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Nano-silica in Holcim general use cement mortars: A comparative study with traditional and prefabricated mortars

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Abstract. Nano-silica's growing use in construction, known for enhancing strength and durability by reducing porosity, drives this research's significance, especially considering Ecuador's reliance on cement in construction. A comprehensive comparative study on mortars made with General Use cement and aggregates from Pifo and San Antonio quarries has been studied. It explores the impact of incorporating nano-silica in varying proportions (0.75%, 1.00%, 1.25%) on mortar properties, contrasting them with conventional and prefabricated mortars. laboratory Testing is conducted according to standards to assess both fresh and hardened state properties, and microscopic analysis reveals the optimal nano-silica proportion's effects on mortar characteristics. Results shows that Incorporating 0.75% nano-silica resulted in a 61% increase in compressive strength at 7 days and. For a nanosilica content of 1.25%, a 14% increase in compressive strength was observed at 28 days in relation to the conventional mortar and the permeability of the mortar decreased by 30% when adding 0.75% nanosilica. It discusses economic viability and provides insights through SEM and EDS analyses. Overall, it underscores nano-silica's potential to enhance mortar properties and its relevance in creating more efficient and durable construction materials.

Keywords: concrete additives; Holcim GU Cement; mortar; nano-materials; nano-silica; properties in plastic and hardened states; surface microscopic characterization

1. Introduction

1.1 Nanotechnology in construction

In the construction industry, there is a strong focus on innovation and improving materials and techniques. One exciting advancement is the use of nanoparticles, tiny structures that are changing how we build (Casini 2016). These nanoparticles are very small and are making buildings stronger, more durable, energy-efficient, and environmentally friendly. Nanoparticles, which are incredibly small objects measured in nanometers, have become important in scientific and technological research. They vary in size and have unique properties, like a high surface area, increased reactivity, and special characteristics in areas like mag netism, optics, and electricity. This has opened up many possibilities in fields like medicine, electronics, energy, and industry (Alvansazyazdi *et al.* 2024b, Feizbahr *et al.* 2020).

In the past few years, there has been a significant rise in the application of nanoparticles in the construction sector, specifically in integrating them into the manufacturing of concrete and mortar (Alvansazyazdi *et al.* 2024c, Feizbahr *et al.* 2013, Oruji *et al.* 2023, Shaikh *et al.* 2014, Zhang *et al.* 2021). This trend has led to the achievement of higher strengths and enhanced properties in construction materials. One such nanoparticle gaining significant attention is nano-silica, which has demonstrated remarkable effects on the densification, porosity reduction, and overall strength and durability enhancement of cementitious matrices (Abhilash *et al.* 2021, Alvansaz *et al.* 2022b, Bi *et al.* 2012, Esmaeili and Andalibi 2013, Said *et al.* 2012, Tadayon *et al.* 2010).

The incorporation of nano-silica in cement mortars has been found to have a substantial impact on the mechanical properties of the resulting materials (Abd Elrahman *et al.* 2019, Asli and Arabani 2022, Chen *et al.* 2008, Choobbasti *et al.* 2015, García-Taengua *et al.* 2015, Rahmawati *et al.* 2021). Studies have shown that nano-silica contributes to the densification of the matrix, leading to reduced porosity and improved strength. The high surface area of nano-silica particles allows for better interaction with cement hydration products, resulting in enhanced durability and resistance to degradation factors such as chemical attack and freeze-thaw cycles (Duran *et al.* 2014, Ferdosi and Abasi 2022, Tarangini *et al.* 2022, Wei *et al.* 2015).

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Moreover, nano-silica has been shown to have a positive influence on the workability and rheological properties of mortars, facilitating easier application and improved handling characteristics (Berra *et al*. 2012, Chithra *et al*. 2016, Güneyisi *et al*. 2016). Its use can also contribute to the reduction of environmental impact by potentially decreasing the cement content required for achieving desired strength levels (Morales *et al*. 2020, Taherkhani *et al*. 2017). This aligns with the goals of sustainable construction practices, promoting resource efficiency and minimizing carbon emissions associated with cement production.

Mortar in Ecuador

In Ecuador, mortar, a construction material, hasn't seen the same level of research and use as concrete, steel, or wood. This is because it's not commonly used in the country's building structures (Adarsh and Ray-Chaudhuri 2021). This lack of interest and research has led to mortar being used without proper quality control, often resulting in cracks in walls due to poor construction practices. Some studies have shown promising results when adding nano-sized silica particles to mortar to improve its strength. However, more research is needed to understand how this affects fresh mortar, hardened mortar, and the specific characteristics of the nanoparticles themselves, such as their size and composition (Qu and AV Morton 2015). In Ecuador, cement plays a pivotal role in the majority of building projects. According to the Ecuadorian Institute of Statistics and Censuses, cement is employed in 97% of cases for foundation construction, including both reinforced concrete and cyclopean structures. Furthermore, it is utilized in 88% of cases for columns and walls, while 65% of projects utilize cement as a bonding mortar or plaster, commonly referred to as rendering.

This comparative study aims to assess the effectiveness of incorporating nano-silica in Holcim General Use (GU) cement mortars when compared to traditional and prefabricated mortars. Holcim GU Type Cement is a hydraulic cement used in civil engineering constructions where no special properties are required. This cement does not have special additives that provide high early-age strengths or high resistance to sulfate attack or other environmental compounds. The investigation will focus on evaluating the impact of nano-silica on key properties such as strength, durability, and porosity reduction. By comprehensively analyzing and comparing the performance of these different mortar formulations, valuable insights can be gained for sustainable construction practices on a global scale.

The findings of this study will provide valuable information for engineers, architects, and construction professionals, enabling them to make informed decisions regarding the incorporation of nano-silica in cement mortars. By understanding the potential benefits and limitations of nano-silica, practitioners can optimize the design and production processes, leading to improved performance, increased sustainability, and cost-effectiveness in construction projects.

The energy expenditure in buildings ranges between 30% and 60%, making it one of the most demanding consumptions, especially in sectors with significant temperature variations. This leads to the utilization of nano-silica particles in the construction of these buildings, which possess ideal physical and chemical properties for the development of insulation materials with low thermal conductivity (Alvansazyazdi *et al*. 2024a, Chen *et al*. 2016). Based on the above, this research is focused on understanding the influence of incorporating nano-silica into traditional mortar paste, working with two aggregates sourced from the San Antonio and Pifo parishes, both belonging to the Quito canton, compared to a paste without nano-silica addition, and comparing it with a prefabricated mortar. The relationship between green building and nano-silica lies in the potential application of nano-silica as a material to enhance sustainability in construction. Green building focuses on minimizing environmental impact, and nano-silica offers unique properties due to its small particle size. Nano-silica can be used in various ways, such as improving the strength and durability of concrete, enhancing insulation materials, creating self-cleaning surfaces, and improving energy efficiency in windows. However, further research is needed to fully understand its benefits and any associated risks to ensure its sustainable and responsible implementation (Alqamish and Al-Tamimi 2021, Alvansaz *et al*. 2022a, Li *et al*. 2021, Porbashiri and Ferdosi 2022, Singh *et al*. 2013).

This study's importance lies in the exploration of nano-silica as a promising additive in cementitious materials, specifically mortars, and its implications for Green Building and Sustainable Urban Development. By conducting a comparative analysis between nano-silica-based mortars and traditional/prefabricated mortars, the research aims to evaluate their effectiveness and understand their potential benefits and drawbacks. This assessment is significant as it contributes to the knowledge and understanding of sustainable construction practices. The findings have the potential to influence construction techniques globally by promoting resource efficiency through reduced material consumption, enhancing energy efficiency through improved performance, and reducing environmental impacts such as carbon emissions and waste generation. Ultimately, this research aims to aid in the development of sustainable construction techniques, supporting the goals of Green Building and Sustainable Urban Development worldwide. The comparative study of nano-silica in mortar aims to evaluate the impact of the incorporation of nano-silica on the properties of mortars, in contrast to traditional and prefabricated mortars. The aim is to understand how nano-silica can improve the strength, durability and other characteristics of mortar, as well as its economic viability. Additionally, the research aims to contribute to the knowledge and understanding of sustainable construction practices, with the potential to influence construction techniques globally by promoting resource efficiency and reducing environmental impacts. This approach is relevant to green construction and sustainable urban development globally.

1.2 Research objectives

The main objective of this study is to evaluate the impact of incorporating nano-silica in Holcim general-purpose cement mortars, comparing them with traditional and prefabricated mortars. The aim is to analyze the properties in the fresh and hardened state of mortars with different proportions of nano-silica, as well as to understand their economic viability and their potential to improve the efficiency and durability of structures built with these materials.

1.3 Hypothesis

It is proposed that the addition of nano-silica in Holcim GU cement mortars will result in significant improvements in strength, durability and efficiency, surpassing traditional mortars in terms of mechanical properties and microstructural characteristics.

2. Methodology

For the development of this research, the aim is to carry out a comparison of mortars manufactured with two types of aggregates, one from San Antonio and the other from Pifo. During the manufacturing process of each mortar, three percentages of nano-silica were incorporated: 0.75%, 1.00%, and 1.25% relative to the mass of cement, with each type of aggregate. Subsequently, the impact of this addition at different percentages was evaluated through the analysis of the properties and characteristics of the mortar in both the plastic and hardened states.

The mortar's ability to resist loads, durability, ability to remain compact and resistant to the penetration of aggressive elements was tested. An industrial mortar mix was also prepared, and its properties were compared with the mortars manufactured using the aggregates from San Antonio and Pifo. The tests on the mortar, in both the plastic and hardened states, were conducted in accordance with the parameters established by the NTE INEN and ASTM standards at the laboratories of the Ecuadorian Institute of Cement and Concrete (INECYC) and the material testing laboratories of the Central University of Ecuador. The NTE INEN and ASTM standards were used to carry out laboratory tests on cement mortars containing nanosilica. These tests included evaluations of compressive strength, durability, workability, as well as microscopic analysis using SEM and EDS, in addition to X-ray diffraction tests. Scanning electron microscopy (SEM) was carried out with a Tescan Mira 3 SEM equipment equipped with a Schottky field emitter, while energy dispersive X-ray spectroscopy (EDS) was carried out in the SEM chamber, using a Bruker X-Flash 6|30 detector with a resolution of 123 eV in Mn Kα.

2.1 Materials, sources and methods

The materials present in the mortar for rendering with the addition of nano-silica are Holcim GU-type cement, sand, water, nano-silica. Mortar can be defined as the mixture of a binding material (Portland cement and/or other cementitious materials), a filler material (fine aggregate or sand), water, and optionally additives. When it hardens, it exhibits physical and mechanical properties similar to concrete and is widely used for bonding masonry units in wall construction or for plastering, in which case it is known as render (Sánchez de Guzmán 2001). There are various types of mortars, including Type M mortar, Type S mortar, Type N mortar, and Type O mortar (González de la Cadena 2016).

Fine Aggregate

These are particles that come from crushing rocks, particles that in this case pass through sieve No. 8 (2.36 mm) and are entirely retained on sieve No. 200 (0.074 mm).

Cement

Holcim GU-type cement is used for all mixtures, complying with all the requirements of NTE INEN 2380 and ASTM C1157 standards (ASTM 2011, INEN 2011a).

Water

The function of water is to hydrate and provide better workability to the mortar mixture. This water must be clean and free from oils, acids, alkalis, salts, organic materials, or other substances that are harmful to mortars. The water used should generally be potable (INEN 2010).

Nano-silica

Nano-silica is composed of dozens of amorphous nanoparticles consisting of silicon dioxide (SiO_2). This nanocomponent possesses pozzolanic properties that, when reacting with cement, enhance its mechanical properties (Barrionuevo Castañeda and Tapia Vargas 2021). The nano-silica used has a specific surface area of 200 ± 25 m^2/g and was purchased from the distributor COMERQUIN CIA LTDA. The properties of the mortar depend on the quality of its fine aggregates. For the development of this research, aggregates from San Antonio and Pifo in the province of Pichincha were used. The fine aggregates were obtained from two quarries, namely San Antonio and Pifo, located in the province of Pichincha. Holcim GU-type cement and AEROSIL® 200 nano-silica from Evonik, marketed by the chemical company Comerquim Cia. Ltda., were used. The characterization of the fine aggregates from both San Antonio and Pifo was carried out using laboratory tests according to the specifications mandated by the INEN and ASTM standards (ASTM 2011, INEN 2011a). This was done to ensure the quality of the materials used for the preparation of the mortar with nano-silica addition.

2.1.1 San Antonio fine aggregate

Origin: The parish of San Antonio, located in the Quito canton, Ecuador.

Geological Characteristics: San Antonio is located in the Ecuadorian Andean region, recognized for its volcanic geology. In this area, deposits of volcanic ash, tuffs and other pyroclastic materials can be found that could affect the physical and chemical properties of the fine aggregate extracted from this area.

2.1.2 Pifo fine aggregate

Origin: The parish of Pifo, located in the Quito canton, Ecuador.

Geological Features: Pifo is also located in the Ecuadorian Andean region and shares geological similarities with San Antonio due to its geographical proximity. The deposits at Pifo are likely to include volcanic

Table 1 Summary of characterization tests for San Antonio fine aggregate

Property	Unit	Values
Absorption capacity	%	3.93
Bulk loose density	g/cm^3	1.55
Bulk compacted density	g/cm^3	1.69
Specific weight	g/cm^3	2.54
Fineness modulus	-	2.49

Table 2 Summary of characterization tests for Pifo fine aggregate

Property	Unit	Values
Absorption capacity	%	1.96
Bulk loose density	g/cm^3	1.49
Bulk compacted density	g/cm^3	1.69
Specific weight	g/cm^3	2.52
Fineness modulus	-	2.47

Table 3 Summary of real densities of the materials

Material	Real density (g/cm^3)
Cement	2.83
Nano-silica	2.00

and sedimentary materials that influence the composition and properties of the fine aggregate obtained in this region. For the characterization of the fine aggregates, a series of laboratory tests were conducted to determine properties such as apparent, loose, and compacted densities, specific weight, particle size distribution, and absorption capacity. The test results are presented in Tables 1, 2, and 3.

The real density of the cement was determined through laboratory tests and the real density of Nano-silica Aerosil 200 was obtained from its technical datasheet. The required properties are obtained according to the characteristics needed in the mortar to be used. This design method is based on finding the base dosage of the mortar, which provides the necessary quantities of its components. The dosage used in this research is presented in Table 4.

Table 4 Base dosage of mortar with Portland cement, w/c ratio = 0.485 for 6 specimens (INEN)

Material	Weight (g)
Cement	500
Water	242
Sand	1375

Table 5 Quantities of materials for mortar with San Antonio fine aggregate, w/c ratio = 0.62 for 6 specimens of 50 mm edge cubes

Material	Weight (g)
Cement	500
Water	300
Sand	1375

Table 6 Quantities of materials for mortar with Pifo fine aggregate, w/c ratio = 0.64 for 6 specimens of 50 mm edge cubes

Material	Weight (g)
Cement	500
Water	320
Sand	1375

Knowing the properties of the materials used and using the base dosage, the dosage is modified using the density data of cement nano-silica and nano-silica, as well as the characterization of the aggregates from San Antonio and Pifo. This modification of dosages is carried out according to the w/c ratio used for a quantity of 6 specimens of 50 mm edge cubes. The data can be seen in Tables 5 and 6.

Once the quantities of each material for the preparation of the standard mortar, the desired weight percentage of nano-silica is added to the dosage relative to the mass of cement. In this way, the quantities to be used in each dosage of the mortar with nano-silica addition at percentages of 0.75%, 1.00%, and 1.25% relative to the mass of cement are obtained, quantities shown in Tables 7 and 8.

Before each mixture is made, the moisture content of the aggregates must be determined using the procedure

Table 7 Nano-silica Quantities of materials for mortar with fine San Antonio aggregate and nano-silica addition for specimen preparation

MATERIAL	WEIGHT QUANTITIES OF MATERIALS		
	NANO-SILICA 0.75%	NANO-SILICA 1.00%	NANO-SILICA 1.25%
Absorption capacity (%)	3.950	3.950	3.950
Moisture content (%)	2.620	2.040	5.240
Cement (Kg)	7.890	7.890	7.890
Water (lt)	5.180	5.300	4.610
Sand (Kg)	21.400	21.270	21.970
Nano-silica (Kg)	0.059	0.079	0.099

Table 8 Quantities of materials for mortar with fine Pifo aggregate and nano-silica addition for specimen preparation. nano-silica

MATERIAL	WEIGHT QUANTITIES OF MATERIALS		
	NANO-SILICA 0.75%	NANO-SILICA 1.00%	NANO-SILICA 1.25%
Absorption capacity (%)	1.950	1.950	1.950
Moisture content (%)	3.380	4.290	3.380
Cement (Kg)	7.890	7.890	7.890
Water (lt)	4.740	4.540	4.740
Sand (Kg)	22.000	22.190	22.000
Nano-silica (Kg)	0.059	0.079	0.099

described in (INEN 2011b) to make corrections for moisture in the dosage. Additionally, the quantity of component materials to be used in mortar production is weighed along with the percentage of nano-silica to be added. The addition of nano-silica is done in a high-speed mixer (ultrasonic machine) at 8000 revolutions per minute for a duration of 25 minutes, using a portion of the mixing water. Next, the mixing equipment, such as the mixer drum, is moistened to prevent the mixing water from being consumed. Subsequently, the fine aggregate is placed in the mixer along with a portion of the mixing water and mixed for approximately one minute. Then, the cement is added to the mixer and mixed together for about thirty seconds. Afterward, the nano-silica is added to the mixer according to its specified percentage and mixed for another two minutes. Then, the remaining mixing water is added to the mixer, and all materials are mixed until achieving the final mixture, which takes approximately 5 minutes. Finally, mortar test specimens were made according to the tests to be performed on the mortar, both in the fresh and hardened state. The number of replicates or specimens used for each test mention in Appendix 1.

2.2 Curing conditions

Curing conditions for fresh mortar generally involve maintaining a constant temperature of approximately 23°C and a relative humidity of 50% during the initial setting period. For hardened mortar, samples are stored at a temperature of 23 ± 2°C and a relative humidity of at least 50% for periods of 4, 7, 14 and 28 days. Controlling temperature and humidity is essential to ensure reliable and comparable results. The determination of tests for fresh state mortar was carried out after completing the mixture, thus conducting the flow test according to (INEN). Tests were conducted on the hardened state mortar specimens to measure the most important mechanical properties. The tests performed included compressive strength test, mortar shrinkage test, indirect tensile strength test, and permeability test.

3. Results and discussions

For the fresh state mortar, flow tests were conducted, while for the hardened state, the increase in strengths at 1, 3, 7, and 28 days of age was analyzed, in addition to

Table 9 Summary table of compressive strengths of Pifo aggregate mortar cubes with nano-silica addition at 1, 3, 7, and 28 days of setting

Simple Compressive Strength (MPa)				
DAYS	1	3	7	28
0.00%	2.24	8.32	14.51	20.60
0.75%	4.10	11.78	16.92	25.63
1.00%	3.16	11.07	14.62	25.30
1.25%	3.34	10.29	16.04	24.31

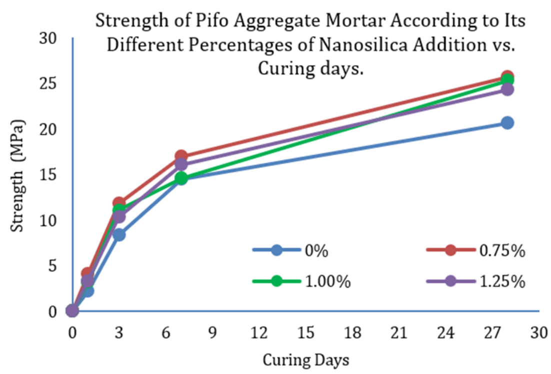


Fig. 1 Diagram of simple compressive strengths of Pifo fine aggregate mortar cubes with nano-silica addition vs. curing days

indirect tensile strength tests to directly relate it to adhesion, setting shrinkage tests to evaluate volume changes, and permeability tests. These results were represented using graphs that allowed determining the variation in properties between conventional mortar and the addition of nano-silica, establishing that the addition of nano-silica improves properties in the hardened state, such as compression, tensile strength, setting shrinkage, and permeability.

In the mortar made with fine aggregate Pifo, it was observed that the addition of nano-silica in percentages of 0.75%, 1.00%, and 1.25% contributes to an increase in compressive strength. When compared to the sample without the addition of nano-silica, the compressive strength increased from the first day of setting up to 28 days of setting. For this mortar, the ideal addition of nano-silica was 0.75% as it exhibited the highest compressive strengths

Table 10 Summary table of simple compressive strengths of San Antonio aggregate mortar cubes with nano-silica addition at 1, 3, 7, and 28 days of setting

Simple Compressive Strength (MPa)				
DAYS	**1**	**3**	**7**	**28**
0.00%	2.09	6.95	10.67	20.02
0.75%	3.37	7.70	16.91	21.59
1.00%	2.91	9.64	12.70	20.15
1.25%	3.96	8.92	12.84	19.25

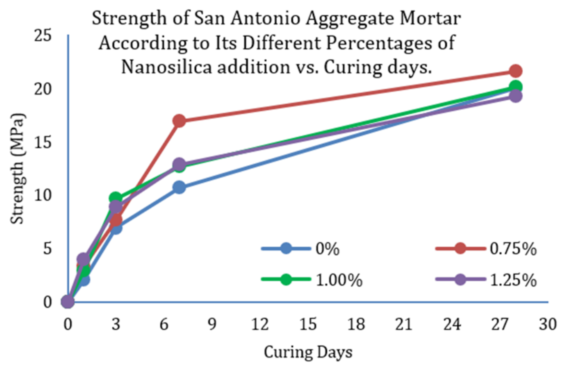


Fig. 2 Diagram of simple compressive strengths of San Antonio fine aggregate mortar cubes with nano-silica addition vs. curing days

at 1, 3, 7, and 28 days.

Similarly, to the mortar made with fine aggregate Pifo, in the mortar made with fine aggregate San Antonio, the addition of nano-silica in percentages of 0.75%, 1.00%, and 1.25% increases the compressive strength compared to the sample without the addition of nano-silica. For this mortar, the addition of nano-silica at 0.75% and 1.25% demonstrates the highest compressive strength. For the monitoring days of 1 and 3, the samples with 0.75% addition exhibit the highest compressive strengths, while for the monitoring days of 7 and 28, the samples with a 1.25% addition have the highest compressive strength.

In the case of samples made with the industrial mortar Enlumax 80, the compressive strength increased according to each monitoring date. For this case, at 1, 3, 7, and 28 days after setting, however, the obtained strengths were significantly lower compared to traditional mortars, also known as mortars without the addition of nano-silica, and lower than mortars made with the addition of nano-silica, whether it be with fine aggregate Pifo or San Antonio.

In the preparation of this mortar with fine Pifo aggregate and the addition of manually mixed nano-silica at percentages of 0.75%, 1.00%, and 1.25%, an increase in compressive strength was obtained. In this case, two control points were considered: at 7 days and 28 days, where the highest strength was achieved in the sample prepared with a 1.25% nano-silica addition and manual mixing at the 28-day control point.

In the mortar made with fine San Antonio aggregate and the addition of manually mixed nano-silica at percentages of 0.75%, 1.00%, and 1.25%, an increase in compressive

Table 11 Summary table of simple compressive strengths of Enlumax industrial mortar cubes at 1, 3, 7, and 28 days of setting

DAYS	STREGHT (MPa)
1	0.83
3	3.30
7	4.14
28	5.82

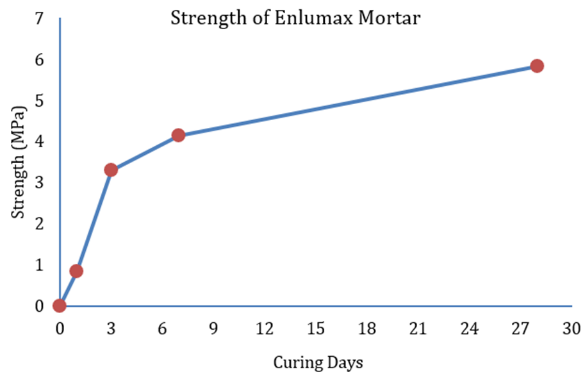


Fig. 3 Diagram of simple compressive strengths of Enlumax industrial mortar cubes vs. setting curing days

strength was observed compared to a mortar without nano-silica addition. For this mixture, two control points were considered: at 7 days and 28 days, where the highest

Table 12 Summary table of compressive strengths of Pifo fine aggregate mortar cubes with manual addition of nano-silica at 7 and 28 days of curing

Simple Compressive Strength (MPa)		
DAYS	**7**	**28**
0.00%	14.51	20.60
0.75%	12.04	22.04
1.00%	14.13	23.49
1.25%	14.43	25.57

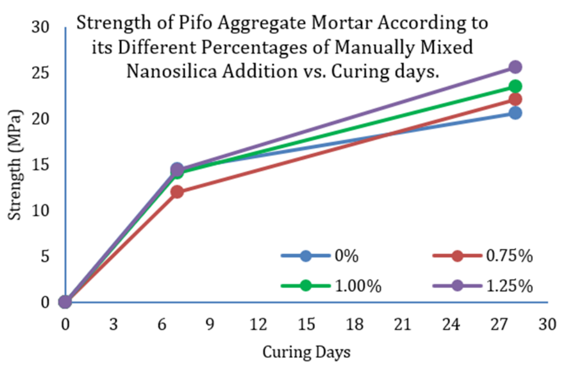


Fig. 4 Diagram of compressive strengths of Pifo fine aggregate mortar cubes with manual addition of nano-silica vs. curing days

Table 13 Summary table of compressive strengths of San Antonio fine aggregate mortar cubes with manual addition of nano-silica at 7 and 28 days of curing

Simple Compressive Strength (MPa)		
DAYS	**7**	**28**
0.00%	10.67	20.02
0.75%	11.39	20.26
1.00%	13.64	19.08
1.25%	11.76	21.28

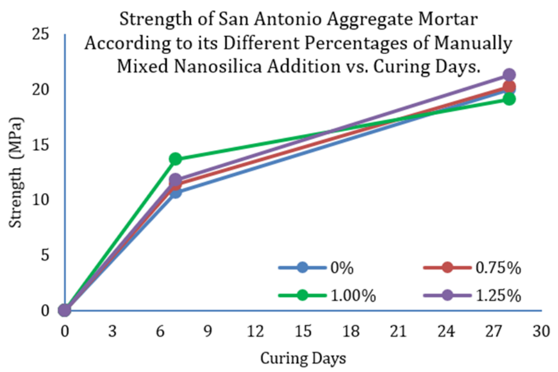


Fig. 5 Diagram of compressive strengths of San Antonio fine aggregate mortar cubes with manual addition of nano-silica vs. curing days

Table 14 Summary table of indirect tensile strengths in Pifo fine aggregate mortar cylinders with addition of nano-silica at 28 days of curing

Percentage of nano-silica (%)	**Indirect tensile strength (MPa)**
0.00	3.02
0.75	2.11
1.00	2.90
1.25	3.08

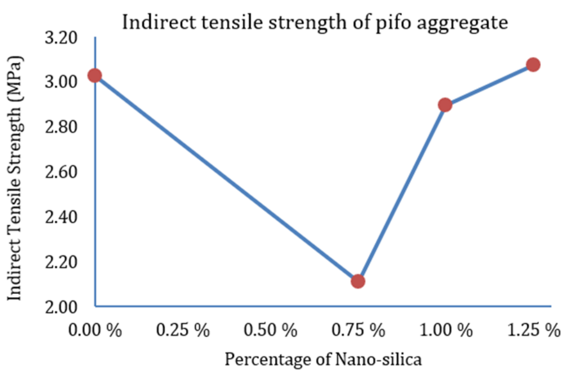


Fig. 6 Indirect tensile strength diagram of Pifo fine aggregate mortar cylinders using 0.00%, 0.75%, 1.00%, and 1.25% nano-silica addition

strength was observed in the sample prepared with a 1.25% nano-silica addition and manual mixing at the 28-day control point.

0.75% nano silica in concrete may not sufficiently improve strength due to limited interaction with the matrix, potentially causing water reduction and reduced workability. Increasing to 1% nano silica significantly enhanced the concrete strength by forming more calcium silicate hydrate gel, offering pronounced benefits. Raising the dosage to 1.25% increase strength, but excessive nano silica could negatively affect workability and other properties, with diminishing returns.

In the mortar made with fine Pifo aggregate, both without nano-silica addition and with nano-silica additions of 0.75%, 1.00%, and 1.25%, indirect tensile strength values were obtained. The specimens made with 0.75% and 1.00% nano-silica additions show lower strengths compared to the specimens made without nano-silica addition. However, the mixture with a 1.25% nano-silica addition exhibits a higher strength value compared to the sample without addition. The sample with the highest indirect tensile strength value is the one with a 1.25% nano-silica addition.

In the mortar made with fine San Antonio aggregate, both without nano-silica addition and with nano-silica additions of 0.75%, 1.00%, and 1.25%, indirect tensile strength values were obtained. The values show an increase with the addition of nano-silica at 0.75% and 1.00%. However, the value of indirect tensile strength significantly decreases when the nano-silica addition percentage is 1.25%. The sample with the highest indirect tensile strength

Table 15 Summary table of indirect tensile strengths in San Antonio fine aggregate mortar cylinders with addition of nano-silica at 28 days of curing

Percentage of nano-silica (%)	**Indirect tensile strength (MPa)**
0.00	2.26
0.75	2.31
1.00	2.30
1.25	1.85

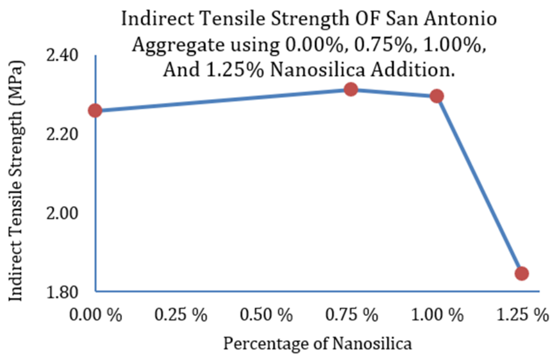


Fig. 7 Indirect tensile strength diagram of San Antonio fine aggregate mortar cylinders with addition of nano-silica

Table 16 Summary table of indirect tensile strengths in Enlumax industrial mortar cylinders at 28 days of curing

Indirect tensile test on cylindrical specimens (l = 200 mm, d = 100 mm)						
Sample	**Diameter (mm)**	**Diameter (mm)**	**Length (mm)**	**Length (mm)**	**Load (N)**	**Stress (MPa)**
	101		200			
1	103	101.33	200	201.67	30100	0.94
	100		205			
	102		200			
2	103	103.33	208	202.67	29400	0.92
	105		200			
	101		203			
3	107	103.33	206	204	28300	0.88
	102		203			
Average stress (mpa)						**0.91**

Table 17 Summary of length change tests in San Antonio bars with nano-silica

	AGE	**San Antonio without addition**	**San Antonio 0.75%**	**San Antonio 1.00%**	**San Antonio 1.25%**
	Days	**ΔLx %**	**ΔLx %**	**ΔLx %**	**ΔLx %**
Initial reading	**1**	0.000	0.000	0.000	0.000
Reading	**4**	-0.170	-0.160	-0.156	-0.151
Reading	**7**	-0.319	-0.334	-0.329	-0.322
Reading	**14**	-0.559	-0.563	-0.555	-0.573
Reading	**28**	-0.609	-0.707	-0.681	-0.677

value is the one with a 0.75% nano-silica addition. In the specimens made with Enlumax 80 industrial mortar, a value of 0.91 MPa was obtained for indirect tensile strength, which is lower than the mortars made with fine Pifo and San Antonio aggregates, both without addition and with 0.75%, 1.00%, and 1.25% nano-silica additions.

The shrinkage test values show a reduction in shrinkage in the first 4 days for each percentage of nano-silica addition. The maximum value is observed in the bar without nano-silica addition, with a percentage value of 0.17%, demonstrating that the addition of nano-silica allows for a reduction in initial shrinkage of 0.01%. At 7 days, the samples show similar values, as well as at 14 days. The variation of the samples compared to the sample without nano-silica is minimal. However, at 28 days, a maximum variation of 0.07% is observed. Additionally, we can observe that the percentage of nano-silica that exhibits the lowest maximum deformation at 28 days is 1%.

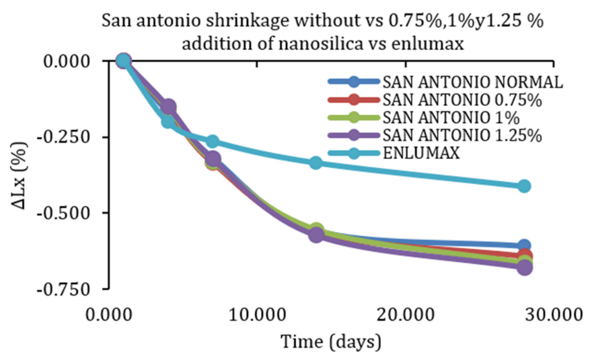


Fig. 8 Deformation vs Time Chart of Mortar Bars Manufactured with San Antonio Fine Aggregate with the Addition of Nano-silica vs Enlumax

Additionally, we can observe that the curve corresponding to the prefabricated Enlumax mortar exhibits higher deformation at 4 days compared to the samples with nano-silica addition. However, it stabilizes from 14 days onwards, resulting in significantly lower deformation compared to the samples with nano-silica addition.

The shrinkage test values show a reduction in shrinkage in the first 4 days for each percentage of nano-silica addition. The maximum value is observed in the bar without nano-silica addition, with a percentage value of -0.172%. The maximum value for the samples with nano-silica addition is -0.159%, corresponding to the sample with the lowest addition. This demonstrates that the addition of nano-silica allows for a reduction in initial shrinkage of 0.011%.

At 7 days, the samples show somewhat similar values, as well as at 14 days, with the maximum deformation value observed in the sample with 1.25% nano-silica addition. The variation of the samples compared to the sample without nano-silica is minimal. However, at 28 days, a maximum variation of 0.105% is observed in the sample

Table 18 Summary of length change tests in Pifo bars with nano-silica

	AGE	Pifo	Pifo 0.75%	Pifo 1.00%	Pifo 1.25%
	Days	**ΔLx %**	**ΔLx %**	**ΔLx %**	**ΔLx %**
Initial reading	**1**	0	0	0	0
Reading	**4**	-0.172	-0.159	-0.147	-0.151
Reading	**7**	-0.273	-0.288	-0.265	-0.274
Reading	**14**	-0.435	-0.439	-0.436	-0.45
Reading	**28**	-0.462	-0.502	-0.544	-0.567

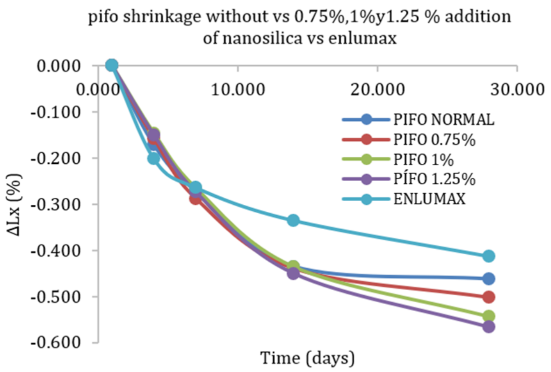


Fig. 9 Deformation vs Time Chart of Mortar Bars Manufactured with Pifo Fine Aggregate with the Addition of Nano-silica vs Enlumax

with 1.25% addition. Additionally, we can observe that the percentage of nano-silica that exhibits the lowest maximum deformation at 28 days is 0.75%.

It can be observed that the slope for the three percentages of nano-silica addition, as well as the normal sample, remains constant until 14 days, where a variation in the slope occurs for each percentage, showing a continuous increase in deformation over time. We can also observe that the curve corresponding to the prefabricated Enlumax mortar exhibits higher deformation at 4 days compared to the samples with nano-silica addition. However, it stabilizes from 14 days onwards, resulting in significantly lower deformation compared to the samples with nano-silica addition.

It was determined that the maximum penetration value was achieved by the traditionally made cylinders without the incorporation of nano-silica, with a value of 190 mm. On the other hand, the addition of nano-silica that showed the lowest penetration for the mortar made with fine San Antonio aggregate was the 1% addition, with a value of 179.3 mm, demonstrating a permeability reduction of 5.63% compared to the mortar without addition. Regarding the mortar made with fine Pifo aggregate, it was found that the maximum penetration value was reached by the cylinders made without the incorporation of nano-silica, with a value of 197.3 mm. The addition of nano-silica that showed the lowest penetration for the mortar made with fine Pifo aggregate was the 1% addition, with a value of 183.3 mm, demonstrating a permeability reduction of 7% compared to the mortar without addition. The maximum penetration value for the prefabricated mortar was

Table 19 Summary table of water penetration tests under pressure in mortar cylinders manufactured with San Antonio and Pifo aggregates with the addition of nano-silica

TYPE	Penetration
	(mm)
ENLUMAX	9.17
SAN ANTONIO without addition	19.00
SAN ANTONIO 0.75%	18.60
SAN ANTONIO 1.00%	17.93
SAN ANTONIO 1.25%	18.34
PIFO without addition	19.73
PIFO 0.75%	19.00
PIFO 1.00%	18.33
PIFO 1.25%	18.70

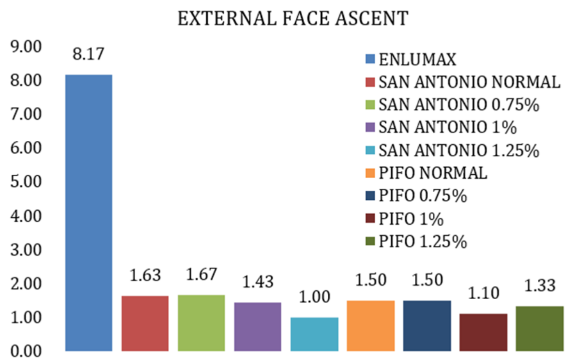


Fig. 10 Water Absorption Bar Chart in Mortar Cylinders Manufactured with San Antonio and Pifo Aggregates with the Addition of Nano-silica and Prefabricated Enlumax Mortar

determined to be 9.17 mm, demonstrating a higher waterproofing capacity compared to the traditional mortar and mortars with nano-silica additions for both aggregates.

It was found that the maximum external water uptake value corresponds to the prefabricated mortar samples, while both traditional mortars and mortars with nano-silica additions for both types of aggregates show lower values. In the case of San Antonio, the maximum value of external water uptake is 16.7 mm, while for Pifo, the maximum value was 15 mm. This indicates that the internal morphology

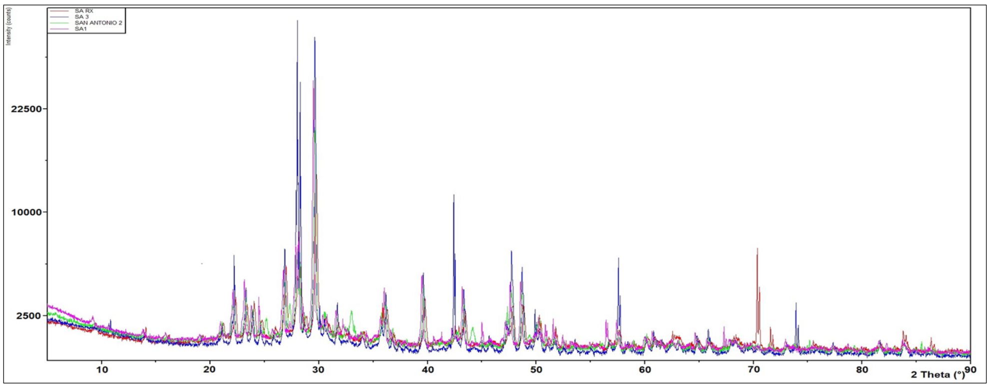


Fig. 11 X-ray diffraction spectrum of mortars manufactured with San Antonio Aggregate without the addition of nanosil

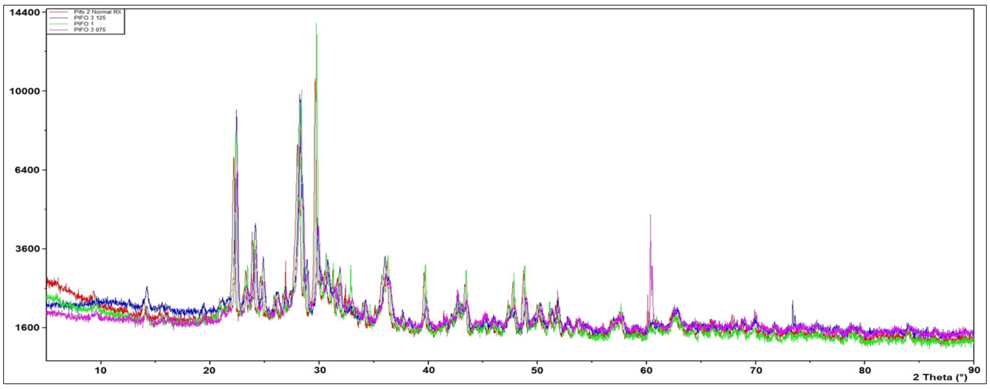


Fig. 12 X-ray diffraction spectrum of mortars manufactured with Pifo aggregate without the addition of nano-silica and with the addition of 0.75%, 1%, and 1.25%

of the traditional mortars provides better particle confinement, preventing water from seeping to the exterior.

X-ray Diffraction (XRD) Test

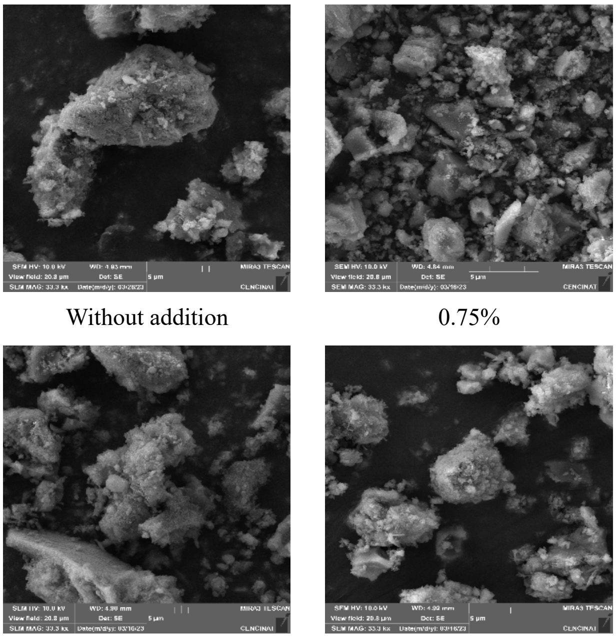
X-ray diffraction allows us to determine the homogeneity of a mixture, primarily applied in quality control. XRD takes advantage of X-rays to determine the crystal structure and atomic arrangement in a material. The scattering of X-rays through the sample generates a diffraction pattern that contains information about its structure. The angles and intensities of the diffracted X-rays reveal details about the crystal structure, lattice parameters and atomic positions. XRD is used to analyze the crystalline structure, phase composition and modifications in mortars and concretes that incorporate nanomaterials. The test was conducted to determine the chemical composition of the mortar and the reaction of the cement with the additive. The crystal structure of the samples was studied using X-ray diffraction (XRD) on the PANalytical Empyrean X-ray Diffractometer with a Bragg-Brentano configuration. The X-ray tube operated at 45kV and 40 mA, and copper was used as the X-ray source.

The diffraction pattern shown in the mortars manufactured with both aggregates displays a typical distribution of cement components, with the different mixtures made with varying percentages of nano-silica addition (0.75%, 1%, and 1.25%) overlaid. It can be observed that the variation in peak positions compared to the standard sample is minimal and below the detection limits. This could be attributed to the fact that the considered addition percentages are relatively low to be detected, as the detectable ranges typically fall between 3% and 5%.

Scanning Electron Microscopy (SEM) Test

The morphology and semi-quantitative elemental composition were evaluated using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). This instrument uses a focused electron beam to capture detailed images of the surface of a sample. The electron beam scans the sample and records the signals resulting from interactions with its surface. It is used to examine cement mortar and concrete that incorporate nanomaterials and provides data about the microstructure, morphology and composition of the material.

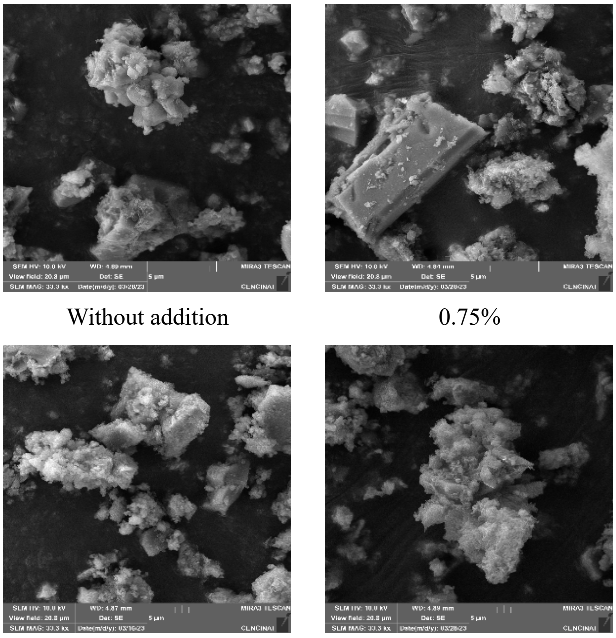
For this purpose, a section of the sample was fixed onto an aluminum sample holder using a double layer of carbon tape. These analyses were carried out using the Tescan Mira 3 SEM equipped with a Schottky field emitter. EDS was performed in the SEM chamber using a Bruker X-Flash 6|30 detector with a resolution of 123 eV at Mn Kα. This test is analyzed through images and chemical microanalysis to determine the composition of the mortar sample with the addition of nano-silica compared to the conventional mortar made with two types of aggregate, evaluated at 28 days of age. For the execution of the test, cubic samples similar to



Without addition 0.75%

1.00% 1.25%

Fig. 13 SEM Test of mortars manufactured with San Antonio aggregate without the addition of nano-silica and with the addition of 0.75%, 1.00%, and 1.25%



Without addition 0.75%

1.00% 1.25%

Fig. 14 SEM Test of mortars manufactured with San Antonio aggregate without nano-silica addition and with addition of 0.75%, 1.00%, and 1.25%

those used in compressive strength tests were used, from which a very small amount was extracted for the execution of the aforementioned tests. The composition of the mortar samples for each percentage of nano-silica addition can be observed. However, it was not possible to carry out an exact characterization for both mortars, so each one exhibits a similar particle distribution.

4. Conclusions

Comparing the mortar made with fine aggregate Pifo and fine aggregate San Antonio with the addition of nano-silica at 0.75%, 1.00%, and 1.25%, the highest compressive strength results were obtained with fine aggregate Pifo, with compression strength values of 25.63 MPa at 0.75% addition, 25.30 MPa at 1.00% addition, and 24.31 MPa at 1.25% addition. This demonstrates that a stronger mortar was achieved with this aggregate in terms of compressive strength. The lowest compressive strength was obtained with the mortar made with Enlumax 80, with a value of 5.82 MPa.

In the case of mortars manufactured with fine aggregate Pifo, the tensile strength increases as the addition of nano-silica increases. However, in the mortar with fine aggregate San Antonio, the compressive strength decreases when the addition of nano-silica is 1.25%.

Based on the obtained values of indirect tensile strength, it was observed that the samples of Pifo fine aggregate mixes containing a higher amount of nano-silica exhibited greater particle adhesion, resulting in higher values of indirect tensile strength, as mentioned earlier. For specimens made with San Antonio fine aggregate, good particle adhesion was observed when 0.75% and 1.00% of nano-silica were added. However, this changes significantly when 1.25% of nano-silica is added, indicating that for the San Antonio fine aggregate, an increase in nano-silica content, as well as the presence of slightly coarse particles in the aggregate, result in a somewhat dry mix with voids, leading to a reduction in particle adhesion.

The manufacturing of render mortars with the addition of nano-silica is economically viable in this research case, as it involves relatively low addition percentages of 0.75%, 1.00%, and 1.25%, which are accessible in terms of cost. However, increasing the percentage of nano-silica addition would lead to an increase in the manufacturing cost of the mortar, making it economically unfeasible. The mechanical properties of mortars with the addition of nano-silica manufactured with aggregates from both Pifo and San Antonio indicate that the use of nano-silica in percentages greater than 0.75% and less than 1% are viable proposals as they exhibit superior performance compared to conventional mortars.

Although the permeability test shows that prefabricated mortars demonstrate better permeability capacity, it should be taken into consideration that they do not exhibit higher confinement compared to traditional mortars with the addition of nano-silica. Prefabricated mortars allow the uniform upward movement of water in larger quantities compared to traditional mortars, to the extent that they become completely saturated, even with surface films of water. In contrast, conventional mortars with nano-silica show minimal internal moisture and upward movement of water, without the presence of surface water films. Additionally, the external walls of conventional mortars with nano-silica exhibit minimal upward movement of water compared to prefabricated mortars.

Regarding SEM and EDS analyses, it was observed that the content of Ca and Si in the San Antonio samples is high and very similar for both elements, unlike the Pifo samples where the Si content is higher than Ca. However, in both types of samples, the content of Si and Ca is higher than other elements such as Al, Fe, O, Mg, K, and there is also a presence, albeit in smaller proportions, of Ni. Of course, the intensity or height of the peaks in the EDS peak diagram will depend on the proportions used in each case of nano-silica, meaning that the area and height of the peaks vary due to the proportions of SiO_2 used, ranging from 0.75%, 1%, and 1.5%. However, what can be concluded initially is the general behavior of the samples.

In the SEM images, it is evident that in the mortar mixtures with SiO_2 in various proportions, small particles of 0.1 microns or larger are adhered to the surface of other lamellar materials. This phenomenon is due to the presence of silica nanoparticles, which are not visible in the mortar samples without these particles. This observation holds true for both the Pifo and San Antonio mortars.The true effect of the presence of nano-silica in the mixtures is observed in mechanical and physical tests such as density, compaction, and even in surface tests such as hydrophobicity or hydrophilicity. In the diffraction spectra, a significant variation of the peaks representing the typical composition of a traditional mortar was not observed, unlike the mortar with additions of nano-silica for both aggregates. This could be mainly attributed to the low concentration of nano-silica in relation to the total mass of the mortar. Additionally, the additions made are below the detection limit of the equipment, and several factors, primarily a low homogeneity of the mixture, may contribute to this.

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Appendix 1: Number of replicates or specimens used for each test

Added Pifo

1. At 1 day of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
2. After 3 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
3. At 7 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
4. At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

Added San Antonio:

1. At 1 day of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
2. After 3 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
3. At 7 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
4. At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

Manually mixed Pifo aggregate

1. At 1 day of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
2. After 3 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
3. At 7 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
4. At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

Added San Antonio manual mixing:

1. At 1 day of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
2. After 3 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
3. At 7 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
4. At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

Enlumax:

1. At 1 day of setting: with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 9 samples.
2. After 3 days of setting: with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 9 samples.
3. At 7 days of setting: with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 9 samples.
4. At 28 days of setting: with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 9 samples.

The number of tests for indirect traction are as follows:

Added Pifo:

- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- Added San Antonio:
- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

The number of tests for length change are as follows:

Added Pifo:

- At 1 day of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 4 days of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 7 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 14 days of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

Added San Antonio:

- At 1 day of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 4 days of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 7 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 14 days of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

Enlumax:

- At 1 day of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 4 days of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 7 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 14 days of setting: without addition of nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

The number of penetration tests are as follows:

Added Pifo:

- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- Added San Antonio:
- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- Enlumax:
- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

The number of tests for XRD are as follows:

Added Pifo:

- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- Added San Antonio:

- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.

The number of tests for SEM are as follows:

Added Pifo:

- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.
- Added San Antonio:
- At 28 days of setting: without adding nanosilica 3 samples, with 0.75% 3 samples, 1% nanosilica 3 samples and 1.25% 3 tests, in total there are 12 samples.