Study of an Environmentally Friendly High-Performance Concrete (HPC) Manufactured with the Incorporation of a Blend of Micro-Nano Silica

Estudio de un hormigón de alto rendimiento (HPC), respetuoso con el medio ambiente, fabricado con la incorporación de una mezcla de micronano sílice

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[1]Jhon Fabricio Tapia Vargas, [2,3,4]Mohammadfarid Alvansazyazdi,
[5]Alexis Andrés Barrionuevo Castañeda

[1]Maestría en Construcciones de Obras Civiles Mención Gestión y Dirección, Facultad de Ingeniería y Ciencias Aplicadas, Universidad Central del Ecuador, Av. Universitaria. ing.jftapiav@outlook.es.
ORCID: 0000-0002-6089-040X

[2]Institute of Science and Concrete Technology, ICITECH, Universitat Politècnica de València,Spain.
[3]Carrera de Ingeniería Civil, Universidad Central del Ecuador, Av. Universitaria, Quito 170521, Ecuador.
[4]Facultad Ingeniería, Industria y Construcción, Carrera Ingeniería Civil, Universidad Laica Eloy Alfaro de Manabi, Manta, Ecuador. faridalvan@uce.edu.ec. ORCID: 0000-0001-8797-5705

[5]Gobierno Autónomo Descentralizado Municipal del Cantón Pastaza. alexis_3214@hotmail.com.
ORCID: 0009-0000-7634-5513

Abstract:

This study focuses on the evaluation of the impact of the addition of different percentages of nanosilica (NS) (0.75 %, 1.5 % and 3 % - and microsilica (MS) – 5 %, 10 % and 15 %), as partial cement substitutes in the formulation of high performance concrete (HPC). Mechanical assessments, including compression, tension, flexural strength, dynamic modulus, Poisson's ratio, and elasticity measurements, were performed at intervals of 3, 7, 28, 56, and 91 days to understand the impact on HPC's structural characteristics. Additionally, scanning electron microscopy (SEM), transmission electron microscopy (TEM), and energy-dispersive X-Ray spectroscopy (EDS) were carried out to examine changes in microstructure. Results indicate that incorporating 15 % microsilica in the concrete mix yields a more pronounced improvement in mechanical properties compared to adding only 3 % nano-silica, surpassing even the combination of 15 % microsilica and 3 % nano-silica. This substitution approach enhances sustainability by reducing cement usage.

Keywords: *Cementitious Environmentally Friendly, HPC Materials, Microsilica, Nano-silica, Physical-mechanical properties, sustainability.*

Resumen:

Este estudio se centra en la evaluación del impacto de la adición de diferentes porcentajes de nanosílice (NS) (0.75 %, 1.5 % y 3 % - y microsílice (MS) – 5 %, 10 % y 15 %), como sustitutos parciales del cemento en la formulación de concreto de alto desempeño (HPC). Se realizaron evaluaciones mecánicas, incluidas mediciones de compresión, tensión, resistencia a la flexión, módulo dinámico, índice de Poisson y elasticidad, en intervalos de 3, 7, 28, 56 y 91 días, para comprender el impacto en las características estructurales del HPC. Además, se llevaron a cabo microscopía electrónica de barrido (SEM), microscopía electrónica de transmisión (TEM) y espectroscopia de rayos X de dispersión de energía (EDS), para examinar los cambios en la microestructura. Los resultados indican que la incorporación de un 15 % de microsílice en la mezcla de hormigón, produce una mejora más pronunciada en las propiedades mecánicas, en comparación con la adición de sólo un 3 % de nanosílice, superando incluso la combinación de un 15 % de microsílice y un 3 % de nanosílice. Este enfoque de sustitución mejora la sostenibilidad al reducir el uso de cemento.

Palabras claves: Cementos ecológicos, materiales HPC, microsílice, nano-sílice, propiedades físico-mecánicas, sostenibilidad.

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1. INTRODUCTION

The economic development and evolution of countries are closely engaged with the construction industry and the creation of new materials. Improving the durability of cement has been instrumental in prolonging the service life of concrete structures [1-5]. The introduction of nanotechnology into the construction sector, particularly through the use of nano-silica (NS), has been shown to significantly improve the mechanical properties and durability of cement-based products due to its high purity and specific surface area, which affect the hydration and microstructure of cement [6, 7].

Building upon this foundation, the integration of various nanomaterials beyond nano-silica, such as nano-alumina, carbon nanotubes, and others, continues to push the boundaries of concrete's capabilities [8, 9]. These materials contribute to a significant enhancement in the compressive, tensile, and flexural strengths of concrete by optimizing the particle packing and reducing the porosity of the cementitious matrix, leading to denser and more robust concrete structures [10-12]. This evolution in concrete technology not only supports structural integrity but also extends the lifespan of infrastructure, marking a pivotal shift towards more sustainable construction practices [13].

Moreover, the addition of nanomaterials has been found to improve the workability and reduce the water absorption of concrete, factors that are crucial for the practical application and longevity of concrete structures in various environmental conditions [14]. Enhanced workability facilitates easier mixing and application, while reduced water absorption minimizes the risk of damage from freeze-thaw cycles and chemical attack, thereby preserving the structural health and integrity over time [15, 16].

In this regard, it is necessary to design high-performance concretes (HPC) with nanomaterials incorporated into the concrete matrix, aiming to achieve good workability, durability, and superior strength properties compared to conventional concrete. This can be accomplished by employing existing calculation methods and available materials [7, 17-20].

Nowadays, HPC plays a crucial role in the construction of specialized structures due to the enhancements it offers over conventional concrete. HPC enables the construction of increasingly slender structures by reducing the cross-sections of structural elements, thereby providing more available space within buildings [21, 22].

Moreover, the development of Environmentally Friendly High-Performance Concrete (HPC) incorporating a blend of micro-nano silica represents a significant stride towards sustainable construction practices. This innovative approach not only aims to enhance the mechanical and durability properties of concrete but also focuses on reducing the environmental impact associated with traditional concrete production methods. By integrating micro and nano silica, the concrete matrix can be significantly improved, leading to a reduction in the carbon footprint of construction materials and promoting eco-friendly building solutions [23, 24].

Lastly, the environmental sustainability of concrete is significantly enhanced through the use of nanomaterials. By improving the material's mechanical properties and durability, the lifecycle of concrete structures is extended, reducing the overall environmental impact associated with their construction and maintenance [25]. Furthermore, an example of sustainable practices in the construction industry, although not analyzed in this study, is the use of nanomaterials such as fly ash contributes to sustainable development practices by recycling industrial waste, further diminishing the construction industry's carbon footprint[26].

The importance of this study extends beyond the technical advancements in concrete properties. The research aims to provide a comprehensive understanding of how the combined effects of micro and nano silica can optimize HPC's performance, offering a viable solution that aligns with global sustainability goals. By exploring alternative micro and nano silica dosage and methods that reduce the reliance on conventional cementitious materials, this research contributes to the development of more sustainable urban environments.

2. EXPERIMENTAL PROCEDURE

2.1. Materials Used

For the analysis in this research, aggregates from the Pifo quarry, located in the province of Pichincha in Ecuador, were utilized. Holcim type Gu cement [27] and a superplasticizer 7955 from Basf [28] were also employed.

For this research, MasterlLife SF 100 microsilica is used from the company Basf and distributed by Imperquik, whose technical specification recommends the use of microsilica in percentages of between 5% and 15% as an addition to the cement [28].

Nanosilica is made up of dozens of nanometer-sized amorphous particles composed of silica dioxide (SiO2), which is the interaction of silicon with oxygen that is commonly called silica. This nano component has pozzolanic properties that, when reacting with the cement, improve its mechanical properties.

Among all the characteristics, the coarse aggregate has a maximum size of ½", a specific gravity of 2.47 g/cm3, and an absorption capacity sof 4.92%. The fine aggregate is a crushed natural quarry sand with a specific gravity of 2.57 g/cm3, an absorption capacity of 3.1%, and a fineness modulus of 2.96. All the parameters for both the coarse and fine aggregates comply with the requirements specified in the ASTM [29].

2.2 Mixing and Testing Procedure

The concrete mixture process was meticulously followed to ensure optimal consistency and strength of the final product. First, we dampened the interior of the concrete mixer to prevent any dry materials from sticking and to facilitate an even mix. Then, we added both the coarse and fine aggregates into the mixer, allowing them to blend for a full minute to achieve a uniform distribution.

Following the initial mixing, we introduced the specified amount of cement to the aggregate mixture, continuing the blending process for an additional 30 seconds to ensure the cement was thoroughly integrated with the aggregates. After the cement had been mixed in, we added water that had been pre-mixed with nano-silica to the mixer. This combination was then mixed for approximately two minutes, allowing the nano-silica to disperse evenly throughout the mixture, which enhances the concrete's mechanical properties and durability.

Finally, we incorporated the additive into the mixture. This step was done carefully to allow sufficient time for the additive to react properly with the other components, ensuring proper particle adherence and achieving the desired chemical and physical properties in the finished concrete. This methodical approach to mixing ensures that the concrete possesses the necessary workability, strength, and longevity required for our construction needs. The mixture proportion is provided in Table.

To enhance the properties of nano-silica in the concrete, a mechanical mixer is used to achieve a homogeneous mixture of nano-silica and water, producing a slurry that guarantees improved properties in the concrete fabrication process.

Once the mixture was ready, a portion of it was used to measure the slump flow according to the standard ASTM C-161 [30] s, and the remaining mixture was poured into

100 mm molds for compression and tensile studies. The specimens fabricated were left to cure in the curing chamber for the assigned ages of 3, 7, 28, 56, and 91 days for their respective tests.

3.LABORARY TEST, RESULTS AND DISCUSSION

3.1. Slump Flow Test

According to the data presented in Table 1, for a water-to-cement ratio (w/c) of 0.3 and varying percentages of added microsilica and nano-silica particles to the high-performance concrete (HPC), an increase in their content leads to a reduction in the flow diameter of the mixture compared to the control mix. This observation can be attributed to the specific surface area of the microsilica and nano-silica particles, which causes cohesion forces between both micro and nanoparticles, resulting in the formation of silica agglomerates. As a result, these agglomerates exhibit high adsorption and significant water retention capacity due to their high specific surface area and porosity at the micro and nanoscale.

The specific surface areas of microsilica and nano-silica particles significantly impact their cohesion forces, leading to the formation of silica agglomerates. This phenomenon is attributed to factors such as the surface energy of the particles and their interaction with surrounding conditions. Studies have shown that higher surface energy in substances like amorphous silica spheres enhances adhesion forces between particles, facilitating their aggregation (Kamel, 2016). Additionally, the presence of hydrophobic silica nanoparticles can induce anti-adhesive forces at interfaces, altering the adhesive properties and promoting the formation of aggregates [32]. Furthermore, the dynamic adhesion behavior of silica particles is highly dependent on surface and electrostatic heterogeneity, influencing how particles adhere and aggregate under different conditions [33].

The formation of a dense agglomeration of solid particles in the mixture containing microsilica and nano-silica is another reason for the substantial increase in flowability and viscosity of the cementitious materials. To address this, higher dosages of water-reducing superplasticizer are recommended to maintain workability and inhibit flow reduction in high-performance concrete (HPC) due to the increased percentage of cement substitution and the increased specific surface area of microsilica and nano-silica particles.

Table 1. Proportion of HPC mixes (Kg/m^3)

Mix code	Type	w/b	Cement	Water	Micro-SiO2	Nano-SiO2	Gravel	Sand	SP	Slump flow diameter (cm)
C	-	0,30	550	165	-	-	944,53	652,63	6.6	59
5% MS	ML SF100		522.5	165	27.5	-	940.4	649.8	7.15	51
10% MS	ML SF100		495	165	55	-	946.9	646.9	7.7	53
15% MS	ML SF100		467.5	165	82.5	-	932	644	8.8	56
0,75% NS	NS200		545.875	165	-	4.125	943.6	652	11	52.5
1,5% NS	NS200		541.75	165	-	8.25	942.7	651.4	14.3	55
3% NS	NS200		533.5	165	-	16.5	940.9	650.1	17.05	56
15% MS+ 1,5% NS	ML+NS		459.25	165	82.5	8.25	930.2	642.7	23.1	54
15% MS + 3% NS	ML+NS		451	165	82.5	16.5	928.4	641.5	25.85	51

3.2. Mechanical Properties

3.2.1. Compressive Strength

The results of the mechanical tests for compressive strength and indirect tensile strength are shown in Table 2 and Table 3, respectively.

The incorporation of nanosilica into concrete has been specifically studied for its impact on compression resistance. Nanosilica acts as a partial replacement for cement, contributing to the improvement of the concrete's mechanical properties due to its pozzolanic reaction and microstructural refinement. For instance, Ganesh et al. [34, 35] and Ardalan et al. [35] observed that the addition of nanosilica improves the compressive strength of concrete by enhancing the hydration process and refining the microstructure of the cementitious matrix. Additionally, Zanon et al. [36] and Lim & Mondal [37] reported that the combined use of nanosilica with other admixtures, like silica fume, can further increase compressive strength, reduce capillary absorption, and minimize chloride penetration, primarily attributed to the synergetic effect of nanosilica in the cementitious composite. This demonstrates that nanosilica contributes positively to the compression resistance of concrete, making it a valuable component for enhancing the structural properties of concrete mixtures.

Based on the results obtained with the incorporation of microsilica and pyrogenic nano-silica in the mixture, the mechanical strengths have improved as the curing ages increase for both the mixtures with the incorporation of micro and nanoparticles compared to the control concrete.

There is a positive effect for nano-silica, as its incorporation into the matrix of cement-based materials like concrete is attributed to a 4-fold increase in performance. Both microsilica and nano-silica demonstrate high pozzolanic activity and control unfavorable crystallization due to a large number of micro and nanoparticles among hydration products, along with their confinement role.

Table 2. Compressive strength test result (MPa)

Mix code	Curing Age				
	3 Days	7 Days	28 Days	56 Days	91 Days
C	31.42	43.92	58.65	64.74	69.71
5% MS	31.99	43.86	62.06	70.76	76.39
10% MS	30.17	42.98	62.06	71.53	78.19
15% MS	25.11	41.90	74.62	79.90	81.85
0,75% NS	24.36	41.47	57.55	64.66	70.23
1,5% NS	27.39	38.59	57.71	65.34	71.37
3% NS	27.53	39.61	57.52	65.52	73.27
15% MS+ 1,5%NS	17.33	36.57	61.85	72.77	78.51
15% MS + 3% NS	22.42	42.37	64.21	74.98	80.24

Table 3. Indirect tensile strength test result (MPa)

Mix code	Curing Age			
	3 Days	7 Days	28 Days	56 Days
C	2.22	3.63	4.29	4.59
15%MS	2.24	3.62	4.78	5.89
3%NS	2.22	3.45	4.75	5.83
15%MS + 3%NS	1.93	3.39	4.79	5.87

Nanosilica, when incorporated into the matrix of cement-based materials such as concrete, has been shown to have a significantly positive effect on their performance. This study has shown that the addition of nanosilica results in an increase of up to 4 times the strength and durability of concrete. Both microsilica and nanosilica exhibit high pozzolanic activity, allowing them to control unfavorable crystallization in the concrete matrix.

Research by Qing, Zhang, Li, and Chen [38] demonstrates that nano-SiO2 exhibits notably higher pozzolanic activity compared to silica fume, contributing to improved compressive and bending strength in concrete, especially at early ages. Furthermore, Hassan [39] explores the inefficiency of traditional testing methods for nano-silica in concrete, proposing a modified approach due to nano-silica's unique properties such as its high surface area and pozzolanic reactivity.

Micro and nano particles incorporated in concrete help control micro and nanoscale porosity within its microstructure, specifically in the transition zone between aggregates and cement paste, thus contributing to increased strength. For a water-to-binder ratio (w/b) of 0.30, higher values were obtained using 15% microsilica and 3% nano-silica, as compared to other percentage additions. This is attributed to the particles' ability to act as filler agents, reducing the formation of micro pores and enhancing the material's density [40, 41].

According to Table 2, the compressive strength is greater for microsilica, nano-silica, and their combination across various curing periods. The highest values were achieved for 15% MS, 3% NS, and 15% MS + 3% NS. This resulted in an increase of 17%, 5%, and 15% respectively at 91 days, thereby obtaining higher strengths than the control mix. The compressive strength of High-Performance Concrete (HPC) incorporating microsilica, nano-silica, and the combination of both was higher than the control mix. At early ages, slightly lower strengths were obtained for the values of 15% MS, 3% NS, and 15% MS + 3% NS. However, these differences may be attributed to the increased pozzolanic activity. While there is no standardized method for enhancing the dispersion of micro- and nanoparticles of silica, employing expensive techniques like ultrasonic mixing has resulted in better distribution of nanoparticles throughout the microstructure.

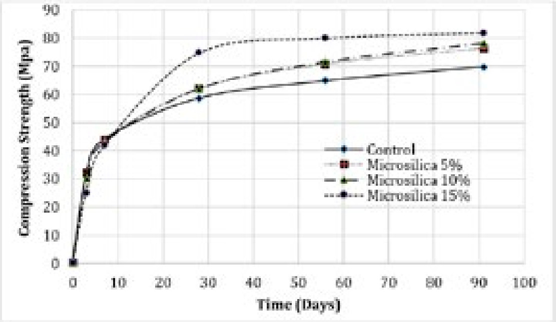

Figure 1. Compression Strength of Microsilica

Figure 1 presents the results of the compression tests for the control specimen compared to specimens containing microsilica at concentrations of 5%, 10%, and 15%. The influence of microsilica is evident, as the trend curve lines for all concrete samples with added microsilica surpass that of the control specimen in terms of compression behavior. Notably, specimens with a 15% microsilica content exhibited superior compressive strength compared to those with 5% and 10%, which displayed nearly identical levels of compression resistance. It was observed that all specimens demonstrated comparable resistance at the age of 7 days; however, beyond this period, the compressive strength of the specimens containing 15% microsilica increased significantly. This trend was particularly noticeable at 28 days. By day 96, the differences in compressive resistance among various microsilica dosages became minimal, suggesting that the variations in microsilica content (5%, 10%, and 15% in this study) primarily affect early-age compressive strength rather than long-term strength. Nevertheless, additional experimental studies are required to verify these findings conclusively.

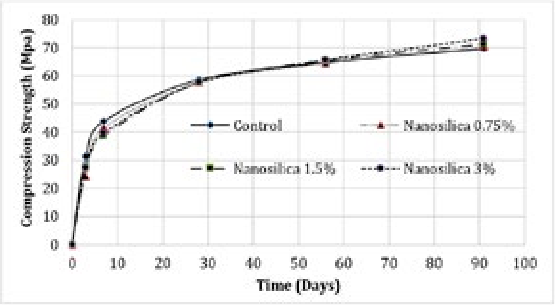

Figure 2. Compression Strength of Nano-silica

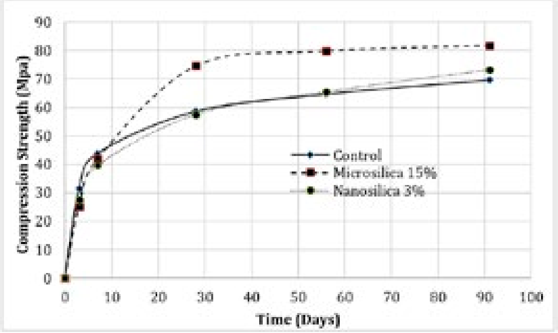

Figure 3. Compression Strength of Micro and Nano-silica

Regarding concrete samples that just incorporated nanosilica, no significant differences were observed in compression behavior, contrasting with results from concrete samples containing microsilica. Figure 2 illustrates the compression test outcomes for concrete specimens incorporating varying concentrations of nanosilica in their mix designs, specifically 0.75%, 1.5%, and 3%. These findings suggest that, unlike microsilica, the inclusion of nanosilica at these specific percentages does not notable affect the compressive strength behavior of the concrete.

To better understand the differential impacts of microsilica and nanosilica on compressive strength, Figure 3 displays the comparative resistance trends between concretes incorporating the highest percentages used in this study: 15% microsilica and 3% nanosilica, respectively. It is evident that microsilica exerts a significant influence on compressive strength when compared with both the nanosilica-enhanced concrete and the control specimen. This effect is pronounced both in the early age (28 days) and at a more advanced age (96 days). Specifically, a notable increase of 22.8% in compressive resistance at 28 days was observed for the concrete containing microsilica.

3.2.2. Indirect tensile strength (Brazilian test)

The utilization of nanosilica and microsilica in concrete compositions has been extensively studied, revealing significant enhancements in the mechanical properties relevant to the Brazilian test for concrete. These admixtures are found to notably improve the splitting tensile strength and flexural strength of concrete. This improvement, however, can coincide with reductions in compressive strength and modulus of elasticity, illustrating the need for careful balance in composite formulations. The enhancements attributable to nanosilica and microsilica are particularly pronounced when used in tandem, suggesting a synergistic interaction that bolsters the concrete's mechanical integrity [42-44].

Moreover, the inclusion of nanosilica has been linked to considerable improvements in the compressive and tensile strengths of concrete, specifically when optimal dosages are employed. This finding is critical for early-age concrete curing, where strength development is crucial for subsequent construction phases and long-term durability [34, 45]. The combined use of nanosilica and microsilica not only contributes to superior hardened properties but also aligns with sustainable construction practices by potentially lowering the cement content required for achieving desired strength levels. This dual benefit underscores the importance of integrating these materials into modern concrete mixes for enhanced performance and sustainability [46, 47].

The results from the indirect Brazilian tensile strength tests (Fig. 4) indicate a significant enhancement in tensile strength with the incorporation of microsilica, nanosilica, and their combination. At 56 days, an increase of 28% in tensile strength was noted for mixtures with a 15% microsilica substitution as well as for those with a combined substitution of 15% microsilica and 3% nanosilica. In both instances, the performance improvement was substantial, with only a marginal difference of one percentage point compared to mixtures that contained solely 3% nanosilica.

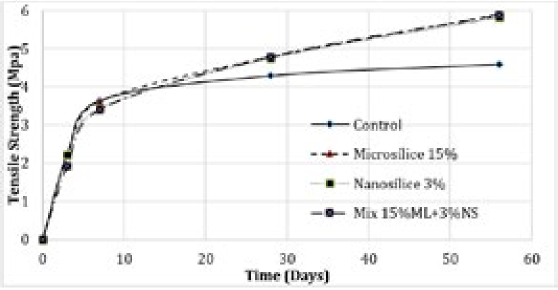

Figure 4. Tensile Strength of Micro-Nano-silica and Hybrid

3.2.3. Flexure test

The integration of nanosilica and microsilica into concrete formulations has shown significant improvements in the flexural behavior and bond strength of reinforced concrete. Research indicates that the addition of nanosilica enhances the bond between concrete and reinforcement bars, leading to increased load-carrying capacity, reduced crack widths, and improved ductility. These improvements suggest that nanosilica may serve as an effective pozzolanic admixture for enhancing structural properties in concrete applications [48]. Furthermore, experimental results have demonstrated the superior performance of nanosilica-added high-performance concrete over traditional and microsilica-added concretes, particularly in terms of the concrete-rebar interface and flexural strength [49].

In addition to the enhanced bond strength, nanosilica has also been found to significantly improve the mechanical and transport properties of lightweight aggregate concrete. Even small dosages of nanosilica result in considerable strength improvements and a reduction in transport properties. This is attributed to the compaction of the concrete matrix and modification of the air-void system, which leads to a more refined pore structure and improved overall mechanical performance [50]. The addition of nanosilica not only contributes to higher flexural and compressive strengths but also enhances the durability of lightweight concrete structures [51].

Explain the test approach. Samples and etc. or photo.

Regarding flexural strength, the mixtures show relatively low increase values, with the highest being 7% observed for the mixture with 15% Micro silica substitution, and the lowest value of 3% for the mixture with 3% Nano silica substitution. Considering the Mixed Mixture with 15% Micro silica + 3% Nano silica substitution, the flexural strength is not statistically significant, with only a one-percentage-point increase compared to the nano silica mixture.

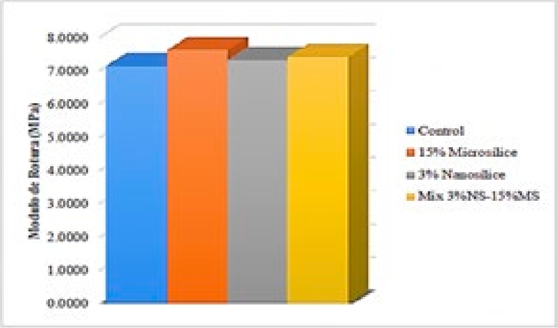

Figure 5. Flexural strength by percentage of cementitious additions at 56 day.

3.2.4. Tests for modulus of elasticity and Poisson's ratio

The modulus of elasticity (MOE) is a critical parameter for both ultra-high performance concrete (UHPC) and conventional concrete as it directly influences the structural behavior and serviceability of constructed facilities. For UHPC, the MOE is significantly impacted by the composition and characteristics of the materials used. Recent studies have proposed new equations for predicting the MOE at different ages based on the specific mixtures and local materials used, which can lead to a better understanding of the structural behavior of UHPC and its applications in design [12, 20, 52, 53].

In contrast, conventional concrete exhibits a wider range of MOE due to variations in mix design, aggregate type, and other factors. Extensive research has been conducted to evaluate the MOE of conventional concrete under different conditions, highlighting the effects of water/cement ratio, aggregate size, and type, as well as the inclusion of fly ash [54, 55]. These studies have led to the development of predictive models that provide a reliable estimation of the MOE based on the compressive strength and other easily measurable properties of concrete [56, 57].

The modulus of elasticity obtained for the different tested cementitious additions at 28 days shows an increase in its value compared to the control mixture. The mixtures with 15% microsilica and the mixed mixture with 3% nano silica and 15% microsilica are particularly representative in this regard.

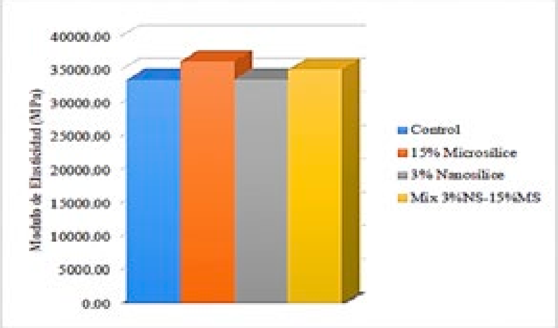

Figure 6. Modulus of Elasticity by percentage of cementitious additions at 28 days

3.2.5. X-ray Diffraction Analysis (XRD)

X-ray Diffraction Analysis (XRD) is a powerful non-destructive testing technique used to analyze the phase composition and crystalline structure of materials, including concrete. In the context of concrete tests, XRD is used to identify the types of cement hydrates and other crystalline substances formed during the hydration process of cement and to assess the presence of potentially harmful compounds like alkali-silica reaction (ASR) products or ettringite [58].

Figure 7 displays the diffractogram obtained from X-ray testing for dosages of 0.75% at ages of 3, 7, and 28 days. The peaks observed in the graph allow us to estimate the different compounds present in the analyzed sample.

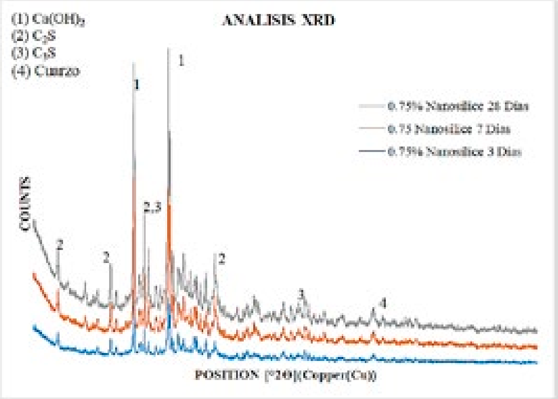

Figure 7. X-ray Diffraction (XRD) of 0.75% nano-silica at 3, 7, and 28 days

Figure 8 displays the diffractogram obtained from X-ray testing for dosages of 1.5% nano-silica at 3, 7, and 28 days. The peaks observed in the graph allow us to estimate the different compounds present in the analyzed sample.

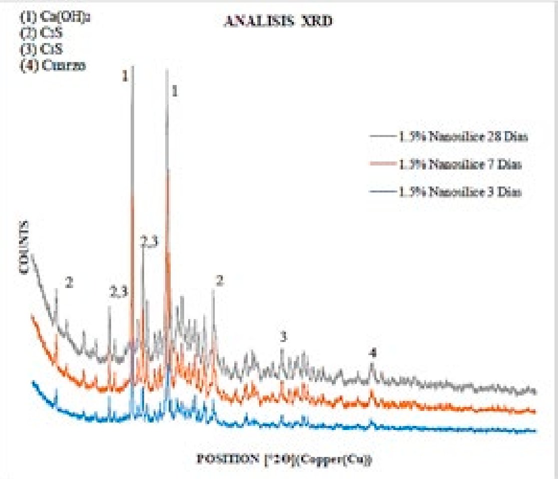

Figure 8. X-ray Diffraction (XRD) of 1.5% nano-silica at 3, 7, and 28 days

Figure 9 displays the diffractogram obtained from X-ray testing for dosages of 3% nano-silica at 3, 7, and 28 days. The peaks observed in the graph allow us to estimate the different compounds present in the analyzed sample.

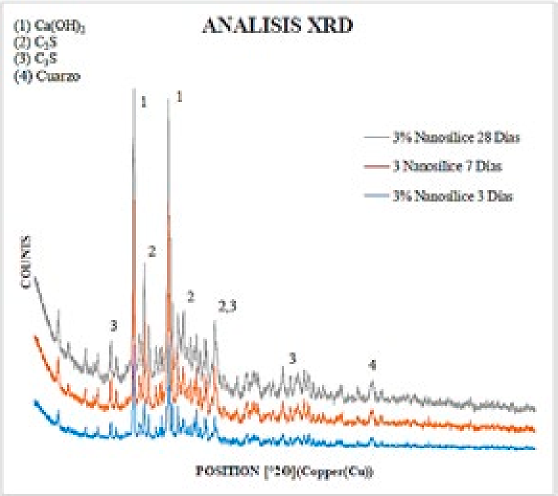

Figure 9. X-ray Diffraction (XRD) of 3% nano-silica at 3, 7, and 28 days

Figure 10 displays the diffractogram obtained from X-ray testing for dosages of 1.5% NS + 15% MS at 3, 7, and 28 days. The peaks observed in the graph allow us to estimate the different compounds present in the analyzed sample.

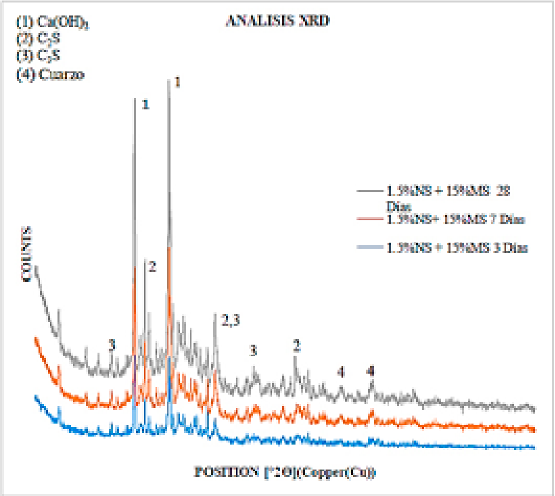

Figure 10. X-ray Diffraction (XRD) of 1.5% NS-15% MS at 3, 7, and 28 days

Figure 11 displays the diffractogram obtained from X-ray testing for dosages of 3% NS + 15% MS at 3, 7, and 28 days. The peaks observed in the graph allow us to estimate the different compounds present in the analyzed sample.

Scrivener, K., et al. [58] research has demonstrated similar trends, revealing significant alterations in the microstructure corresponding to various nano-silica dosages, paralleling the findings from this study at nano-silica concentrations of 0.75%, 1.5%, and 3% across different timeframes. The comparative examination underscores a uniform trend of enhanced pozzolanic reactions and concrete matrix densification with increased nano-silica levels, aligning with the outcomes observed in this work. Additionally, the findings from the combined application of 1.5% nano-silica and 15% micro-silica in this research Scrivener, K., et al. observations, shedding light on the combined effects of these additives, corroborating with his results on optimized mix designs for reactive powder concrete.

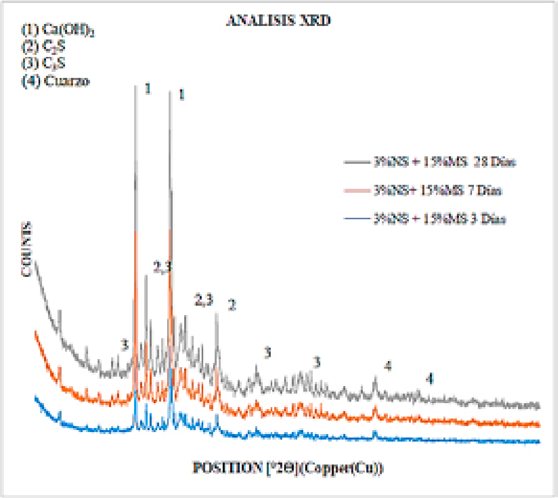

Figure 11. X-ray Diffraction (XRD) of 3% NS-15% MS at 3, 7, and 28 days

3.2.6. SEM and EDS Analysis

Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS, also known as EDX or EDXS) are complementary techniques used in materials science, biology, and various other fields to analyze the surface topography, composition, and properties of materials.

Figure 12 presents the specimens with a 1.5% nano-silica substitution for the cementitious material, indicating the percentages of each element present in the sample.

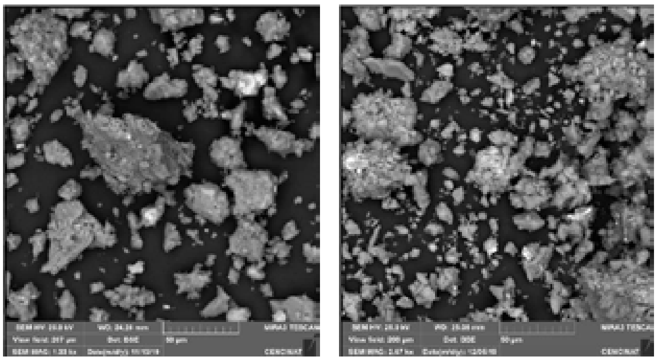

Figure 12. SEM Micrograph a) Micrograph of 1.5% nano-silica at 3 days b) Micrograph of 1.5% nano-silica at 28 days

Tvhe elements constituting the concrete sample with 3% nano-silica substitution for the cementitious material are presented, and the percentages of each element present in the sample can be seen in the table.

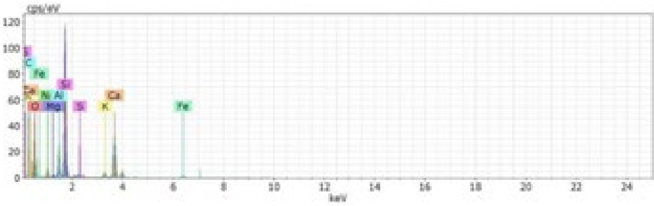

Figure 13. EDS Analysis for a nano-silica mixture with 1.5% content

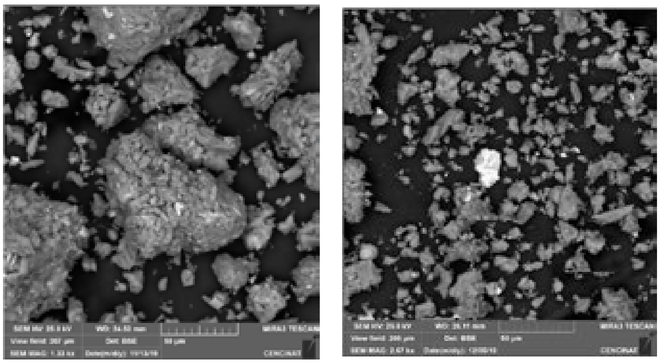

Figure 14. SEM Micrograph a) Micrograph of 3% nano-silica at 3 days b) Micrograph of 3% nano-silica at 28 days.

The elements constituting the concrete sample with a mixed incorporation of 1.5% NS + 15% MS as a substitution for the cementitious material are presented, and the percentages of each element present in the sample can be seen in the table.

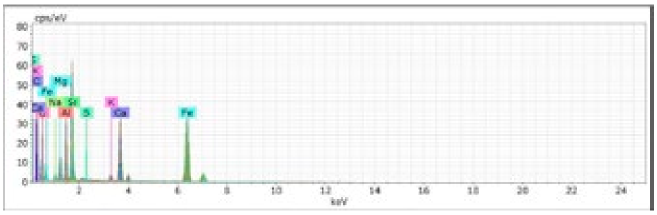

Figure 15. EDS Analysis for a nano-silica mixture with 3% content

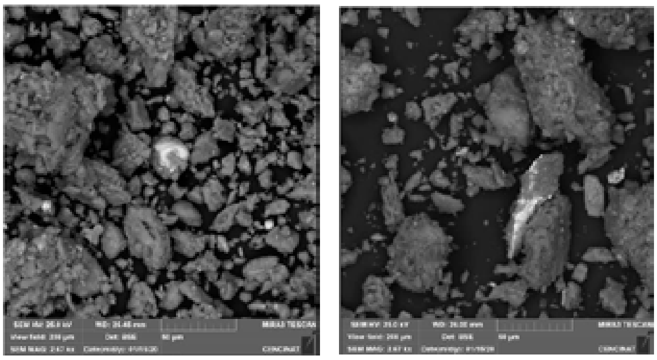

Figure 16. SEM Micrograph a) Micrograph of nano-silica and microsilica with a percentage of (1.5 % + 15%) at 3 days b) Micrograph of nano-silica and microsilica with a percentage of (1.5 % + 15 %) at 28 days.

The elements constituting the concrete sample with a mixed incorporation of 3% NS + 15% MS as a substitution for the cementitious material are presented, and the percentages of each element present in the sample can be observed in the table.

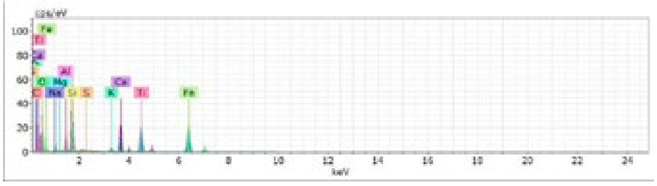

Figure 17. EDS Analysis for a mixture of 1.5% nano-silica and 15% microsilica

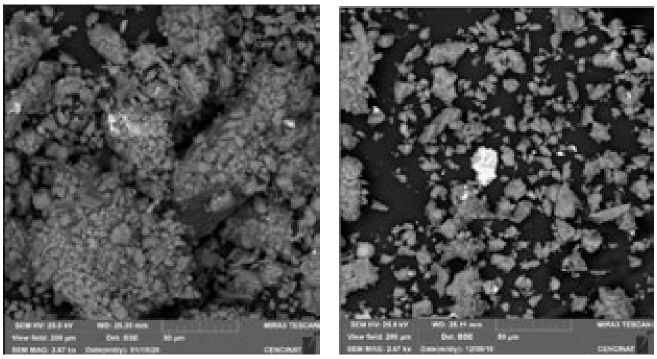

Figure 18. SEM Micrograph, a) Micrograph of the mixed mixture of 3 % nano-silica and 15 % microsilica at 3 days, b) Micrograph of the mixed mixture of 3 % nano-silica and 15 % microsilica at 28 days

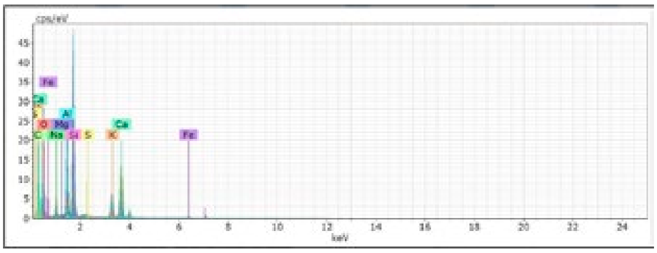

Figure 19. EDS Analysis for a mixture of 3 % nano-silica and 15 % microsilica

4. SUMMARY AND CONCLUSIONS

In this study, an experimental design was carried out that incorporated different percentages of microsilica and nanosilica. The findings revealed that the substitution of 15% microsilica resulted in a notable 28% increase in compressive strength at 28 days, and a 17% increase at 91 days, in contrast to the control mixture. On the other hand, the inclusion of 3% nanosilica showed a minor impact, improving compressive strength by only 5% at 91 days. These results led to the identification of an optimal formulation that combines 15% microsilica and 3% nanosilica, giving the concrete greater strength compared to the control mixture. This finding highlights the importance of the specific combination of microsilica and nanosilica in improving the mechanical properties of concrete, which has significant implications in the construction industry and opens new possibilities for the development of high-performance materials.

The inclusion of nanoparticles as partial substitutes for cement has been shown to significantly improve the mechanical properties of concrete, highlighting a notable increase in compressive and tensile strength. These results were achieved without significantly affecting the flexural strength, elastic modulus or Poisson's ratio compared to the base mix. Additionally, this modification has been shown to improve concrete workability by mitigating aggregate segregation and ensuring adequate concrete slump. These findings not only highlight the potential of nanoparticles in improving concrete properties, but also suggest a promising approach for the development of high-performance construction materials with practical applications in the construction industry.

In summary, the incorporation of microsilica in high-performance concrete not only improves its mechanical properties and workability, but also contributes significantly to meeting sustainability requirements. By reducing the amount of cement needed, the use of microsilica decreases the environmental impact associated with cement production, including reducing carbon dioxide emissions. This positions microsilica as a viable and environmentally friendly alternative in the construction industry, in line with global sustainability objectives and current environmental regulations.

5. RECOMMENDATIONS

It is necessary to perform a larger number of test specimens as the results presented in this study are indicative rather than representative of concretes in order to obtain a statistical analysis.

It is proposed to perform various tests on specimens with different additions of nanosilica ranging from 1.5% to 3% of nanosilica, as well as micro-silica in the range of 10% to 15%. The objective is to find an optimal addition to achieve maximum strength.

It is advisable to conduct tests in the fresh state of the cementitious material with additions of nano-silica and micro-silica in order to determine normal consistency and setting times. This is because the reaction between these additives produces an exothermic reaction, leading to an increase in hydration heat.

DECLARATION OF COMPETING INTEREST

The authors hereby state that they have no known financial interests or personal relationships that may have influenced the work reported in this paper.

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