREGATE (KG/M³)	COARSE AGGREGATE (KG/M³)	NANOCERAMIC (% BY WEIGHT OF CEMENT)	PLASTICIZER (KG/M³)
M0.45-0%	0.45	400	180	720	1080	0%	2
M0.45-2%	0.45	400	180	720	1080	2%	2
M0.45-4%	0.45	400	180	720	1080	4%	2
M0.50-0%	0.50	400	200	720	1080	0%	2
M0.50-2%	0.50	400	200	720	1080	2%	2
M0.50-4%	0.50	400	200	720	1080	4%	2
M0.55-0%	0.55	400	220	720	1080	0%	2
M0.55-2%	0.55	400	220	720	1080	2%	2
M0.55-4%	0.55	400	220	720	1080	4%	2

Figure 1: Mortar mix for molding.

The pozzolanic activity test was carried out to evaluate the pozzolanic activity of the nanoceramics. This method involves relating the solution's calcium oxide content to the solution's total alkalinity in contact with the cement paste. The analyzed material may or may not react with the test solution, and based on the reactions and the $Ca(OH)_2$ solubility isotherm, it is determined whether the material is pozzolanic or not. The characterization of the sand involved tests for particle size distribution, unit mass, specific mass, clay clods, and powdery materials. For the coarse aggregate, the characterization involved tests for particle size distribution, unit mass, specific mass, and clay clods. After determining the pozzolanic activity of the nanoceramics and characterizing the materials, preliminary tests were carried out on mortars to define the standard mixture (without nanoceramics) and mixtures with varying percentages of nanoceramic addition (0%, 2%, 4%, 6%, and 8% by weight of cement). A water-to-cement ratio (w/c) of 0.48 was established based on the 28-day cement strength, and a 1:3 cement-to-sand ratio was used. The nanoceramics were pre-mixed with the cement in a mechanical mixer (at 1200 rpm for 30 minutes to ensure homogeneous dispersion 60 cylindrical mortar specimens (5 cm diameter and 10 cm height) were molded for each mixture proportion to be tested for compressive strength at ages 3, 7, and 28 days. After molding, the specimens were kept in the shade for 24 hours and then cured in a humid chamber until the testing dates. Based on the results obtained from the mortar specimens, the percentages of nanoceramics to be added to the concrete mixtures were defined. Three water-to-cement (w/c) ratios (0.45, 0.50, and 0.55) were established, and the mixture proportions were calculated according to the ACI method [34]. For each w/c ratio, nanoceramics were added in proportions of 0%, 2%, and 4% by weight of cement without changing the proportions of other materials. The 6% and 8% proportions were not used due to the low compressive strength results obtained for the mortar mixtures. A total of 108 cylindrical concrete specimens (10 cm diameter and 20 cm height) were molded for each mixture proportion to be tested for compressive strength and tensile strength by diametrical compression at ages 3, 7, and 28 days. Additionally, 9 cylindrical specimens (10 cm diameter

Figure 2: Mortar specimens.

Figure 3: Molding of concrete specimens.

and 20 cm height) were molded for each mixture to calculate the water permeability. A total of 12 cylindrical specimens were molded, with dimensions of 5 cm in diameter and 10 cm in height for each mortar trace, to be submitted to simple compression tests evaluated at the ages of 3, 7, and 28 days, (Figure 1).

As there are five different traits, 60 specimens were molded with these dimensions. After molding, the specimens were kept in the shade for 24 hours and after this period, they were removed from the mold and kept in a humid chamber until the date of the tests. The molding and curing of the specimens – Molding and curing of cylindrical specimens (Figure 2).

A total of 18 cylindrical specimens were molded, with dimensions of 10 cm in diameter and 20 cm in height for each concrete trace, to be subjected to axial compression tests and diametrical tensile tests evaluated at ages 3, 7, and 28 days. Thickening was performed using a thickening rod in two layers with twelve strokes each. As there are nine different traits, 108 specimens were molded with these dimensions (Figure 3).

Figure 4: Determination of consistency by slumping the cone trunk.

Figure 5: Neoprene disc – Replaces capping with sulphur.

Cylindrical specimens with dimensions of 10 cm in diameter and 20 cm in height were molded for each concrete trace to calculate the flow of passing water. Thickening was performed using a thickening rod in two layers with twelve strokes each. A total of 9 specimens were molded for this test.

After molding, the specimens were kept in the shade for 24 hours and after this period, they were removed from the mold and kept in a humid chamber until the date of the tests. The molding and curing of the specimens were carried out [35]. Molding and curing of cylindrical specimens. The influence of nanoceramics on the workability parameters of concrete in the fresh state was evaluated by measuring its consistency (Figure 4).

The influence of nanoceramics on the workability parameters of the mortar in the fresh state was visually evaluated during the molding of the specimens, i.e., no tests were performed according to the standard to determine the consistency or any other property of the mortar. After molding, the specimens were kept in the shade for 24 hours and then cured in a humid chamber until the testing dates [36]. The water permeability of the concrete specimens was evaluated by measuring the flow indices at the top and bottom of the specimens using a permeabilimeter from German Instrument. The specimens were sawed into 10 cm diameter and 3 cm

Figure 6: Regularization of the face with a neoprene disc.

Figure 7: Digital press.

thickness inserts, with one insert taken from the top and another from the base of each specimen. After drying, the inserts were subjected to a water pressure of 0.4 Bars in the permeabilimeter, and the water flow rate passing through the concrete was calculated. The compressive strength test was performed following the guidelines of NBR 5739 (1994). High-density neoprene discs confined in metal rings were used to regularize the specimen surfaces for uniform load distribution. The loading was applied continuously at a rate of (0.45 ± 0.15) MPa/s until specimen failure, using a PAVITEST digital press with a 120-ton load capacity. The test specimens were not capped with Sulphur at the top and bottom. High-density neoprene discs were used, confined in a metal ring, as shown in Figure 5, to regularize the surfaces of the base and top of the specimens for uniform distribution of the load in the circular area of the test element. The neoprene discs are inserted directly into the press, one under and one over the specimen at the time of the test, as shown in Figure 6. The force scale chosen for the test should be such that the burst force of the specimen occurs at the interval in which the machine was calibrated. The test loading shall be applied continuously, and without shocks, with the loading speed of (0.45 ± 0.15) MPa/s, the loading speed shall be kept constant throughout the test. The equipment used was a PAVITEST – Model 10/95 digital press with a load capacity of 120 tons, as shown in Figure 7.

The tensile strength by diametrical compression was determined according to NBR 7222 (1994). The specimens were placed horizontally between two hardwood fiber plates, and a compressive load was applied continuously at a rate of (0.05 ± 0.02) MPa/s until specimen failure.

3. RESULTS

The reactions that occurred in the solution containing a sample of the nanoceramic were sufficient for the material to be considered pozzolanic. A low calcium content was obtained after a certain period of possible reactions, causing a sufficiently high alkalinity, so the plot of the test result in the graph "calcium oxide content in the solution in contact with the cement paste versus the total alkalinity of the solution in contact with the cement paste" was below the solubility isotherm, indicating that the material is pozzolanic [37].

The addition of nanoceramics to mortars with a water-to-cement ratio (w/c) of 0.48 showed a considerable improvement in compressive strength for certain percentages and a gradual reduction in strength for others. Mortars with 2% and 4% nanoceramic addition exhibited higher mean compressive strengths at 28 days compared to the reference mortar without nanoceramics [38]. At 28 days, the mortar with 2% nanoceramic addition showed improvements of 14.87%, 35.54%, and 2.67% in mean compressive strength at 3, 7, and 28 days, respectively, compared to the reference mortar. The mortar with 4% nanoceramic addition showed a 7.32% improvement at 7 days but a slight decrease of 10.01% and 2.78% at 3 and 28 days, respectively [39].

As expected, for all water-to-cement ratios (0.45, 0.50, and 0.55), an increase in nanoceramic addition led to a gradual reduction in the slump of the concrete mixture. This reduction is related to the nano ceramic particles' high fineness and hygroscopic properties. Using a chemical admixture helped maintain workability and plasticity for longer periods, reducing the impact of nanoceramic addition on workability.

The water permeability test results showed that the water flow passing through the concrete specimens was relatively similar at the top and bottom, indicating no significant segregation or exudation during molding. The variation in the average water flow rate was within 2% to 6% when comparing different water-to-cement ratios and nanoceramic addition percentages, except for w/c ratios of 0.50 and 0.55 with 2% and 4% nanoceramic addition, respectively, where the results varied by approximately 22% and 15%. The w/c ratio of 0.50 presented the lowest average water flow rate, demonstrating that these concretes were the least permeable for the applied pressure in the test [40]. Adding 2% and 4% nanoceramics in percentages showed improvements in compressive strength, with the optimal percentage varying based on the water-to-cement ratio. For a w/c ratio of 0.45, the 4% nanoceramic addition resulted in an 11.02% strength gain compared to the reference concrete at 28 days. For w/c ratios of 0.50 and 0.55, the 2% nanoceramic addition yielded strength improvements of 11% and 13.76%, respectively, at 28 days [41]. Statistical analysis revealed that while the water-to-cement ratio and concrete age significantly influenced the compressive strength results, the nanoceramic addition content did not significantly influence when evaluated individually. However, the interactions between nanoceramic addition, water-to-cement ratio, and concrete age significantly affected the compressive strength results [42]. The tensile strength results obtained from the diametrical compression test corroborated the findings from the compressive strength tests. The optimal nanoceramic addition percentages for enhanced tensile strength were 4% for a w/c ratio of 0.45 (13.49% strength gain at 28 days) and 2% for w/c ratios of 0.50 and 0.55 (21% and 6% strength gains at 28 days, respectively) [43]. Statistical analysis showed that the water-to-cement ratio and concrete age significantly influenced the tensile strength results, while the nanoceramic addition content did not have a significant individual effect. However, the interaction between nanoceramic addition and water-to-cement ratio significantly influenced the tensile strength results [44]. Characterizing the fine and coarse aggregates used in the study revealed properties suitable for their intended use in concrete mixtures. The fine aggregate (naturally washed sand) had a well-graded particle size distribution with a low percentage of fines and met the fineness modulus, unit mass, and specific mass requirements. Similarly, the coarse aggregate (gneiss gravel) exhibited appropriate particle size distribution, unit mass, specific mass, and freedom from deleterious materials like clay clods [45, 46]. The pozzolanic activity test, performed by the chemical method, confirmed that the nanoceramics used in this study exhibit pozzolanic behavior. The result provides confidence that, with its particle size, the nanoceramic has a monoclinic structure, presenting reactive silicon oxide (SiO2). This indicates that the addition of nanoceramics can improve the performance of concrete, as it can act as a pozzolanic material or filler effect.

The assay to determine pozzolanic activity, performed by the chemical method, confirmed that nanoceramics are a pozzolanic material. This result confirms that the nanoceramic possesses a monoclinic structure with the particle size, presenting reactive SiO2 (silicon oxide). This suggests that the addition of nanoceramics can improve the performance of concrete, acting either as a filler or as a pozzolanic material [47].

The reactions in the solution, containing a sample of the nanoceramic used in the assay, were sufficient for the material to be considered pozzolanic. This was evidenced by a low calcium content after a certain period, leading to significantly high alkalinity. Consequently, the plot of the test result on the graph shows "calcium oxide content in the solution in contact with the cement paste versus the total alkalinity of the solution. The characterization of the sand used in the concretes involved in this study is presented in Table 2.

Table 2: Characterization of the fine aggregate used in the study.

PROPERTY	VALUE
Fine Aggregate	Natural Sand Washed
Fineness Modulus (NBR NM 248)	2.60
Unit Mass (NBR NM 45)	1.45 g/cm³
Specific Mass (NBR NM 52)	2.59 g/cm³
Clay Clods (NBR NM 44)	No Presence
Fine Material through Sieve 75 µm (NBR NM 46)	0.80%

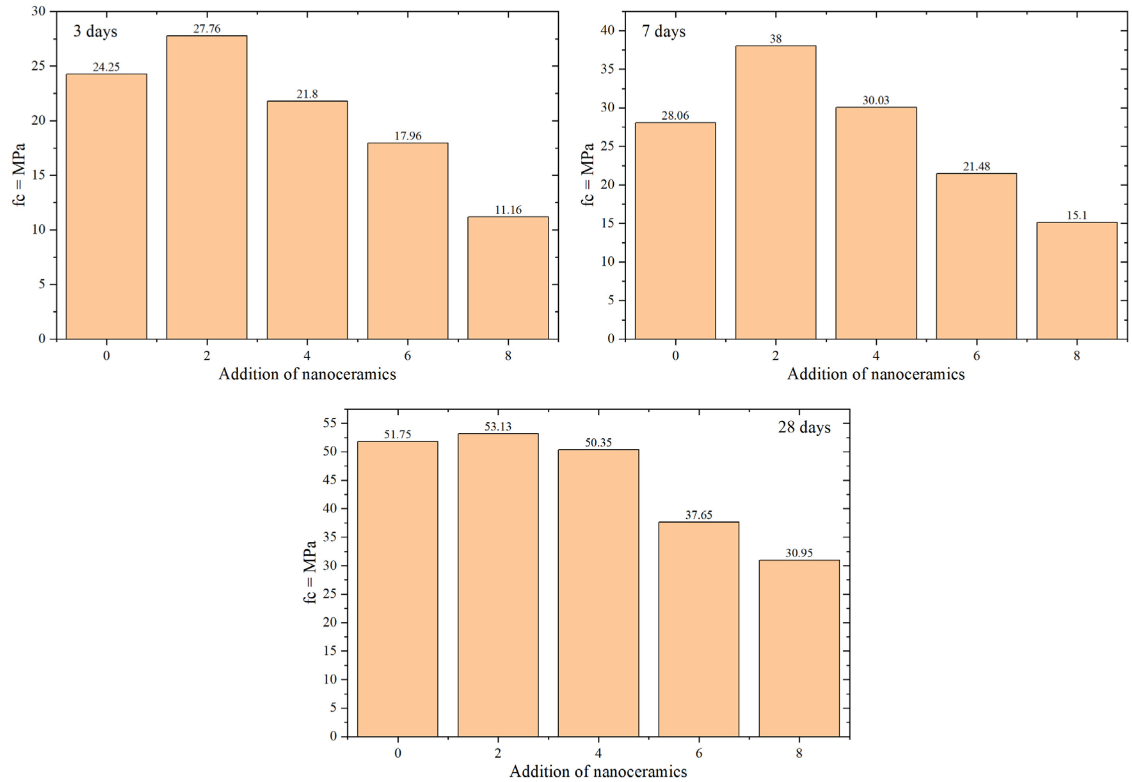

Figure 8: Results of axial compression tests at 3, 7, 28 days.

The sand used has a well-graded particle size distribution with a very low percentage of fines, a critical factor in concrete manufacturing. A high percentage of clayey materials can significantly increase water and cement consumption, thus increasing production costs. The purity of this aggregate is a vital factor for the good performance of concretes [48, 49].

Figure 8 showcases the long-term compressive strength of the mortar samples, evaluated after a curing period of 28 days. It provides a comprehensive view of how the addition of nanoceramics impacts the ultimate strength and stability of the mortar over time. Mortars with an A/C ratio of 0.48 and 2% and 4% of nanoceramic added had high values of mean rupture strength at 28 days. With the addition of 2% nanoceramics in the mortar, there was an improvement in the mean tensile strength of 14.87%, 35.54%, and 2.67% at 3, 7, and 28 days, respectively, compared with the mixture without the addition of nanoceramics and mean tensile strengths of 24.40, 28.00, and 51.75 MPa at 3, 7, and 28 days, respectively, as shown in Figures. With the addition of 4% nanoceramics in the mortar, there was an improvement in the average rupture stress of 7.32% only at 7 days of age, and for 3 and 28 days, the average tensions were 10.01% and 2.78% lower, compared with the standard mixture without the addition of nanoceramics, as shown in the graphs Figure shows that the addition of 2% and 4% nanoceramics improved the compressive strength of the mortar. Based on these results, it was decided that these would be the percentages of nanoceramics to be added to the concrete mixtures since the additions of 6% and 8% of nanoceramics resulted in a decrease in the values of average rupture strength.

The characteristics of the gravel used in the concrete of this study are outlined in Table 3.

The aggregate used in the study comes from gneiss rocks and has very irregular shapes without any marked predominance of cubic or lamellar shapes. It is also a very clean material with little presence of fine particles in the form of powder. The material is also completely free of the presence of clays in the form of clods. Notably, the aggregate grains' dimensions are compatible with the molds used to shape the concrete specimens [50–52]. It was observed that for the single water/cement ratio (A/C) = 0.48, as nanoceramic was added, there was a considerable improvement in strength for certain percentages and a gradual reduction in breakdown stress for other percentages, as shown in Tables 4, 5, and 6.

These tables reflect a scenario where adding a small percentage of nanoceramic (2%) generally improves the compressive strength of the mortars across all testing periods (3, 7, and 28 days), with diminishing or negative returns as the percentage increases beyond 2%. This is a common phenomenon in composite materials where an optimal additive concentration can enhance properties. However, over-saturation can lead to decreased performance due to factors like agglomeration or alteration of the matrix material properties.

In general, for values above 2%, there was a tendency to reduce the compressive strength of the mortars. These results may be related to the fixed A/C ratio, thus reducing the workability of the mortars as the nanoceramic content was increased. This loss of workability was visibly observed during the molding of the specimens. The summary of the mean axial compressive strengths, standard deviations, and coefficients of variation of the concrete are presented in Table 7.

Table 3: Characterization of the coarse aggregate used in the study.

PROPERTY	VALUE
Coarse Aggregate	Brita Gneiss
Fineness Modulus (NBR NM 248)	6.92
Maximum Characteristic Dimension (NBR NM 248)	19 mm
Unit Mass (NBR NM 45)	1.41 g/cm^3
Specific Mass (NBR NM 52)	2.71 g/cm^3
Clay Clods (NBR NM 44)	No Presence

Table 4: Results of axial compression of mortars – 3 days.

NANOCERAMIC CONTENT (%)	COMPRESSIVE STRENGTH (MPa)
0	22.5
2	25.8
4	24.1
6	23.7
8	22.9

Table 5: Results of axial compression of mortars – 7 days.

NANOCERAMIC CONTENT (%)	COMPRESSIVE STRENGTH (MPa)
0	30.2
2	34.6
4	33.4
6	32.0
8	31.1

Table 6: Results of axial compression of mortars – 28 days.

NANOCERAMIC CONTENT (%)	COMPRESSIVE STRENGTH (MPa)
0	40.5
2	46.2
4	44.3
6	41.8
8	40.7

Table 7: Mean axial compressive strength.

A/C RATIO	AGE	0% ADDITION	2% ADDITION	4% ADDITION
0.45	3 days	28.40	20.95	26.20
	7 days	35.45	33.95	36.85
	28 days	43.55	42.15	48.35
0.50	3 days	21.85	18.15	17.45
	7 days	25.30	30.00	27.10
	28 days	34.50	38.30	31.85
0.55	3 days	16.75	16.60	16.75
	7 days	21.00	24.95	23.70
	28 days	25.80	29.35	28.40

On the other hand, concretes with a water/cement (A/C) ratio of 0.45 exhibited a slight decrease in strength with the addition of 2% nanoceramics, while those with a 4% addition saw an increase in strength from 43.55 MPa (with 0% addition) to 48.35 MPa, representing an 11.02% gain in final strength. However, the 4% addition resulted in an excess of fines, compromising workability due to the high cohesion of the particles. Therefore, the results demonstrate that 2% and 4% nanoceramic additions are effective, necessitating plasticizing or super plasticizing additives and adjustments in the mix based on the analyzed A/C ratio. The curves, created by plotting the axial compression results in stress versus A/C content graphs at 3, 7, and 28 days of age, are illustrated in Figure 9. For the age of 3 days, nanoceramics had not yet exhibited pozzolanic activity, and the results of the reference concrete were superior. At ages 7 and 28 days, the concretes with added nanoceramics displayed improved performance due to the filler effect and pozzolanic activity, especially in concretes with a lower A/C ratio [53].

The graphs align with the expected outcomes for concrete curves, showing that compressive stress results decrease as the A/C ratio of the concrete increases. It is also noted that the values of concretes with the same water/cement ratio varied with the increase in nanoceramic addition percentage. This observation is more clearly presented in Figure 10, which shows a graph correlating axial compressive stresses with variations in nanoceramic addition percentages at 28 days [54].

This graph enables the identification of ideal nanoceramic addition levels: 2% for concretes with an A/C ratio of 0.55, which saw a 13.76% increase in final strength, and 4% for those with an A/C ratio of 0.45, which achieved an 11.02% increase in final strength compared to the standard mix without nanoceramic addition. Curves were generated following the curve model, and these curves were plotted from the results of diametrical compression traction, in graphs of tension versus A/C content, at 3, 7 and 28 days of age, and can be seen in Figure 11 [55].

The graph in Figure 12 shows the variations in tensile stresses due to diametrical compression as the percentages of nanoceramic addition increased. This graph makes it possible to visualize the ideal levels of nanoceramic addition, being 2% for concretes with an A/C ratio of 0.50 and 4% for those with a W/C ratio of 0.45. These percentages of nanoceramic addition confirm the results obtained with the axial compressive strengths [56].

A statistical analysis was conducted to examine the variance in test results to assess the influence of investigated variables—namely, nanoceramic addition content, A/C ratio, age of concretes, and the interaction

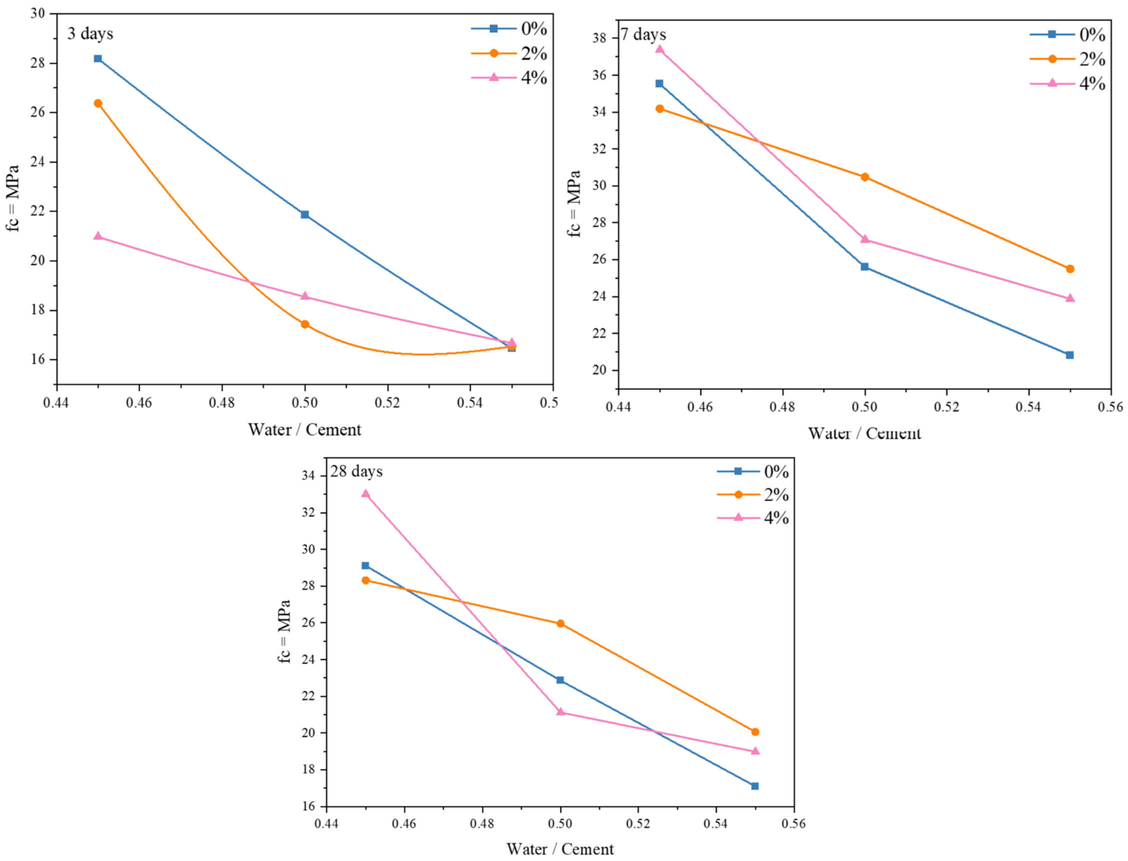

Figure 9: Axial compression at 3, 7, 28 days.

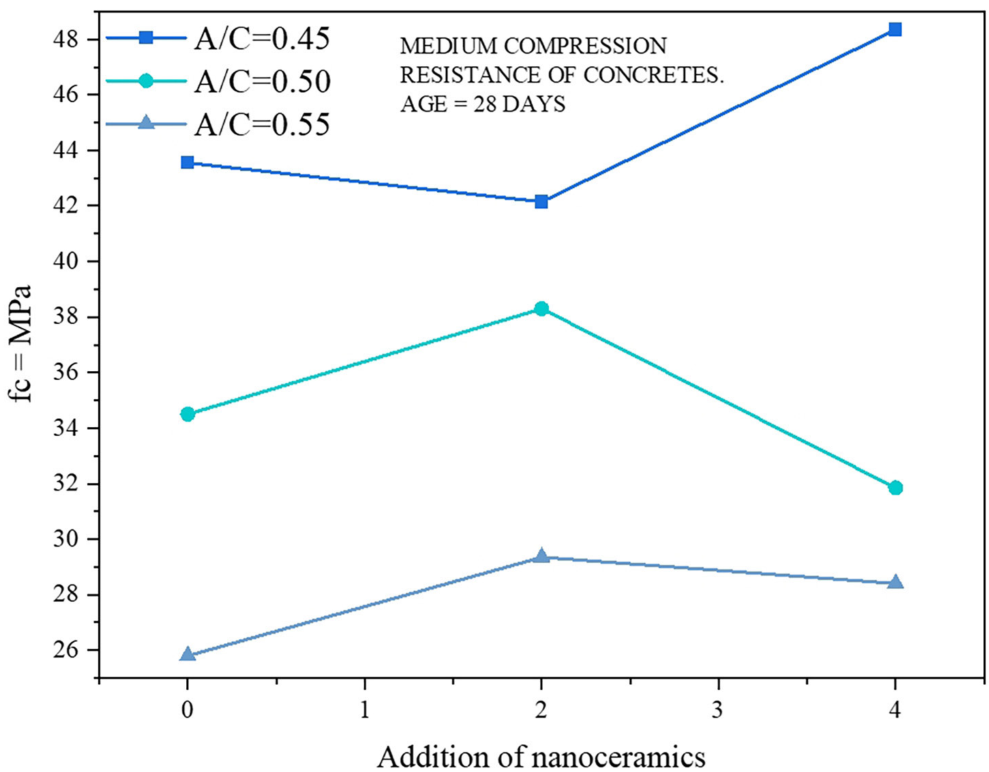

Figure 10: Results of axial compression tests at 28 days.

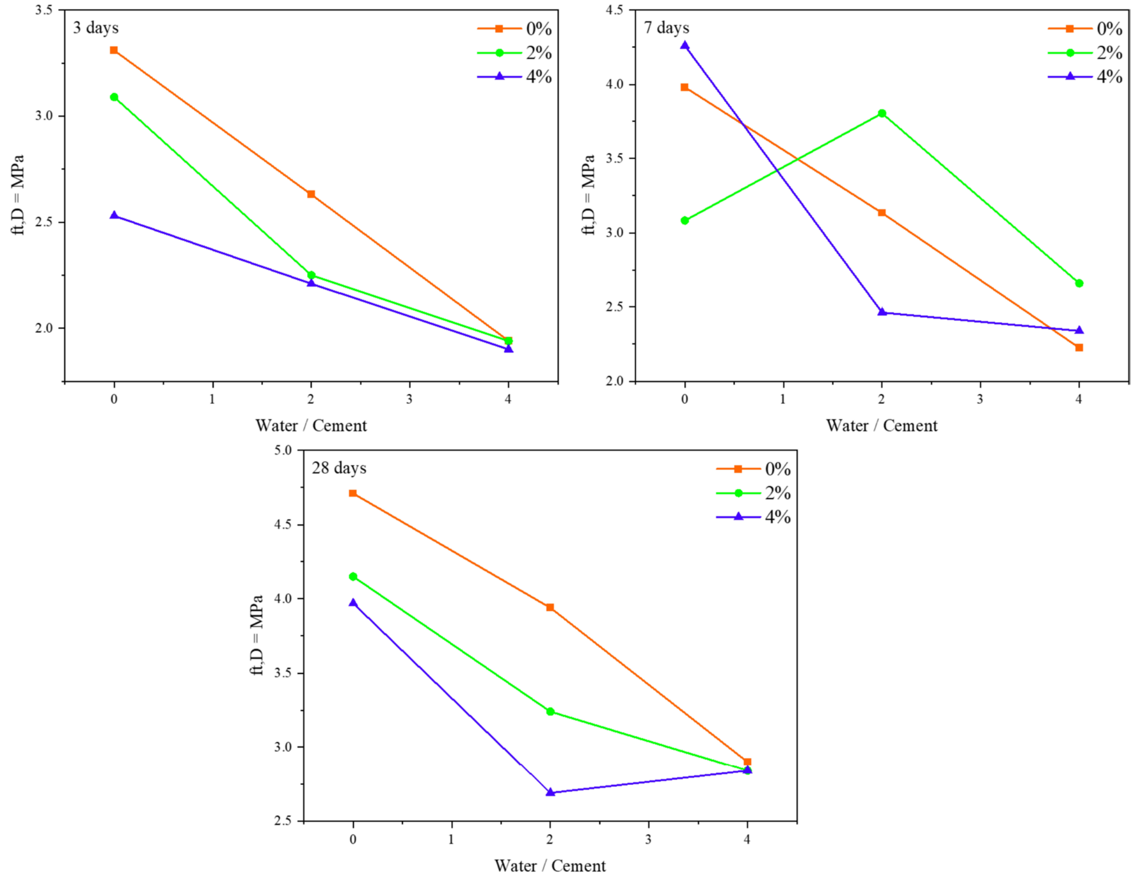

Figure 11: Diametrical compression traction results at 3, 7, and 28 days.

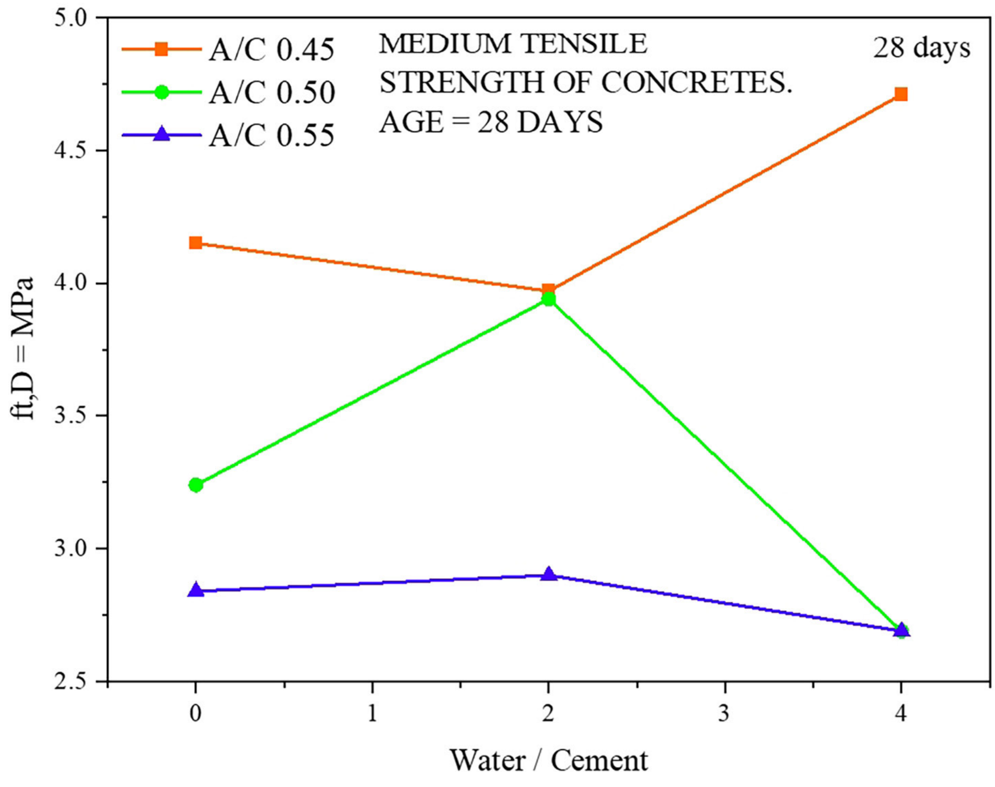

Figure 12: Diametrical compression traction results at 28 days.

among these variables—on the mechanical strength of the concretes, as determined by axial compression. The significance of each variable's effect was determined using analysis of variance (ANOVA) [57]. This technique compares groups of observations by evaluating the variability of means across groups against the variability within each group [58]. The impact of a specific factor on a response variable under analysis is determined by comparing the calculated F-values (from the data) with the tabulated F-values (from the Fisher probability distribution function) for a given significance level. A factor significantly influences the results if the calculated F exceeds the tabulated F. The analyses adopted a significance level of 5%, a common threshold in civil engineering. The comprehensive study and analysis in the sections on tensile strength by diametrical compression and the axial compression tests offer a detailed examination of how nanoceramics affect concrete properties at various ages and A/C ratios. The statistical analyses reinforce the complexity of interactions between nanoceramic content, water/cement ratio, and age on concrete's mechanical strengths [59].

– The A/C ratio and the age of the concrete significantly impact both the axial compressive strength and the tensile strength by diametrical compression, confirming the variability observed in the experimental results.
– The addition of nanoceramics shows varied influence: it significantly affects the compressive and tensile strengths when considering interactions with A/C ratio and age, but not as an isolated factor. This suggests that the beneficial effects of nanoceramics on concrete strength are context-dependent and optimized when other factors are carefully controlled [60].

For concretes with A/C ratios of 0.45 and 0.50, ideal nanoceramic addition levels were identified as 4% and 2%, respectively, for enhancing tensile strength, which aligns with findings from axial compressive strength tests [61]. The data suggest that incorporating nanoceramics into concrete mixes can improve mechanical properties, especially when combined with the right A/C ratio and considering the concrete's aging process. However, the complexity of the interactions highlighted by the statistical analysis underscores the importance of a nuanced approach to mix design, particularly when introducing novel materials like nanoceramics. The necessity of using plasticizing or super plasticizing additives with higher nanoceramic contents also points to the balance required between achieving desired mechanical properties and maintaining workable concrete mixes. The curve models for axial and diametrical compression traction further illustrate the relationship between concrete strength, A/C ratio, and nanoceramic addition, providing a useful tool for predicting concrete performance [62]. The findings contribute valuable insights into the design of concrete mixes with enhanced mechanical properties by adding nanoceramics, emphasizing the need for comprehensive testing and analysis to understand the multifaceted impacts of such additions [63]. Concretes with an A/C ratio of 0.50 showed an ideal nanoceramic addition content of 2% for 28 days, changing from 34.50 MPa to 38.30 MPa.

Concretes with an A/C ratio of 0.45 showed a slight loss of strength with the addition of 2% of nano ceramics, while those with 4% of addition had an increase in strength that went from 43.55 MPa (with 0% of addition) to 48.35 MPa, representing an 11.02% gain in the value of the final strength. However, a 4% addition caused the concrete to have excessive fines. It compromised its workability due to the great cohesion of the particles [64]. Therefore, the results show that the additions of nanoceramics in the 2% and 4% percentages are adequate, requiring plasticizing or super plasticizing additives and an adjustment in the mix depending on the A/C ratio analyzed [65]. For the age of 3 days, the nanoceramics had not yet developed pozzolanic activity, and the results of the reference concrete were higher. At 7 and 28 days, the concretes with the addition of nanoceramics already showed better performance due to the filler effect and pozzolanic activity, especially for concretes with a lower A/C ratio [66]. The compressive strength results for mortar samples at 7 days of curing are presented here. The graph depicts the trend observed at 3 days, offering insight into the progression of strength development influenced by nanoceramic additives.

This study found that the addition of nanoceramics improved the compressive and tensile strengths of mortars and concretes, with optimal percentages varying based on the water-cement ratio. Researchers reported an increase in apparent porosity and water absorption, with specific mass changes due to calcium oxide addition. Studies observed that mixtures with waste incorporation were within technical parameters, despite mechanical tests being below standard formulation. Recent studies indicated potential application of sludge in ceramics due to the presence of elements with melting characteristics. Some outcomes showed that masonry with polymeric compound achieved comparable compressive strength to cementitious mortar.

This study noted that higher nanoceramic percentages led to workability issues, requiring plasticizers or superplasticizers, similar to the challenges faced by researchers with waste materials. This study also highlighted the role of nanoceramics in reducing porosity and enhancing strength, akin to findings by studies. Overall, the addition of nanoceramics and other materials to cement and ceramic composites can significantly enhance mechanical properties. However, the optimal content of these additives needs to be carefully determined to balance enhancements in strength with workability and durability concerns. Future research should focus on the long-term durability of these composites under various environmental conditions and the potential for scaling up these findings to industrial applications. The studies collectively demonstrate the potential of various additives to improve the properties of cement-based and ceramic materials, with each study contributing unique insights into the mechanisms and optimal conditions for such enhancements.

4. CONCLUSIONS

This study investigated the influence of nanoceramic addition on the performance of cement-based materials, including mortars and concreted with varying water-to-cement (w/c) ratios. The key findings and conclusions are as follows:

- The nanoceramics used in this study exhibited pozzolanic activity, as confirmed by the chemical method test. This pozzolanic behavior, combined with the filler effect of the nano ceramic particles, contributed to the improved performance of the cement-based materials.
- The addition of nanoceramics to mortars with a w/c ratio of 0.48 showed improvements in compressive strength at certain percentages. The optimal percentages were 2% and 4%, with strength gains of up to 35.54% at 7 days compared to the reference mortar.
- In concrete mixtures, the workability decreased with increasing nanoceramic addition due to the nanoparticles' high fineness and hygroscopic nature. The use of chemical admixtures helped mitigate this workability loss.
- The water permeability of the concrete specimens was relatively low, with the w/c ratio of 0.50 exhibiting the lowest average water flow rate.
- The compressive and tensile strengths of the concretes were enhanced by adding nanoceramics. The optimal nanoceramic addition percentages varied based on the w/c ratio, with 4% ideal for a w/c ratio of 0.45 and 2% optimal for w/c ratios of 0.50 and 0.55.
- Statistical analysis revealed that while the nanoceramic addition content did not significantly influence the mechanical strengths individually, the interactions between nanoceramic addition, w/c ratio, and concrete age significantly affected the compressive and tensile strength results.
- The failure modes and crack patterns observed in the specimens were typical of compressive and tensile loading, indicating that adding nanoceramics did not significantly alter the failure mechanisms.

This study demonstrated the potential of nanoceramics as a mineral admixture for enhancing the performance of cement-based materials. The optimal nanoceramic addition percentages were determined for different w/c ratios, considering strength gains and workability concerns. Further research is recommended to investigate the durability aspects, microstructural analysis, and superplasticizers' influence on nanoceramic-modified concretes' workability.

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