Journal of Al-Azhar University Engineering Sector

Vol.20, No. 76, July 2025, 765-778

ENHANCING CONCRETE PROPERTIES THROUGH USING NANO-CLAY AND NANO-SILICA IN CONCRETE MIX

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Citation:

A. Fawzi, M. Lasheen, A. F. Elkashif, M. Gamil, "Enhancing Concrete Properties Through Using Nano-Clay and Nano-Silica in Concrete Mix", Journal of Al-Azhar University Engineering Sector, vol 20, pp. 765-778, 2025.

Received: 12 October 2024

Revised: 04 May 2025

Accepted: 31 May 2025

Doi: 10.21608/auej.2025.327867.1720

ABSTRACT

Substituting cement with modern materials in the field of construction became essential in the last few years to avoid the adverse effect of carbon diaoxide emissions on the environment. The current study focuses on nano-materials as a sustainable alternative for green building practices drawing from a wide range of previous research where optimal proportions of 6% nano-clay and 3% nano-silica were selected to enhance the mechanical properties of concrete. The study mainly examines different concrete mixes behaviors using these percentages and extends its objective to identify ordinary concrete mixes that exhibit mechanical properties equivalent to those containing nano-silica and nano-clay. Though nano-materials are currently costly due to their new production technology, large-scale production will decrease cost, leading to the emergence of specialized companies in these fields. Subsequent tests, including flexural strength, modulus of elasticity, and scanning electron microscopy (SEM), were conducted to compare the mechanical properties of mixes incorporating nano-materials with conventional mixes. The study confirmed that incorporating nanomaterials in concrete mixtures, particularly nano-clay particles, enhances structural properties and promotes denser C-S-H gel formation. This sustainable approach not only improves concrete performance but also addresses environmental concerns by reducing pollution and advancing green building practices.

KEYWORDS: Compressive Strength, Flexural Strength, Mechanical Properties, Nano-Clay, and Nano-Silica.

تحسين خواص الخرسانة باستخدام النانو كلاى والنانو سيلكا بالخلطات الخرسانية

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الملخص

استبدال الأسمنت بمواد حديثة في مجال البناء أصبح ضروريًا في السنوات الأخيرة لتجنب التأثير السلبي لانبعاثات ثاني أكسيد الكربون على البيئة. تركز الدراسة الحالية على المواد النانوية كبديل مستدام لممارسات البناء الأخضر مستفيدة من مجموعة واسعة من الأبحاث السابقة حيث تم اختيار النسب الأمثل للنانو كلاي بنسبة ٦٪ ونانو السيليكا بنسبة ٣٪ لتعزيز الخصائص الميكانيكية للخرسانة. تفحص الدراسة بشكل رئيسي سلوك الخلطات الخرسانية المختلفة

باستخدام هذه النسب وتوسع أهدافها لتحديد الخلطات العادية للخرسانة التي تظهر خصائص ميكانيكية مكافئة لتلك التي تحتوي على النانو سيليكا والنانو كلاي. وعلي الرغم من أن المواد النانوية مكلفة حاليًا بسبب تكنولوجيا إنتاجها الجديدة، فإن الإنتاجية على نطاق واسع ستقلل من التكلفة، مما يؤدي إلى ظهور شركات متخصصة في هذه المجالات. تم إجراء اختبارات لاحقة، بما في ذلك اختبار الانحناء، ومعامل المرونة، والمجهر الإلكتروني الماسح (SEM)، لمقارنة الخصائص الميكانيكية للخلطات التي تحتوي على المواد النانوية مع الخلطات التقليدية. أكدت الدراسة أن إضافة المواد النانوية في الخلطات الخرسانية، خاصة جزيئات النانو-كلاي، تعزز الخصائص الهيكلية وتعزز تشكيل جل C-S-H الأكثف. هذا النهج المستدام لا يحسن فقط أداء الخرسانة ولكنه يعالج مخاوف بيئية من خلال تقليل التلوث وتعزيز ممارسات البناء الخضراء.

الكلمات المفتاحية : مقاومة الضغط، مقاومة الانحناء، الخواص الميكانيكية، نانو كلاى، نانو سليكا.

1. INTRODUCTION

It is widely acknowledged that the cement industry significantly pollutes the environment and contributes substantially to climate change and global warming. Consequently, exploring alternatives to cement has become imperative to minimize reliance on this industry. As a result, numerous studies have been undertaken to investigate the substitution of a portion of cement in concrete, aiming to produce concrete with equivalent properties, reduce environmental pollution, mitigate global warming, and advance towards sustainable construction practices. Nano-materials have emerged as one of these alternatives, with researchers examining their effects when added to or replacing cement in concrete blends.

In an effort to enhance concrete properties through the incorporation of nano-clay and nano-silica in concrete mixtures, a series of studies have been conducted. These studies covered critical success factors in regional development programs, the management of experiments in engineering and science, systematic reviews on structural materials health monitoring systems for girder-type bridges, and predictions of residual strength under elevated temperatures.

The impact of hybrid additions of nano-clay and carbon nanotubes on the mechanical attributes of concrete has been studied [1]. Through partial substitution of cement with nano-clay at percentages of 2.5, 5, and 7.5 wt.%, the optimal ratio was determined to be 5%, resulting in a 28.4% increase in compressive strength compared to the control mix (without nano-clay). Additionally, the hybrid mix of 5 wt.% nano-clay and 0.01 wt.% carbon nanotubes exhibited enhanced mechanical properties, boasting a 12.77% gain over the single addition of 5% nano-clay (without carbon nanotubes).

Cement has been replaced with a fixed quantity of nano-clay (6 wt.%), while introducing carbon nanotubes at varying ratios of 0.005, 0.02, 0.05, and 0.1 wt.% of cement [2]. The hydrophobic nature, insolubility, and high specific surface area of carbon nanotubes posed challenges in terms of dispersion and adhesion to the cement matrix. Consequently, the addition of nano-clay and carbon nanotubes led to reduced workability [1, 2]. However, results indicated that substituting cement with 6 wt.% nano-clay increased the compressive strength of blended mortar by 18% compared to the control mix, with the combination of 6 wt.% nano-clay and 0.02 wt.% carbon nanotubes boosting compressive strength by 29% over the control mix.

The incorporation of nano-clay particles with newly developed superplasticizers enhanced the workability and strength of high-performance concrete, as nano-clay interpenetrates the polymer network, yielding the mentioned improvements. These enhancements were recorded at 3, 7, and 28 days, with improvement percentages of 36%, 39%, and 7.6%, respectively [3].

Numerous prior studies have advocated for the addition of nano-clay to concrete due to its availability, cost-effectiveness, and environmentally friendly characteristics [2, 4, 5].

The impact of high temperatures on the mechanical performance of concrete samples, partially substituting cement with varying ratios of nano-clay (5, 10, and 15 wt.%) has been explored [6]. Thermal properties were evaluated at room temperature, 100, 200, 400, 600, and 800°C following two hours of exposure to elevated temperatures. The compressive strength of concrete was found to increase up to 10% nano-clay substitution, while a 15% substitution resulted in nano-clay particle agglomeration around cement grains, leading to a retardation in cement hydration. Elevated temperatures reduced the compressive strength of both standard and nano-clay concrete; however, nano-clay concrete consistently exhibited higher compressive strength compared to standard concrete across different temperature ranges.

The addition of nano-clay in concrete mixtures enhances compressive strength at both early and advanced stages compared to the control mix [7]. This increase in compressive strength may be attributed to the efficiency of nanoparticles in activating pozzolanic reactions, which consume calcium hydroxide and form additional calcium silicate hydrate (C-S-H) gel.

SEM observations confirmed that nano-kaolin served not only as a filler but also as an activator, promoting the hydration process to create a denser structure. This resulted in a decrease in the calcium hydroxide (CH) ratio and an increase in the calcium silicate hydrate (C-S-H), which contributed to enhanced strength [7].

The influence of nano-silica additives on the physical and mechanical properties of self-compacting concrete has been explore [8]. The addition of nano-silica at percentages of 1, 2, and 3 wt.% increased compressive strength by 15%, 25%, and 30% at 7 days, and by 9%, 14%, and 31% at 28 days, respectively, compared to the control mix. Moreover, the 56-day compressive strength saw increases of 0%, 31.4%, and 36.7%, respectively. These enhancements were attributed to the filler effect of nano-silica, which improved the interfacial transition zone within the cement paste. Exceeding 3% nano-silica did not further enhance compressive strength.

The structural behavior of self-compacting concrete (SCC) beams by incorporating nano-silica has been investigated [9]. Among ten SCC mixes designed with nano-silica at 1, 2, and 3 wt.%, the optimal additive percentage was determined to be 3% of the cement weight. This percentage yielded the highest compressive, tensile, and flexural strengths while reducing water permeability by 58%, thereby enhancing durability and preventing chloride permeability.

The influence of adding silicon dioxide (SiO_2) nanoparticles to cement pastes using both water and vacuum curing methods has been studied [10]. Specimens containing varying amounts of nano-silica (0, 5, and 10%) were tested at different ages (3, 7, 14, 28, and 56 days). The compressive strength of cement paste increased with higher nano-silica content, up to 5%. However, further increases in nano-silica percentage did not lead to additional improvements in compressive strength. Results showed that the compressive strengths of hardened cement paste with 5% nano-silica particles surpassed those of the control paste for both water- and vacuum-cured specimens. Vacuum-cured specimens exhibited higher strength than water-cured specimens up to 28 days, although final strength for water-cured specimens surpassed that for vacuum-cured specimens.

The strength increase resulting from nanoparticle additions can be attributed to the small size of nanomaterials, which possess a larger surface area, enabling stronger bonding with the cement paste and consequently leading to a more robust concrete matrix [11].

The mechanical performance of high-performance concrete reinforced with three types of nano additives; nano-clay, nano-silica, and hybrid particles has been investigated [12].

The nanomaterials used underwent characterization through XRD and HRTEM to assess their essential properties. The crystal structure and phase composition of the nano and micro additives were identified via X-ray diffraction using a Philips X-ray diffractometer (PW3050/60) with CuKα(λ=0.15406 nm) radiation, while the morphology was examined using High-Resolution Transmission Electron Microscope measurements (HRTEM) on a Philips instrument (FEI Tecani G2 S-Twin) with an accelerating voltage of 200 kV.

The XRD pattern of the nano-silica displayed a distinct broad hump centered at $2\theta \approx 22.45°$, indicative of amorphous nano-silica. No diffraction peaks corresponding to impurities were detected. HRTEM imaging revealed the nano-silica's spherical geometry without any foreign material presence. Additionally, the XRD diffraction pattern of the exfoliated NC sample confirmed well-crystallized rectangular shapes with discernible diffraction peaks at various positions (2θ). The NC used in the study was montmorillonite treated with ammonium chloride at elevated temperatures. HRTEM analysis of the NC showcased a platelet structure with a well-peeled rectangular shape and minimal clumping.

The results demonstrated that all three types of additives enhanced the mechanical properties of the hardened concrete mixes, particularly those with a cement content of 350 kg/m³. Specifically, the addition of 6% NC improved the compressive strength of concrete with 350 kg/m³ by 17.06%, splitting tensile strength by 7.32%, and flexural strength by 13.21%. Likewise, the incorporation of 3% NS boosted the compressive, splitting tensile, and flexural strengths of the same concrete by 9.57%, 12.1%, and 32.87%, respectively. Furthermore, the inclusion of (7.5% SF + 2.5% LS) resulted in a 10% increase in compressive strength, 2.64% in splitting tensile strength, and 51.14% in flexural strength of the concrete.

The incorporation of nano-materials has been shown to enhance concrete strength and durability while reducing total porosity due to their fine particles and expansive surface area. Although conventional concrete includes calcium silicate hydrate (CSH) gel formation as part of the standard mix, nanoscale studies of concrete highlight that nano-materials can improve particle packing, leading to denser micro and nanostructures and ultimately improved mechanical properties. The addition of nano-materials to cement-based materials serves to increase strength by generating additional CSH gel and enhancing the interfacial interaction between the matrix and surrounding elements, subsequently enhancing the concrete mix's Young's modulus.

Additional research explored the effects of cooling methods on the residual properties of sustainable fiber-reinforced SCC, the behavior of sustainable self-consolidating concrete under elevated temperatures, and the physical and mechanical characteristics of sustainable SCC incorporating high-volume fly ash and cement kiln dust. It also examined the punching shear behavior of LWA bubble deck slabs, analytical studies on concrete beams reinforced with FRP bars, and the role of project management offices in the construction sector. Collectively, these studies contribute to advancing methodologies in concrete research and development [13–28].

Furthermore, the main aim of this study is to enhance the mechanical propeties of concrete mixtures using two types of nanoparticles (Nano-clay and Nano-silica). Follwing the previous studies, the optimal enhancements in compressive strength have been observed within the range of 6 % for nano-clay and 3 % for nano-silica, hence these ratios was used in the present study. The mechanical properties of the casted conerete samples was evaluated using slump test, compresive strength, flexural strength, and Young’s mouduls. The microsturcture was examined using scanning electron microscope. Thus, the main objective is to identify ordinary concrete mixes that exhibit mechanical properties equivalent to those containing nano-silica and nano-clay.

2. EXPERIMENTAL PROCEDURE

The current experimental program comprises five primary concrete mixes. The initial three mixes constituted standard blends with cement quantities of 350, 400, and 450 kg/m³, while the other two mixes were formulated with a cement content of 350 kg/m³, supplemented with 6% and 3% of the cement content using nano-clay and nano-silica, respectively. These nanomaterial proportions were selected based on the aforementioned literature, which delineated optimal ratios for enhancing concrete properties. To maintain consistency in slump values, workability, and prevent segregation, varying percentages of a superplasticizer (Sikament 163) were incorporated. The design mix for the five blends is presented in **Table 1**.

Table 1: Design Mix of all Prepared Samples

	Cement (kg)	Coarse agg. (kg)	Fine agg. (kg)	Water (litre)	Super plastizer (litre)	Nanomaterial (kg)	w/B
C350	350	1092	728.00	195.00	5.25	0.00	0.557
C400	400	1086	724.00	187.50	6.00	0.00	0.468
C450	450	1054	703.00	198.75	6.75	0.00	0.441
NC 6%	350	1058	706.00	206.75	5.63	21.00	0.557
NS 3%	350	1075	717.21	200.80	7.13	10.5	0.557

The experimental program utilized Ordinary Portland cement CEM I (42.5 N), natural siliceous sand, and crushed stone with a nominal maximum size of 10 mm, alongside tap drinking water across all mixes. The nano-clay (NC) employed in this study originated from kaolinite clay sourced from the Middle East Mining Investment Company (MEMCO), boasting an average particle size ranging from 0.07 to 2.55 µm. Typically, the kaolinite clay undergoes chemical treatment and thermal activation. Initially, organic ammonium chloride powder (NH_4Cl) is added to the clay at a ratio of 7 mg NH_4Cl to 1 gm of clay. Subsequently, water is introduced to form a slurry, which is left to stand for 2 hours, enabling NH4Cl particles to permeate between clay platelets. The slurry then undergoes thermal activation, experiencing rapid heating at 750°C for 2 hours to yield activated amorphous nano-metakaolin (NMK) [12].

On the other hand, the amorphous nano-silica (NS) is typically synthesized via the precipitation route [12], featuring an average particle size of approximately 5 to 11 nm and a specific surface area of around 230 m²/g. The nano-silica (NS) and nano-clay (NC) used in this study were prepared by the Building Physics Institute at the Housing and Building National Research Center. Table 2 shows the characteristics of nano-clay and nano-silica used in this study [6, 29]

The experimental program was delineated into two principal stages. The initial stage focused on ensuring an appropriate slump and exploring the compressive strength of the five mixes. Meanwhile, the subsequent stage was limited to three mixes: two incorporating nanomaterials (NC6% and NS3%), alongside the third mix designated as C400, which exhibited a favorable correlated compressive strength with both nanomaterial-containing mixes. The concrete mixes in the second stage were chosen to investigate the flexural strength and modulus of elasticity.

For specimen preparation, moulds were prepared for 100 cubes measuring 150×150×150mm, 24 cylinders measuring 150×300mm, and 15 prisms measuring 100×100×500mm, all of which were lubricated. The cubes and cylinders were employed to ascertain compressive strength, while the prisms were utilized to assess flexural strength, with cylinders additionally used to determine the concrete's modulus of elasticity.

A small electric mixer was utilized to thoroughly blend the nanomaterials in half of the required water volume for 15 minutes. The concrete mixer was initially pre-wetted before the addition of fine aggregate, washed coarse aggregate, and cement. The mixture was blended for one minute before the introduction of water, following which half of the required water volume along with the superplasticizer was added and mixed for another minute. Subsequently, the nanomaterial (previously blended in water) was incorporated and mixed for 3 minutes before casting the concrete into pre-lubricated moulds, as depicted in **Fig. 1**. After 24 hours, the specimens were demoulded and cured in water for 28 and 90 days. The cubes were then air-dried at room temperature for 24 hours.

Table 2: Characteristics of Nano-Clay and Nano-Silica

Property	Nano-Clay	Nano-Silica
Chemical Formula	$(Ca,Na,H)(Al,Mg,Fe,Zn)_2\ (Si,Al)4O_{10}(OH)_2XH_2O$	SiO_2
Crystal structure	Crystalline	Amorphous
Morphology	Platllet	Semi spherical
Crystalline size	Diameter 50 nm Thickness 8 nm	6-15 nm

Fig. 1: Specimens after Casting in Moulds

3. TEST RESULTS

3.1. Slump Test

A slump test was conducted to assess the consistency and workability of the fresh concrete mixture, adhering to the guidelines outlined in the Standard Specification for Ready-Mixed Concrete ASTM C94 [30], illustrated in **Fig. 2**. The incorporation of nano-clay and nano-silica led to a reduction in workability due to their heightened water absorption capabilities stemming from their increased specific surface area. Consequently, the employment of superplasticizers became imperative to enhance both workability and strength.

Fig. 2: The Performed Slump Test

Table 3 shows the slump values of the concrete mixtures. All values of the slump test were approximately close ranging from 130 to 150 mm which indicates the good design of all conducted mixes.

Table 3: Slump Test Values of Concrete Mixtures

Mixture ID	Slump Value (mm)
C350	130
C400	140
C450	130
NC 6%	150
NS 3%	130

3.2. Compressive Strength

The compressive strength of the concrete was determined for the 100 cubes after 28 days (60 cubes) and 90 days (40 cubes), and for 15 cylinders after 28 days according to the Standard for Testing hardened concrete EN12390-3;2019 [31]. Average compressive strength values for each mixture are presented in **Table 4** and **Fig. 3**.

Table 4: Average Compressive Strength at 28 and 90 Days

Mix ID	Cylinder Compressive Strength (N/mm²)	Cube Compressive Strength (N/mm²)	
	28 days	28 days	90 days
C350	28	36	41
C400	33	42	47
C450	36	43	54
NC6%	32	43	45
NS3%	29	36	45

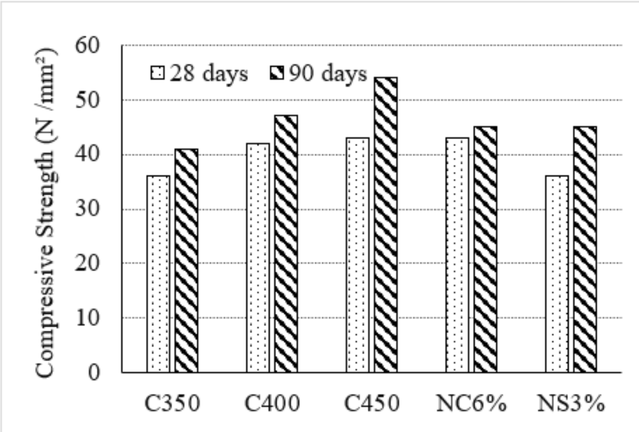


Fig. 3: Compressive Strength Values for Concrete Mixtures at 28 and 90 Days

The analysis reveals that the introduction of 6% nano-clay resulted in a 19.44% increase in compressive strength at 28 days and a 9.76% increase at 90 days compared to the C350 concrete mix. Conversely, for the concrete mix incorporating nano-silica, no noticeable enhancement was observed at 28 days; however, at later stages, specifically at 90 days, a 9.76% strength increase was recorded.

When compared to the C450 mix, blends containing nano-clay and nano-silica exhibited a 16.67% decrease in strength at 90 days. Notably, the concrete mix C400 demonstrated favorable correlated results in terms of compressive strength with both NC6% and NS3% after 90 days, despite the 28-day results for NS3% being 14.3% lower.

Consequently, it is apparent that a reduction of 50 kg/m³ of cement can be achieved by incorporating 6% nano-clay or 3% nano-silica while maintaining the same compressive strength, aligning well with sustainable building practices.

In light of these findings, further investigations were conducted to explore the flexural strength and modulus of elasticity for the C400, NC6%, and NS3% mixes, as detailed in the subsequent sections.

3.3. Flexural Behavior

The flexural strength examination was conducted in adherence to the Egyptian Specifications [32] for the three concrete mixes (C400, NC6%, and NS3%). Each mix was evaluated using five plain concrete prisms subjected to a 3-point bending test, depicted in **Fig. 4**. A strain gauge was affixed at the middle lower segment of each prism to capture strain data, enabling the plotting of the relationship between the recorded strain and calculated flexural stress, illustrated in **Fig. 5**. **Table 5** shows the average flexural strength of the prisms for each concrete mix.

Table 5: Modulus of Rupture (Flexural Strength)

Mixture ID	f_b flexural strength (N/mm²)
C400	5.31
NC 6%	5.16
NS 3%	5.42

The flexural strength (f_b) is the ratio of the calculated maximum bending moment to the section modulus of the prism specimen:

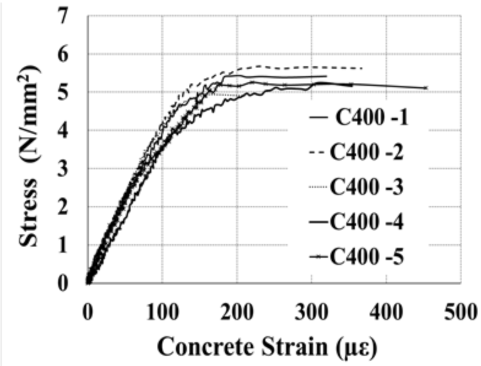
$$f_b = \frac{M_{max}}{Z} \quad (1)$$

Where:

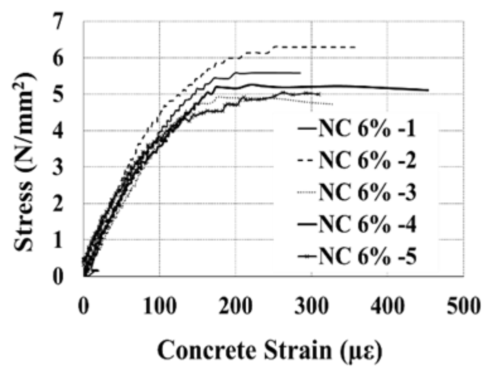
f_b Flexural strength or modulus of rupture
M_{max} Maximum bending moment at the middle of the prism
Z Section modulus

Fig. 4: Test Setup for Flexural Strength

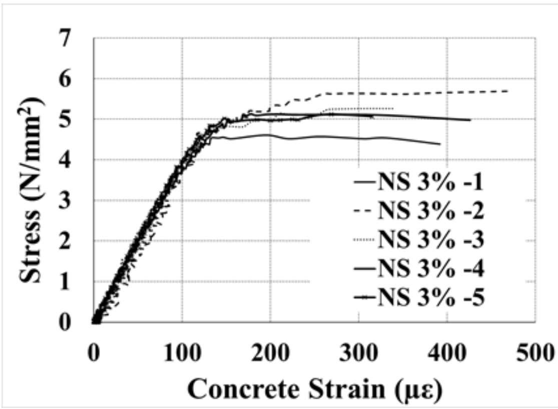
According to **Table 4**, the flexural strength for NS3% was higher than C400 and NC 6% by 2.07% and 5.04%, respectively.



a) Stress-Strain Curves for Specimens of C400



b) Stress-Strain Curves for Specimens of NC6%



c) Stress-Strain Curves for Specimens of NS3%

Fig. 5: Stress Strain Curves for Concrete Mixtures; a) C400, b) NC 6%, and c) NS 3%

The stress-strain curves for all specimens showed a non-linear behavior like reinforced concrete sections.

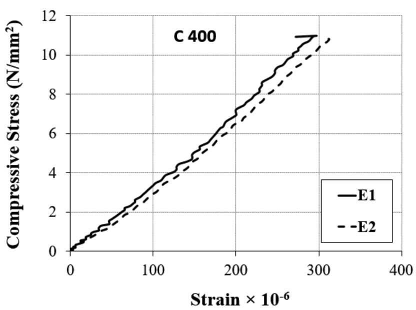
3.4. Young's Modulus

The modulus of elasticity for the concrete mixes (C400, NC6%, and NS3%) was analyzed in accordance with the Egyptian Specifications [31]. This investigation involved attaching a Linear

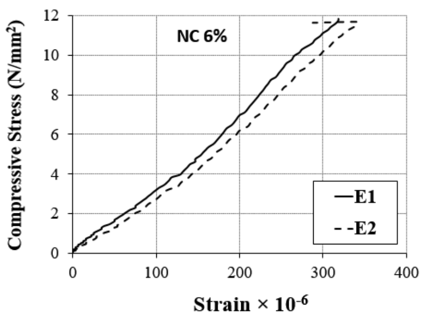
Variable Distance Transducer (LVDT) to the concrete cylinders, as depicted in **Fig. 6**. Three specimens from each mix were utilized for this purpose.

Subsequently, compressive stress-strain curves were generated (as shown in **Fig. 7**), and Young's modulus was computed for each concrete mix, with the results summarized in **Table 6**. Furthermore, the theoretical modulus of elasticity was determined using the Euro Code (EN1992-1-1:1992) [33].

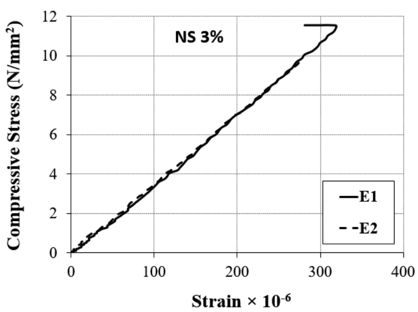
Fig. 6: Test Setup for Investigating Young's Modulus



a) Compressive Stress-Strain Distribution for Concrete Cylinders (C400)



b) Compressive Stress-Strain Distribution for Concrete Cylinders (NC6%)



c) Compressive Stress-Strain Distribution for Concrete Cylinders (NS3%)

Fig. 7: Compressive Stress-Strain Distribution for Concrete Cylinders; a) C400, b) NC 6%, and c) NS 3%

Table 6 displays the Young's modulus values obtained through laboratory measurements and those calculated in accordance with the Euro code. Interestingly, a notable agreement is observed between the experimental and theoretical values of Young's modulus for the C400 concrete mix, indicating a reliable correspondence between the two sets of data.

Table 6: Young's Modulus for Cylinders

Mixture ID	Experimental (N/mm²)	Theoretical (N/mm²) EN [16]
C400	35092	32754
NC 6%	35437	--
NS 3%	34881	--

4. Scanning Electron Microscope (SEM)

Fig. 8 presents the scanning electron microscope (SEM) micrographs of three concrete mixes - C400, NC 6%, and NS 3% - following 90 days of hydration. These images elucidate the alterations in the microstructure of nano mixes when compared to C400, stemming from the incorporation of nano-clays and nano-silica.

The SEM images suggest a change in the mechanical performance of the mixes in contrast to the control mix. The microstructure of the C400 samples revealed the presence of micro-cracks, micropores, and a noticeable separation between the aggregate and the paste, resulting in a non-homogeneous structure, as illustrated in **Fig. 8 a)**.

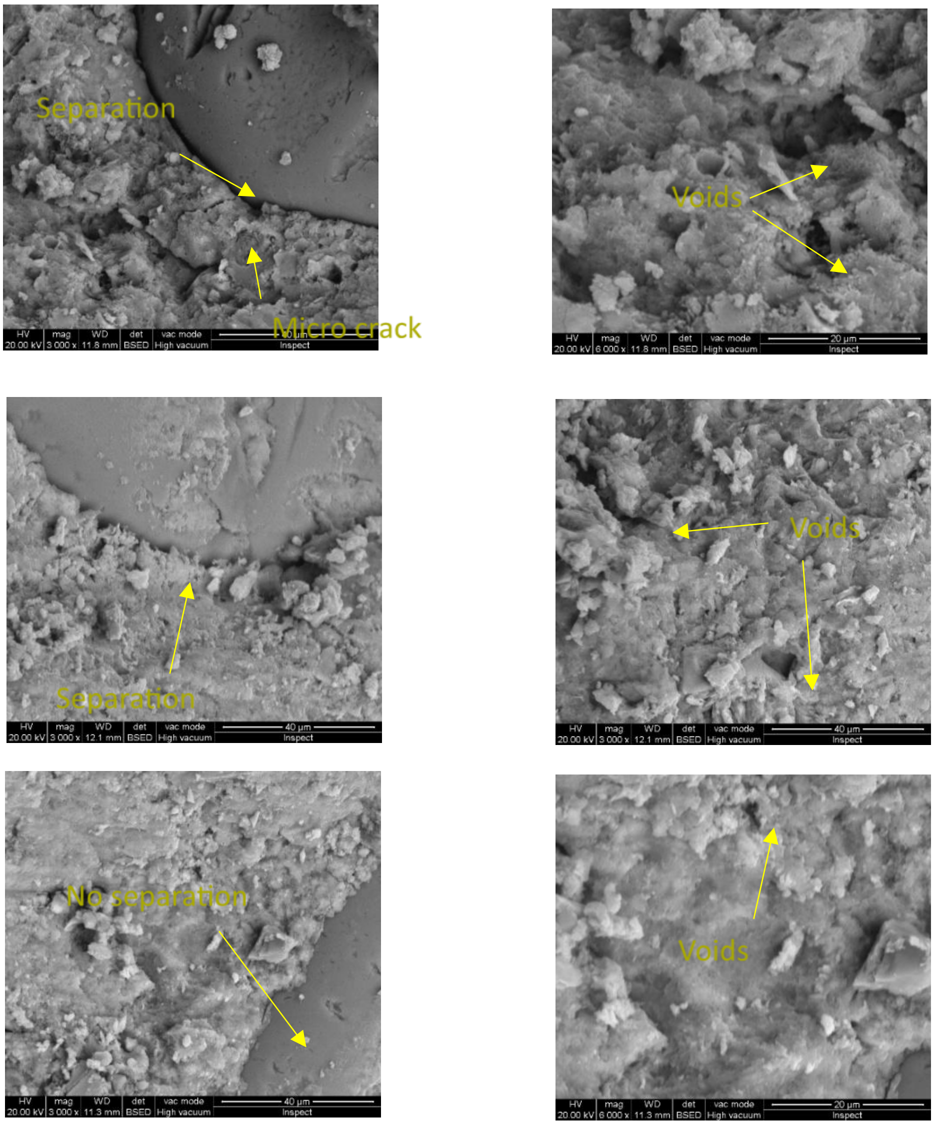


Fig. 8: SEM Micrograph of Concrete Mixtures; a) C400, b) NC 6%, and c) NS 3%

Conversely, with the inclusion of 6% nano-clay (NC), the gel-like C-S-H phase became predominant, exhibiting lower void content and a significant reduction in micro-cracks. This improvement in the microstructure can be attributed to the even distribution of nano-clay in the matrix and its high pozzolanic reactivity. Additionally, the efficacy of nano-clay in functioning as a sub-cytoplasm, forming a conglomerate of C-S-H gel, and providing effective filling led to a more uniform, compact, and denser matrix compared to the C400 samples, as depicted in **Fig. 8 b)**.

Similarly, the addition of 3% nano-silica (NS) facilitated the dispersion of C-S-H gel within the matrix, resulting in the absence of cracks and less voids. This enhancement can be credited to the high pozzolanic reactivity of nano-silica. Moreover, the effectiveness of nano-silica in acting as a sub-cytoplasm, forming conglomerates of C-S-H gel (acting as nucleating agents for C-S-H gel), along with the uniform distribution of nano-silica in the matrix, culminated in a denser and more compact microstructure compared to C400 samples, as demonstrated in **Fig. 8 c)**. These findings align with the concrete compressive strength outcomes after 90 days of curing.

5. Primary Economic Evaluation of using Nano Materials in Concrete

The relatively high cost of nano-materials is a critical consideration for their practical use in concrete production. Nano-silica, depending on its purity and form, typically costs between 3–5 USD per kilogram [34], while nano-clay is more economical, with prices generally below 1 USD per kilogram [35]. Despite their cost, both materials have demonstrated significant potential for enhancing concrete performance, particularly in terms of strength and durability improvements [34-37].

In the present study, nano-clay (NC) and nano-silica (NS) were locally produced with production costs of approximately 0.084 USD per kilogram and 0.663 USD per kilogram, respectively. The lower production cost of nano-clay compared to nano-silica is attributed to the natural abundance and direct extraction of NC from mountain deposits.

Based on the aforementioned local prices, a successful reduction of cement content by 50 kg/m³ was achieved, resulting in an average cost of 4 USD/m³ on the local market for both 6% nano-clay (NC) and 3% nano-silica (NS) incorporation. Additionally, the supplementary cost of integrating 6% nano-clay (equivalent to 21 kg/m³) was estimated at approximately 1.76 USD/m³, while the cost of adding 3% nano-silica (equivalent to 10.5 kg/m³) was around 6.96 USD/m³.

The cost of materials in the local market was determied by local vendors and the cost of treatment for nano materials was detrmided by the Building Physics Institute at the Housing and Building National Research Center. **Fig. 9** shows the cost difference percentages for C400, 6% nano-clay, and 3% nano-silica based on cement cost.

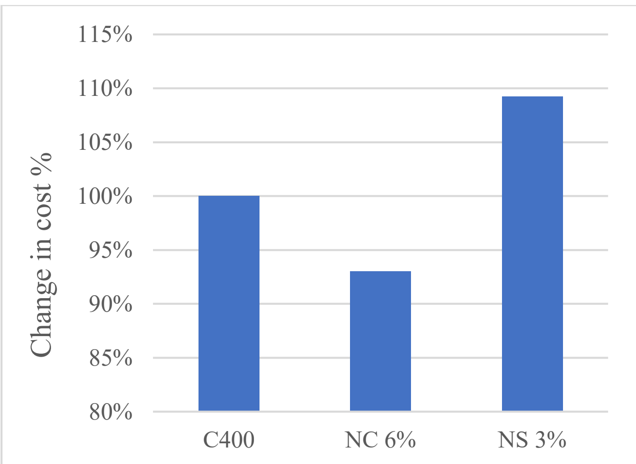


Fig. 9: Change in Cost (%) of the Utilized Materials

The findings underscore that utilizing nano-clay as a partial cement replacement presents a more feasible strategy to achieve the desired concrete properties. It is important to highlight that this cost reduction is anticipated to further escalate with the adoption of mass production practices within the industry. It is recommended to apply these results by using these nano materials with other solid waste materials that may reduce the total cost of the concrete [38] or by using natural pozzolans as a partial replacement for cement [39,40].

SUMMARY AND CONCLUSIONS

There is a crucial need to prioritize the adoption of contemporary materials as substitutes for cement in the construction industry to mitigate the detrimental impact of carbon dioxide emissions on the environment.

This paper introduces a novel study where a conventional concrete mix is engineered to match the compressive strength of nano-clay and nano-silica concrete using a relatively lower cement content. Through a comprehensive review of prior research, optimal ratios of 6% nano-clay and 3% nano-silica were determined to bolster the mechanical characteristics of concrete. The research affirms that the integration of nanomaterials into concrete blends, notably nano-clay particles, enriches structural attributes and fosters the formation of a denser C-S-H gel. This sustainable methodology not only elevates concrete performance but also tackles environmental issues by curbing pollution and advocating for eco-friendly construction practices.

Subsequent tests aimed at determining the mechanical properties, investigations were conducted to analyze the flexural behavior and Young's modulus, resulting in the following conclusions.

1) Slump tests conducted on various concrete mixtures indicated the attainment of the desired plastic consistency.
2) Concrete mix designated as C400 exhibited satisfactory consistency in terms of compressive strength for both NC6% and NS3% after a 90-day period.
3) Flexural strength across different concrete mixtures demonstrated similar behavior.
4) The compressive stress-strain curves for C400, NC6%, and NS3% displayed nearly identical stress-strain relationships.
5) Scanning electron microscope images provided valuable insights, revealing that the addition of nanomaterials enhanced the filling effect, resulting in denser and finer C-S-H gel formation and reduced separation between the aggregate and matrix. The mix containing 3% NS exhibited a denser and finer C-S-H gel structure compared to the 6% NC sample after 90 days of curing.
6) The incorporation of nano-clay particles in concrete proved effective in achieving properties akin to a mix with higher cement content. This approach has a positive impact on environmental sustainability by reducing pollution, combating global warming, and contributing to climate change control, thereby fostering the advancement of green building practices.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Concrete Structures Research Institute and its testing laboratory at the Housing and Building National Research Centre, Egypt.

Special thanks are extended to Prof. Dr. Hadad Said Hadad, Head of the Concrete Structures Research Institute, for his valuable technical, financial, and moral support throughout the completion of this research. The authors are also grateful to Prof. Dr. Sherif M. Elzeiny and Prof. Dr. Tamer H. K. El-Afandy for their continuous assistance, technical guidance, and encouragement.

Appreciation is also extended to Dr. Mohamed Morsy and Dr. Mahmoud Mokhtar for their support and contributions to this work.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

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