Analysis of the physical-mechanical performance of the concrete partially substituting the cement by nanosilica and the coarse aggregate by rock wool

Análisis del desempeño físico-mecánico del concreto sustituyendo parcialmente el cemento por nanosílice y el agregado grueso por lana de roca

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ABSTRACT

The excessive production of concrete has led to the overexploitation of natural resources, prompting the exploration of high-strength alternative materials like nanosilica (NS) as a superplasticizer substituting cement and rock wool (LR) used in bulk as a partial substitute for coarse aggregate. In this experimental study, both materials are proposed to be incorporated into concrete production with varying percentages: 0.6%, 0.8%, 1.0%, and 1.4% of NS by weight, and 2%, 4%, 6%, and 8% of LR by volume. The objective is to evaluate their physical and mechanical performance, including settlement properties, air content, and mechanical strength. The results indicated a significant increase in settlement with NS, reaching up to 8". Air content decreased to 0.7% with 0.8NS but increased with LR. Additionally, at 28 days, compression resistance increased by 37.19% and 30.53% for C-1 and C-2, respectively, with 1.4%NS compared to the control model. Furthermore, with 1.4%NS+6%LR, it increased by 21.85%. In traction, samples with 1.4%NS increased by 24.10%, and those with more than 6%LR increased by 16.57%. Furthermore, flexion increased by 18.84% for 1.4%NS and 26.68% for 1.4NS+8LR. The study concludes that the optimal addition is 1.4% NS and 6% LR, significantly enhancing the mechanical resistance of concrete compared to control designs.

Keywords: Concrete, physical and mechanical performance, rock wool, nanosilica.

RESUMEN

La producción excesiva de hormigón ha provocado la sobreexplotación de los recursos naturales, lo que ha impulsado la exploración de materiales alternativos de alta resistencia como la nanosílice (NS) como superplastificante en sustitución del cemento y la lana de roca (LR) utilizada a granel como sustituto parcial del árido grueso. En este estudio experimental se propone incorporar ambos materiales a la producción de concreto en porcentajes variables: 0,6%, 0,8%, 1,0% y 1,4% de NS en peso, y 2%,

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4%, 6% y 8% de LR por volumen. El objetivo es evaluar su desempeño físico y mecánico, incluyendo propiedades de asentamiento, contenido de aire y resistencia mecánica. Los resultados indicaron un aumento significativo en el asentamiento con NS, alcanzando hasta 8". El contenido de aire disminuyó a 0,7% con 0,8NS pero aumentó con LR. Además, a los 28 días, la resistencia a la compresión aumentó un 37,19% y un 30,53% para C-1. y C-2, respectivamente, con 1,4%NS respecto al modelo control, además con 1,4%NS+6%LR aumentó un 21,85%. En tracción, las muestras con 1,4%NS aumentaron un 24,10%, y aquellas con más del 6%LR aumentó un 16,57%, así mismo en flexión aumentó un 18,84% para el 1,4%NS y un 26,68% con 1,4NS+8LR, el estudio concluye que la adición óptima es 1,4% NS y 6% LR, significativamente mejorando la resistencia mecánica del hormigón en comparación con los diseños de control.

Palabras clave: Concreto, desempeño físico y mecánico, lana de roca, nanosílice.

INTRODUCTION

The extensive concrete production in the construction industry has significantly impacted the components used in its manufacture. For this reason, new alternative materials, such as nanosilica (NS), are being introduced, which has sparked great interest in producing lightweight, foamed, and low-density concrete. On the one hand, this is due to the ability of nanosilica to improve the performance of concrete, acting as a pozzolanic compound that increases its mechanical resistance thanks to its particle size. [1]. On the other hand, studies on the application of rock wool (RW) in the construction industry seek an effect that contributes significantly to both environmental performance and climate change; this is achieved by reusing the RW, which in this case is replaced by recycled wool, in addition to reducing waste that ends up in landfills, in the construction of diverse structures, the incorporation of rock wool is noted for its high water absorption and insulation properties. This inclusion not only alleviates the impacts of climate change but also facilitates water conservation, with potential savings of up to 7.8% and a reduction in raw material resources by 23.6%. However, changes in the specified composition are anticipated to have a more pronounced impact on decreasing gas emissions than on water consumption [2].

Within this framework, [3] argues that NS is an additive classified as a nano-reinforcing composite with particles smaller than those of silica fume so that its application in concrete shows an increase in its mechanical strength; based on those as mentioned earlier, it is considered relevant to determine the influence generated by NS concerning the structural performance of concrete with low densities ranging from 850 kg/m^3, because its nanometer-sized particles allow accelerating the hydration of cement due to its high chemical reactivity, being this the main factor that allows increasing the performance of cement-based composites as opposed to conventional concrete [4].

Furthermore, [5] developed different approaches depending on the performance of concrete, such as thermal insulation, acoustic insulation, or low density; in that sense, he came to determine that polymers that provide the mentioned characteristics cause a considerable reduction in concrete strength due to its porosity, being NS a nanomaterial that can be used not only for filling interfaces or cracks but also allows crystallization in cement hydration processes improving the microstructure and mechanical properties of low-density concrete. Additionally, [6] states that the use of NS estimates better physical and mechanical characteristics in concrete and is more efficient than silica fume. Based on this, it is recommended that its percentage application does not exceed 5% of the weight of cement and that optimal properties are obtained. However, the study also identified that workability and flowability are affected and significantly reduced.

Asian countries have been involved with energy problems in the construction industry, and this was what led them to adapt the technology in the development of ecological blocks and improve indoor comfort, where they chose to assess alternative solutions to avoid such problems as foam concrete insulation, structural insulation panels, vacuum, fiberglass, and LR to improve environmental sustainability in the building [7]. Similarly, [8] evaluated experimentally and theoretically the influence of LR and drainage layers in a concrete

slab by using insulating materials in the wet area to reduce energy consumption. In that sense, it determined that the incorporation of LR directly in buildings as vacuum insulation panels is viable. It is worth highlighting from the general perspective based on the use of LR as a material related to the energy problem; in this sense, [9] emphasizes the concern about the housing deficit regarding energy efficiency; therefore, proposes the development of a mortar for coating with thermal insulation properties, adhesion and mechanical strength compatible using expanded polystyrene waste (EPS) and waste thermal insulation boards such as rock wool, glass wool and expanded vermiculite. In the same line of research, [10] affirm that these materials contribute effectively to the optimization of the thermal behavior in houses that use a process of execution with precast concrete walls, being considered as the most suitable when using the LR residue as the best alternative, since, being a mineral fiber, it allows increasing the tensile strength of the composite as well as the adhesion strength of the coating.

On the one hand, [11] evaluated the mechanical performance of concrete incorporating NS to minimize the cement content in the mixes; the results showed increases of up to 26.53% with 1.5% NS and a w/c ratio of 0.65 at 28 days in addition, with 1% NS and 0.55 w/c ratio, there was an increase of 18.53% concerning the control value. On the other hand, [12] applied NS, where the results showed a positive effect on the mechanical properties; however, the workability was considerably reduced, and its viscosity increased in such a way that the strengths at 28 days of curing increased with an optimum dosage of 1% NS reaching increases of 31% regarding the control sample in the same way, for bending, increases of 28% were observed at 90 days, leading to the conclusion that this additive effectively fills a substantial portion of the voids created by existing porosity. In an alternative assessment, up to 18% compression increases were recorded with 1% nanosilica (NS) for a strength level of 210 kg/cm^2. However, for a higher strength level of 280 kg/cm^2, a more significant increase of 34% was achieved with 1.4% NS, and these effects were observed at the 28-day mark [13]. In the same way, [14] evaluated the concrete at 28 days based on dosages higher and equal to 1%NS, determining significant increases with additions of 3%NS with a maximum of 22.12% as opposed to a 5.25% increase with 1%NS, in addition, for bending, an increase of 13.13% was obtained with 3NS and 3.43% with 1%NS regarding the control concrete, in addition, for tension, an increase of 22.22% and 5.07% of improvement was obtained for 3%NS and 1%NS, respectively.

It is worth considering that, [15] in his study determined the effects on the mechanical behavior of concrete incorporating residual LR, where they applied residual LR powder, achieving an increase in compression with 2.5%, 5% and 7.5%, the results exceeded the base concrete, reaching values of 42.9MPa, 45.7MPa and 43.1MPa respectively, estimating an optimum percentage of 5% of LR with an increase of 9.07% concerning the standard value. In addition, [16] analyzed the behavior of thermal insulators derived from industrial waste as LR in fiber by additions of 10% and 20% LR as partial replacement of fine aggregate, the results obtained show that the application of industrial waste is feasible for a reduction of thermal conductivity and shrinkage, however, the compressive strength was reduced by 9. 23% and 12.98% for 10% and 20% LR, respectively, however, in flexure they demonstrated non-significant increases of 6.4% for 10%LR and 16% for 20%LR concerning the control specimen with a value of 5.3MPa.

[17] after their experimental evaluation incorporating LR concerning different w/c ratios, they obtained considerable reductions in mechanical performance in such a way that, in compression, they estimated reductions that exceeded 100% with percentages higher than 5%LR and 0.4 w/c ratio; in addition, for tension, it deteriorates as the addition of LR increases, likewise for bending, however, it is defined that 2.5%LR and 5%LR obtain the lowest reduction in resistance concerning the control samples. As a consequence of those as mentioned
earlier, [8] sustains in his experimental and
theoretical evaluation that the influence of LR and drainage layers in a concrete slab through the use of insulating materials in the wet area to minimize the excessive energy consumption in that sense, [9] determined as feasible the incorporation of LR and drainage layers in a concrete slab through the use of insulating materials in the wet area to minimize the excessive energy consumption, determined as viable the incorporation of LR directly in buildings as vacuum insulation panels [18], [19].

The present investigation conducts extensive experimentation on concrete performance with the overall objective of assessing concrete's physical and mechanical properties using NS and LR as partial substitutes for cement and refractory aggregate content, respectively. Experimental results of slump and air content, as well as compressive, tensile and flexural strengths, are compared with results obtained from available literature. In addition, the results obtained were detailed from tests carried out at 7, 14, and 28 days. Finally, the optimum addition percentages of both alternative materials are determined.

MATERIALS AND METHODOLOGY

Materials

The present experimental research used alternative synthetic and natural materials such as NS additive and LR, the latter being a product of the treatment of basaltic rock of volcanic origin. Concrete is a mixture of water, cement, coarse and fine aggregates, and additives. This research evaluates the incorporation of NS and LR in concrete.

Cement

Type I Portland Cement was used in this research due to its ability to achieve high initial strengths. This type of cement is composed of finely ground inorganic materials that, together with the aggregates, enable a homogeneous mixture of the concrete, achieving rapid setting. In addition, this cement anticipates a reduced time for stripping. For more detailed information, Table 1.

Aggregates

Stone aggregates from the "Pátapo - La Victoria" quarry were used for the sand, and the "Pacherrez-Pucalá" quarry for the coarse aggregate. They were selected after a granulometric analysis of correct gradation, as shown in Figure 1 and Figure 2, complying with the technical specifications according to NTP 400.037. For this purpose, physical tests of the optimum aggregates were carried out, as detailed in Table 1.

Nanosilica

The GAIA NS admixture was used, which is considered a superplasticizer and waterproofing agent. This silica-based compound in liquid state, as shown in Figure 3, was applied in reduced percentages as a substitute for cement content due to its excellent capacity to create high-performance concrete with a very favorable hydrated calcium silicate (CSH) that allows hydration reactivity and creates a strong cohesion between particles. In that sense, the most relevant characteristics of NS are detailed as shown in Table 2. No control tests were carried out on the additive since the supplier provided its technical data sheet.

Rock wool

It is a mineral compound product of basaltic volcanic rocks. It was extracted in a bulk state to undergo a grinding treatment, as shown in Figure 4a, due to its high water absorption capacity that exceeds 1 kg/m^2 in its natural state. After treatment, the ground particles performed better as coarse aggregates in the mixture, as shown in Figure 4b.

Table 1. Physical properties of cement and stone aggregates.

Cement		
Type	Portland Tipo I	
Specific gravity (kg/cm3)	3150	
Location	Lambayeque	
Aggregates		
Tests	**Quarry "La Victoria"**	**Quarry "Pachérrez"**
Fineness modulus and TMN	2.72	3/4"
Unit weight. Dry loose (g/cm^3)	1.624	1.427
Unit weight. Dry compacted (g/cm^3)	1.766	1.548
Specific mass weight (g/cm^3)	2.532	2.227
Percentage of absorption (%)	0.583	4.100
Moisture content (%)	0.30	0.48

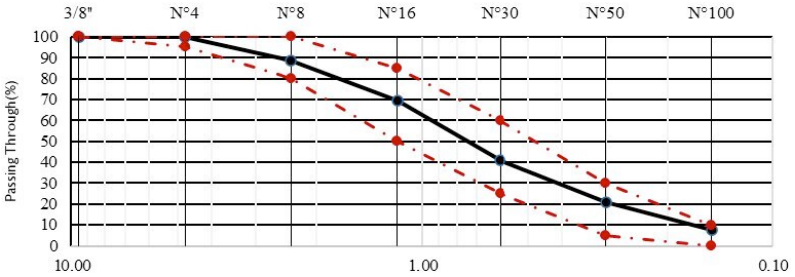


Figure 1. Granulometric analysis of fine aggregate.

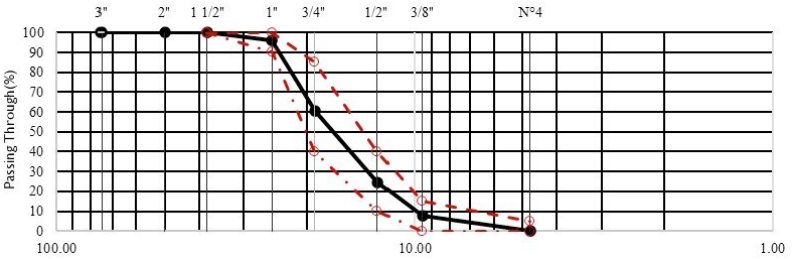


Figure 2. Grain-size analysis of hard aggregate.

Table 2. Properties and Characteristics of GAIA Nanosilica.

Characteristic	Detail
Density	1.03±0.02 g/mL
State	Liquid
Color	Light brown
Type of additive	Superplasticizer
Average resistance in concrete	70 MPa
Properties	High mechanical strength and waterproofing

Figure 3. Nanosilica used in research.

Rock wool comprises 97% dolomite and igneous rocks, which are solidified volcanic magma, specifically basalt and diabase. The remaining 3% of rock wool is composed of binding agents and additives that contribute to providing specific characteristics to the material, depending on its intended use.

METHODOLOGY

Dosages and Mixture Combinations

The mix designs were proposed for strengths f'c = 210 kg/cm^2 (C-1) and 280 kg/cm^2 (C-2). It was carried out according to the procedure described by ACI 211 [20], detailing that designs were made for a CP. Furthermore, NS admixture percentages were incorporated in substitution dosages of 0.6%,

Figure 4. LR grinding treatment; a) bulk LR; b) ground LR.

0.8%, 1%, and 1.4% concerning the weight of cement and LR in percentages of 2%, 4%, 6%, and 8% regarding the volume of coarse aggregate, the identification and description of the dosages are shown in Table 3.

Physical Properties

Settlement and air content tests were carried out through an experimental evaluation, taking as reference the design resistances C-1 and C-2, which were 210 kg/cm^2 and 290 kg/cm^2, respectively. A total of 18 designs were examined, distributed as follows: two for CP21 and CP28, four incorporating nanosilica (NS) in concentrations of 0.6%, 0.8%, 1.0%, and 1.4% for C-1, and four other designs for C-2. Finally, four designs that integrated resin latex (LR) in combination with 1.4NS+2LR, 1.4NS+4LR, 1.4NS+6LR and 1.4NS+8LR for C-1 were evaluated, and four additional designs for C-2.

Slump and Air Content

The slump test is used to evaluate the workability of concrete mixtures, as illustrated in Figure 5a. In this study, the parameters established by the ASTM C143M [21] standard were followed for this test, to determine the consistency of the mixtures in the sixteen experimental designs compared with CP21 and CP28 Designs. Likewise, the air content test was carried out following ASTM C231M [22] to determine the percentage of voids in the concrete in the fresh state. This percentage was obtained using the pressure method, as shown in Figure 5b.

Mechanical Properties

Strength tests were carried out using cylindrical and prismatic concrete samples. These samples were analyzed for nanosilica (NS) and subsequently for nanosilica with resin latex (NS LR) for both C-1 and C-2, compared to CP21 and CP28, covering all 18 mix designs. The results were interpreted and discussed based on a review of the literature mentioned in the study's background. Testing is

Table 3. Design of concrete mixes according to strength.

Design	Ratio A/C	Cement (Kg/m3)	Water (Lts)	Sand (Kg/m3)	Stone (Kg/m3)	NS (gr)	LR (gr)
CP21	0.724	364	264	736	964	–	–
CP28	0.607	438	266	748	894	–	–
0.6NS21	0.724	364	264	736	964	218.4	–
0.8NS21	0.724	364	264	736	964	291.200	–
1.0NS21	0.724	364	264	736	964	364	–
1.4NS21	0.724	364	264	736	964	509.6	–
0.6NS28	0.607	438	266	748	894	262.8	–
0.8NS28	0.607	438	266	748	894	350.4	–
1.0NS28	0.607	438	266	748	894	438	–
1.4NS28	0.607	438	266	748	894	613.2	–
1.4NS+2LR-21	0.724	364	264	736	964	218.4	5.6326281
1.4NS+4LR-21	0.724	364	264	736	964	291.200	11.2652562
1.4NS+6LR-21	0.724	364	264	736	964	364	16.8978843
1.4NS+8LR-21	0.724	364	264	736	964	509.6	22.5305124
1.4NS+2LR-28	0.607	438	266	748	894	262.8	5.22361983
1.4NS+4LR-28	0.607	438	266	748	894	350.4	10.4472397
1.4NS+6LR-28	0.607	438	266	748	894	438	15.6708595
1.4NS+8LR-28	0.607	438	266	748	894	613.2	20.8944793

Figure 5. Fresh concrete tests: a) Settlement; b) Air content.

underway in conjunction with control designs CP21 and CP28 to determine the mechanical performance of Portland cement incorporating NS. Subsequently, through an experimental analysis with the optimal dose of NS and the LR percentages, the hardened concrete's mechanical performance was assessed at different curing stages, such as 7, 14, and 28 days.

In this section, the procedure is detailed through these tests of Compressive, Tensile, and Flexural Strength to compare the behavior of the variables in the concrete mixes with which content and the MP to determine their performance.

The compression test was carried out using cylindrical samples measuring 0.15 meters in diameter and 0.30 meters in height. This analysis assessed the maximum compressive strength the prepared concrete specimens can withstand, as illustrated in Figure 6a. For this purpose, ten concrete samples were distributed for each variable, percentage, and resistance for both C-1 and C-2. Furthermore, in the diametric tensile test, cylindrical specimens were tested, as presented in Figure 6b, with the particularity that they were arranged horizontally.

Similarly, the flexural strength test was carried out using beam specimens with dimensions of 0.15x0.15x0.53 m, as detailed in Figure 6c, following the methodology used and already mentioned in the present investigation regarding the samples and curing of the mixtures obtained. It should be mentioned that in all the designs developed for these tests, the average results of the total samples for the C-1 and C-2 designs of 0.6NS, 0.8NS, 1.0NS, and 1.4NS have been considered. This examination was followed by the analysis of the optimum percentage

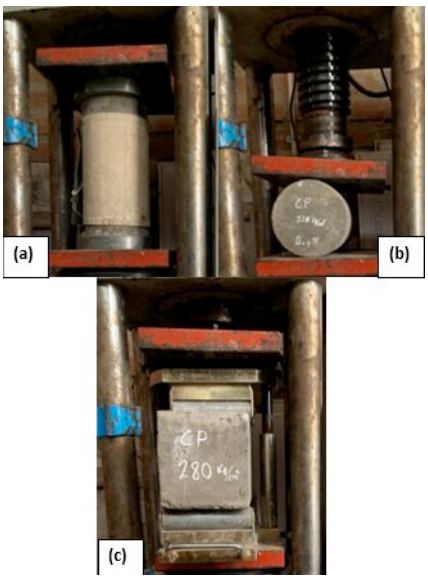


Figure 6. Tests of mechanical resistance of concrete: a) Compression; b) Tensile; c) Flexure.

(O%) of NS in the LR combination concerning the performance of the concrete with the substitution of LR in dosages of 1.4NS+2LR, 1.4NS+4LR, 1.4NS+6LR, and 1.4NS+8LR for C-1 and C-2.

Figure 7 shows the process flowchart, which summarizes the materials used in the research and how they have been used, including their percentages of content and the work methodology already mentioned.

The stone aggregates were obtained after a study of quarries at the regional level in the department of Lambayeque-Peru, with an extraction of stone and sand samples to test through an analysis of their physical properties experimentally; also, a type I cement was used for the preparation of standard concrete mixes (CP) for the 210 kg/cm^2 and 280 kg/cm^2 strength designs. For performance evaluation, the NS and LR were used, partially replacing the cement and coarse aggregate content, respectively. For further details of the experimentation process, Figure 7.

RESULTS AND DISCUSSION

Settlement

Figure 8 shows the slump test results, showing that designs CP21 and CP28 reached an adequate slump value of 4". However, according to the experimental

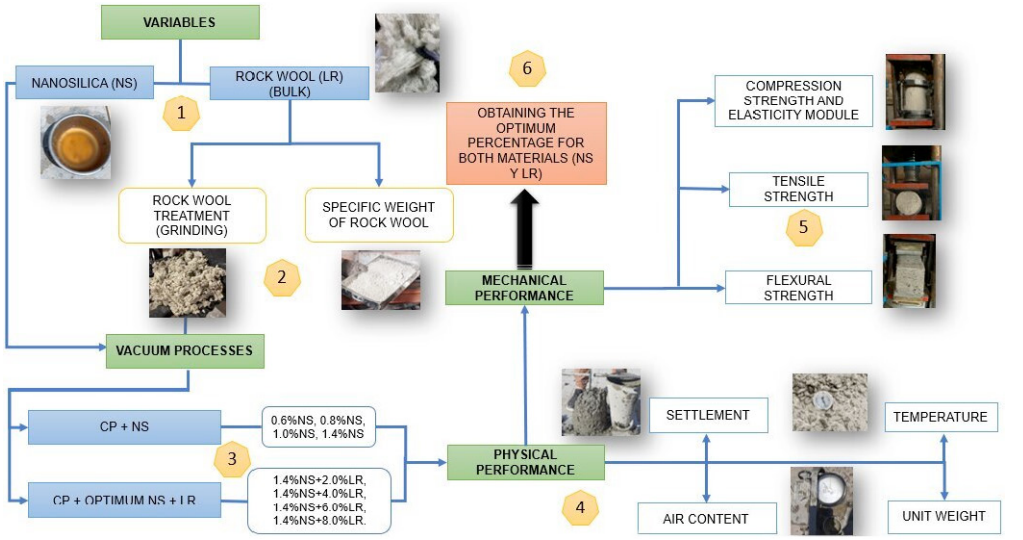
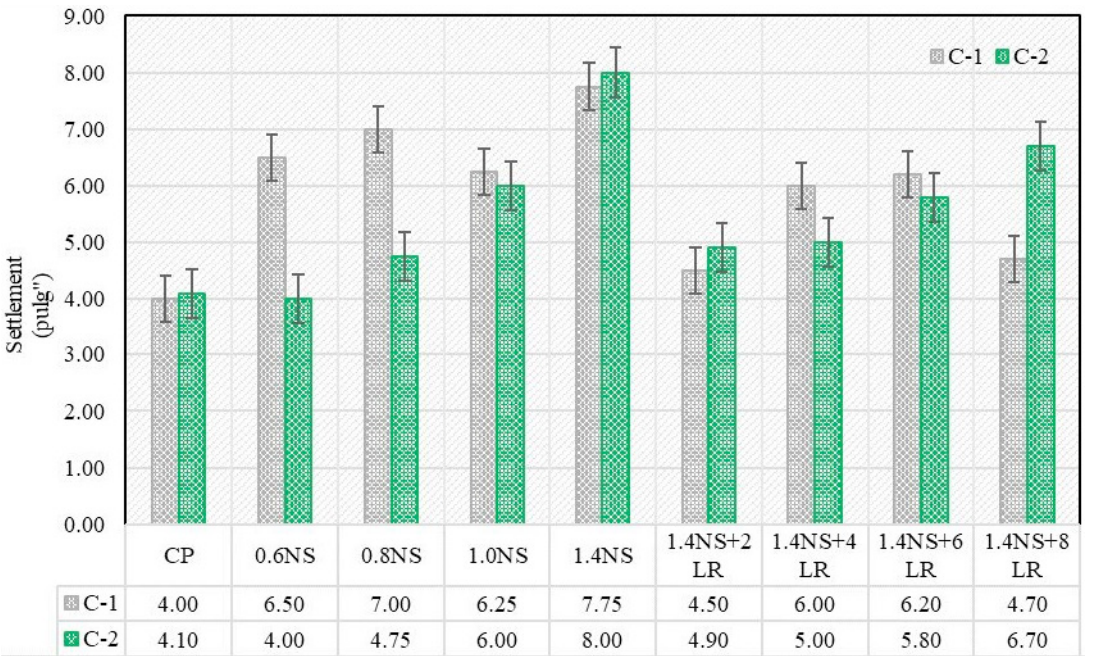


Figure 7. Flowchart of the research process.



	CP	0.6NS	0.8NS	1.0NS	1.4NS	1.4NS+2 LR	1.4NS+4 LR	1.4NS+6 LR	1.4NS+8 LR
C-1	4.00	6.50	7.00	6.25	7.75	4.50	6.00	6.20	4.70
C-2	4.10	4.00	4.75	6.00	8.00	4.90	5.00	5.80	6.70

Figure 8. Settlement test results of CP, NS and NS+LR for C-1 and C-2.

analysis, it is shown that the inclusion of nanosilica (NS) causes an excessive increase of 200% in the spread of the mixtures, reaching a maximum value of up to 8" with 1.4NS for C-2. NS is identified as the factor responsible for this effect, attributable to its silica content and the excessive fineness of its particles [8]. It is highlighted that with 0.6% of NS28, a settlement of 4" is achieved, comparable with CP21 and CP28. More appropriate values are observed in the combined designs, where 4.5 and 4.9 were obtained with 1.4NS+2LR for C-1 and C-2, respectively.

It is emphasized that the introduction of resin latex (LR) allows for controlling the excessive fluidity induced by

NS; However, even so, maximum settlement increases of 55% are recorded for C-1 resistances, with values of 6" and 6.2" for 1.4NS+4LR and 1.4NS+6LR, respectively. It is concluded that the mixtures exhibited high fluidity compared to the CP. The incorporation of NS should be moderate, not exceeding 0.8%, and if controlled with 2LR, up to 1.4NS.

It has been proven that the results obtained are consistent with the research carried out by [6], which indicated, after analyzing the fresh concrete, that using nanosilica (NS) causes a significant reduction in the workability of the concrete and its fluidity. Furthermore, [12] determined that NS in concrete causes a considerable decrease in workability compared to control samples. Both investigations coincide with the findings of the trials carried out in this study.

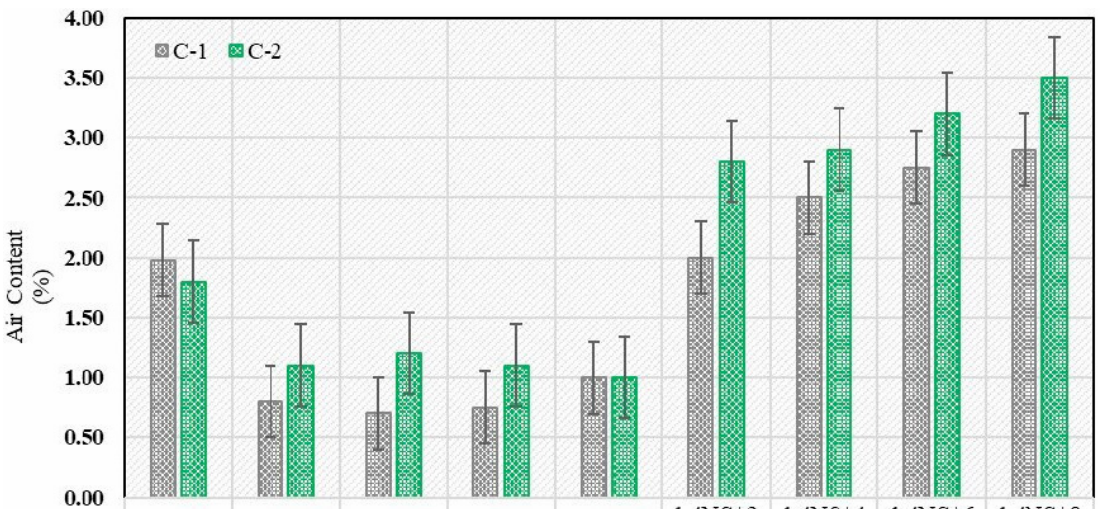
Furthermore, [14] demonstrated that by adding 2% NS, a settlement of 4.65" was achieved, while [11] obtained settlements greater than 4" with 1% NS, recording values of 5.90" and 4.13" with 0.5% NS, results that differ from those obtained in the present investigation.

Air Content

Figure 9 details that the values obtained are variable depending on the nanosilica (NS) content that replaces the cement content. On the one hand, in the test designs, CP21 and CP28 showed percentages of 1.98% and 1.80%, respectively. On the other hand, the designs exhibit a reduction in air content of up to 64.65% with 0.8NS21, estimating the lowest value of 0.7% for C-1 and 1.10% for C-2 with 0.6NS and 1NS.

Furthermore, it was determined that increasing the incorporation of resin latex (LR) increases the voids percentage by up to 2.90% and 3.50% with 1.4NS+8LR for C-1 and C-2, respectively. This is because LR is a porous material with high water absorption rates, as observed in the aforementioned research.

In addition, [12], in their analysis by incorporating NS in concrete, showed slightly significant reductions in air content with 2% and 4% of NS; in addition, they determined that with 1% of NS, a maximum of 16.51% is reduced concerning their control model; likewise, [14] maintains that due to the accelerated pozzolanic reaction between cement and NS, void filling is generated in a considered manner. Furthermore, [17] determined in their study results of increases in void content regarding its permeability, estimating that with 2.5% of LR with w/c ratios of 0.4 and 0.6 a maximum increase of 63% and 35%,



	CP	0.6NS	0.8NS	1.0NS	1.4NS	1.4NS+2 LR	1.4NS+4 LR	1.4NS+6 LR	1.4NS+8 LR
C-1	1.98	0.80	0.70	0.75	1.00	2.00	2.50	2.75	2.90
C-2	1.80	1.10	1.20	1.10	1.00	2.80	2.90	3.20	3.50

Figure 9. Air content test results for CP, NS and NS+LR for C-1 and C-2.

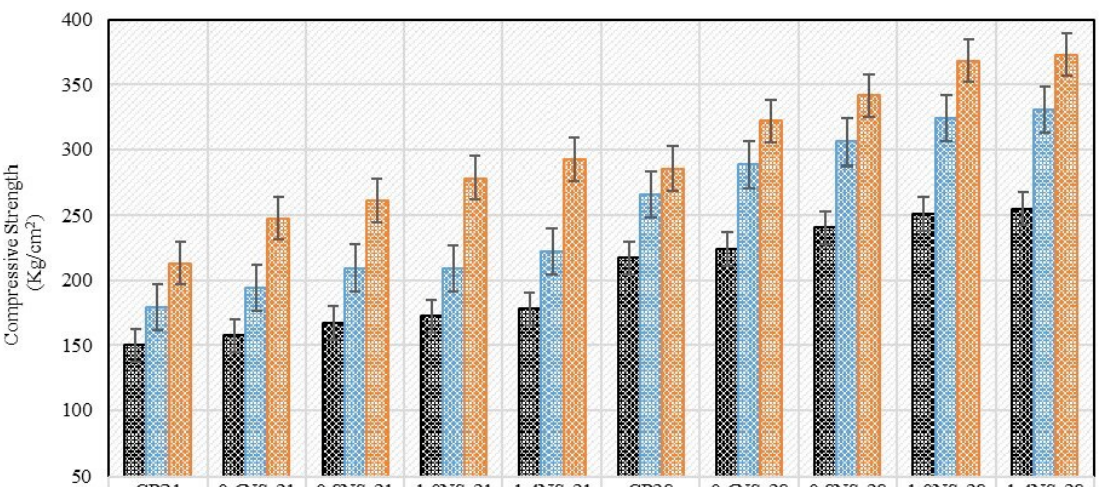
respectively; however, it is defined that the higher the LR content the void volume tends to be reduced by up to 34% with 15% of LR.

Compressive Strength

Figure 10 shows the results of the compressive strength analysis with the addition of NS for C-1 and C-2. The values obtained in the study are positive at all substitution percentages, superior to the control models for all curing ages by up to 37.19% and 30.53% with 1.4NS21 and 1.4NS28 respectively, i.e., reached values of 292.72 kg/cm^2 and 373.10 kg/cm^2 at 28 days of curing unlike CP21 and CP28 with 213.37 and 285.83 kg/cm^2. Correspondingly, with 1NS, significant increases of up to 28.62% were obtained for C-2. On the other hand, Figure 11 shows the results of the combinations with LR for C-1 and C-2, where it is detailed that with 1.4NS+6LR, the maximum resistances were achieved with increases of up to 21.85% and 21.05% for C-1 and C-2, respectively. In the same way, it can be observed that for LR percentages lower than 6%, the resistances increased above the control samples; however, it was determined that with the incorporation of 8%LR, the resistance began to reduce from 21% to 1% concerning the highest resistance for C-1 and by up to 3% regarding the CP for C-2 with the same dosage.

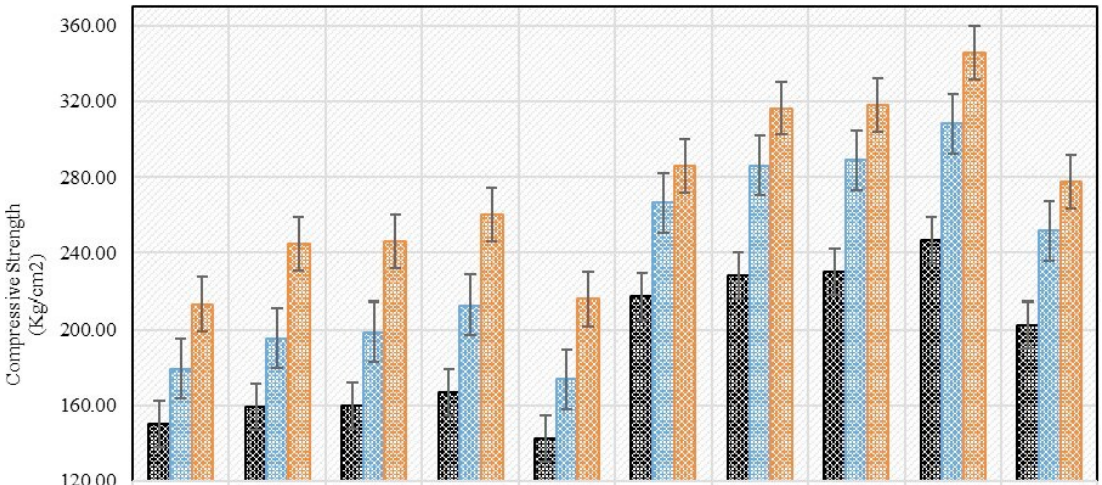
The results obtained are in agreement with the study conducted by [13], which shows that the incorporation of 1.5% NS increases the strength of concrete by up to 34%; likewise, it is in agreement with the research conducted by [12], which considerably increased the strength of concrete by up to 31% regarding the control samples with 1% NS. In addition, [11] determined increases in the experimentation with 1.5% NS, comparable to the results obtained, reaching a maximum of 26.53% concerning the control modulus at 28 days. Conversely, [14] maintained that only determined increases with percentages higher than 1% NS, 3% its optimum with an increase of 22.12%. Conversely, regarding LR additions, it is demonstrated with the study by [15] that determined increases with 5% of LR up to 9.07%; in addition, it agrees with [16] where their results in compression deteriorated significantly with percentages of 10% and 20% of LR up to 12.98%. The addition of nanosilica and rock wool increased the compressive strength of concrete by reducing cracks by forming secondary hydration products, filling pores, and improving internal bonding, resulting in a denser and stronger matrix.

The research consulted agrees on this increase since nanosilica (NS) has pozzolanic properties that react with the hydrated cement to generate more C-S-H



	CP21	0.6NS-21	0.8NS-21	1.0NS-21	1.4NS-21	CP28	0.6NS-28	0.8NS-28	1.0NS-28	1.4NS-28
7 días	150.13	157.53	167.18	172.62	178.24	217.33	224.40	240.73	251.42	255.55
14 días	179.34	194.28	209.62	209.25	222.55	266.53	288.86	306.14	324.16	330.68
28 días	213.37	248.06	261.76	278.77	292.72	285.83	321.95	341.64	368.62	373.10

Figure 10. Compressive strength results for CP and concrete incorporating NS for C-1 and C-2 designs at different curing days.



	CP21	1.4NS+2L R-21	1.4NS+4L R-21	1.4NS+6L R-21	1.4NS+8L R-21	CP28	1.4NS+2L R-28	1.4NS+4L R-28	1.4NS+6L R-28	1.4NS+8L R-28
7 días	150.13	159.46	159.68	167.22	142.81	217.33	228.04	230.13	246.65	202.10
14 días	179.34	195.33	198.68	212.81	173.78	266.53	285.98	289.04	308.18	251.55
28 días	213.37	244.67	246.28	260.00	216.05	285.83	316.47	318.02	345.99	277.61

Figure 11. Compressive strength results for CP and concrete incorporating NS+LR for C-1 and C-2 designs at different curing days.

(GEL) particles when it comes into contact with water. This reaction reduces porosity by partially filling the pores, refining the structure, and providing, as a consequence, greater compressive strength.

Tensile Strength

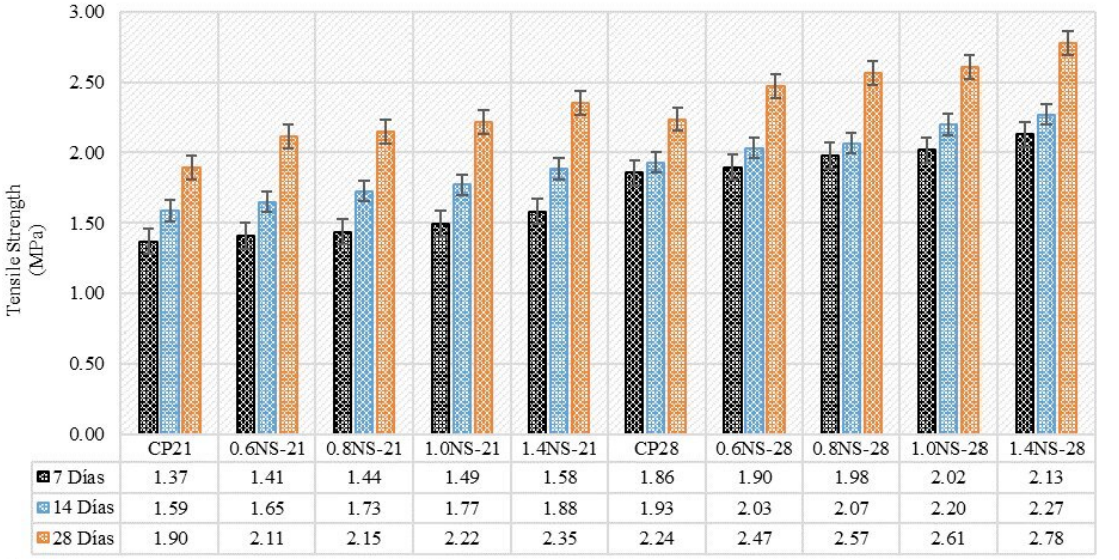
Figure 12 presents the results of the tensile test on cylindrical specimens, where it is observed that at 7 and 14 days, the design percentages in the concrete exhibit higher resistance compared to the standard concrete (CP), although not significantly, with a maximum increase of 15.33% and 18.24% with 1.4 NS2. Considering the mentioned percentages, this result is compared to the reference concrete mix. However, for 28 days, with 1.4NS, an increase of 23.68% is obtained for C-1, notably comparable to the increase of 24.10% for C-2, which has a value of 2.78 MPa with the same percentage as the control model.

Figure 13 details the results of the combinations with resin latex (LR), determining that with 1.4NS+6LR, the maximum resistances were reached with an increase of up to 16.57% for C-1 compared to the pattern mix. Similarly, it is observed that for doses of 1.4NS+8LR, the resistance deteriorates considerably compared to the highest resistance, being slightly below samples CP21 and CP28 by up to 4% at seven days. Therefore, it was concluded that LR additions should be at most 6%.

The results obtained show better performance with lower doses of NS compared to the study by [14], who determined in their results a maximum increase of 22.22% with 3%NS compared to their control sample because incorporating the variables by its already specified characteristics managed to bring significant benefits due to its texture when added to the concentrate mixture, making it denser; nonetheless, with 1% NS it only achieves an increase of 5.07%. On the other hand, the incorporation of LR is comparable with the research by [17], where this resistance is reduced as the percentage of LR increases. However, they affirm that with 2.5% and 5% of LR, the reduction is not significant compared to higher doses; this is because the LR does not retain moisture, and at the time of curing, this characteristic can affect and reduce the resistance of the concrete, according to the research consulted.

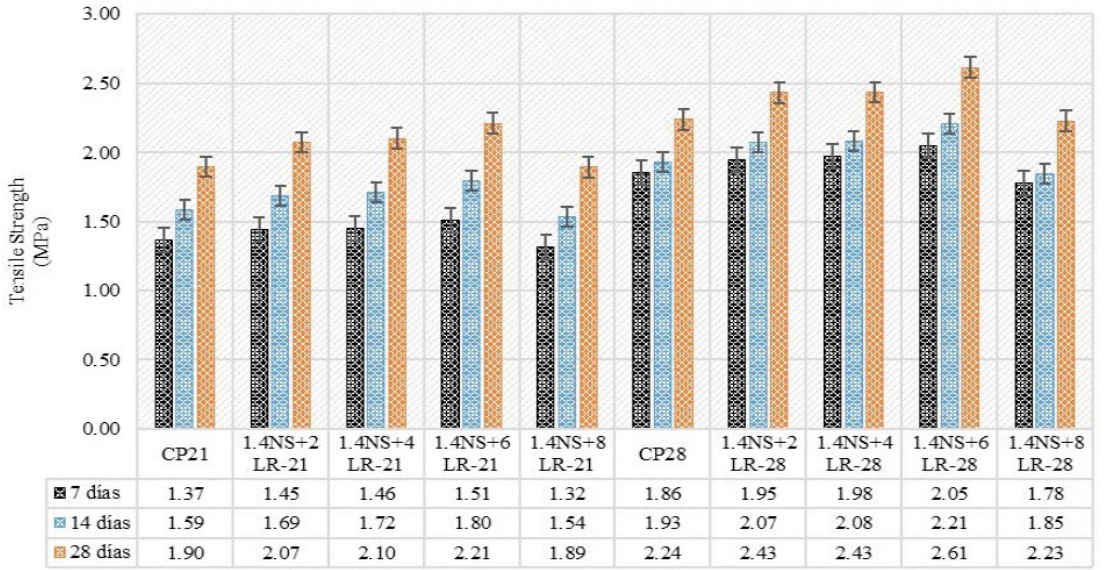
Flexural Strength

Figure 14 presents the results of the beam bending test for C-1 and C-2, where a comparison is made between the base mixture and the mixtures with



	CP21	0.6NS-21	0.8NS-21	1.0NS-21	1.4NS-21	CP28	0.6NS-28	0.8NS-28	1.0NS-28	1.4NS-28
7 Días	1.37	1.41	1.44	1.49	1.58	1.86	1.90	1.98	2.02	2.13
14 Días	1.59	1.65	1.73	1.77	1.88	1.93	2.03	2.07	2.20	2.27
28 Días	1.90	2.11	2.15	2.22	2.35	2.24	2.47	2.57	2.61	2.78

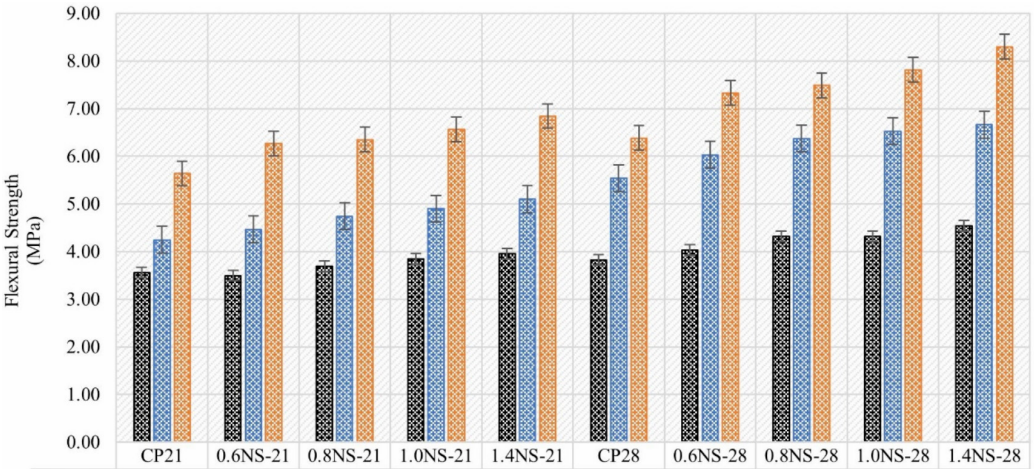
Figure 12. Tensile strength results in MPa for CP and concrete with NS for C-1 and C-2 designs at different curing days.



	CP21	1.4NS+2 LR-21	1.4NS+4 LR-21	1.4NS+6 LR-21	1.4NS+8 LR-21	CP28	1.4NS+2 LR-28	1.4NS+4 LR-28	1.4NS+6 LR-28	1.4NS+8 LR-28
7 días	1.37	1.45	1.46	1.51	1.32	1.86	1.95	1.98	2.05	1.78
14 días	1.59	1.69	1.72	1.80	1.54	1.93	2.07	2.08	2.21	1.85
28 días	1.90	2.07	2.10	2.21	1.89	2.24	2.43	2.43	2.61	2.23

Figure 13. Tensile strength results in MPa for CP and concrete with NS+LR for C-1 and C-2 designs at different curing days.

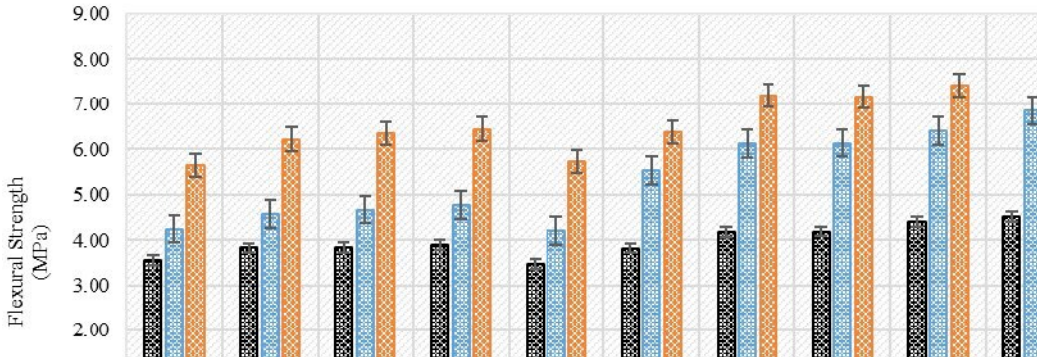
the incorporation of the variables, thus obtaining some percentages of decrease or increase in the properties. It is determined that after 7 days, the percentages of NS in the concrete have a resistance higher than that of CP but are not significant, with an increase of 11.55%, equivalent to 3.96 MPa, and 18.84%, with a value of 4.54 MPa, with 1.4 NS21 and 1.4NS28 respectively. However, at 28 days, the maximum resistance was obtained for C-1, with an increase of 21.28%, and 30% for C-2 with the 1.4NS substitutions, that is, values of 6.84 MPa and 8.30 MPa, respectively. These values are compared with the control model, and with 1NS, an increase of 22.41% was obtained for C-2.



	CP21	0.6NS-21	0.8NS-21	1.0NS-21	1.4NS-21	CP28	0.6NS-28	0.8NS-28	1.0NS-28	1.4NS-28
7 Días	3.55	3.49	3.69	3.84	3.96	3.82	4.03	4.32	4.32	4.54
14 Días	4.24	4.46	4.74	4.90	5.10	5.54	6.03	6.37	6.52	6.66
28 Días	5.64	6.27	6.35	6.56	6.84	6.38	7.33	7.49	7.81	8.30

Figure 14. Flexural strength results in MPa for CP and NS concrete for C-1 and C-2 designs at different curing ages.

Figure 15 shows the results of the NS+LR combinations, determining that at 28 days of curing, the maximum values were obtained from the 1.4NS+6LR dosage increasing up to 14.18% with a value of 6.44MPa for C-1; regardless, for C-2, the maximum resistance of 28.68% equivalent to 8. 21MPa with 1.4NS+8LR. In the same way, it can be observed that, with the substitution of 1.4NS+8LR21, the resistance decreases to a value of 5.73MPa, which is above CP21 in 1.60%; however, for C-2, resistances such dosage is increased. Nevertheless, it is determined that the percentage of LR should be at most 6%. The lowest flexural strength was obtained at seven days with 1.4NS+8LR for C-1 with a reduction of 2.25%, i.e., a value of 3.47 MPa.



	CP21	1.4NS+2 LR-21	1.4NS+4 LR-21	1.4NS+6 LR-21	1.4NS+8 LR-21	CP28	1.4NS+2 LR-28	1.4NS+4 LR-28	1.4NS+6 LR-28	1.4N LR-
7 días	3.55	3.82	3.84	3.90	3.47	3.82	4.18	4.19	4.40	4.5
14 días	4.24	4.58	4.67	4.77	4.19	5.54	6.11	6.13	6.39	6.8

Figure 15. Flexural strength results in MPa for CP and concrete with NS+LR for C-1 and C-2 designs at different curing ages.

The results obtained agree with the research carried out by [12], who managed to increase the flexural strength with 1% NS by up to 28% regarding their control sample in an analysis at 90 days; however, [14] in their research does not show significant increases with 1% NS, where he obtained 3.43% concerning the base concrete as opposed to 3% NS with a non-significant increase of 13.13%. On the other hand, for LR additions, the research of [16] was comparable, showing a maximum increase of 16% with 20% LR; however, with 10% LR, the resistance achieved was lower with a minimum increase of 6.4% regarding the control model. Similarly, the study by [17] shows that the resistance, as mentioned earlier, reduces as the percentage of LR increases, estimating that 2.5% and 5% of LR generate a lower reduction.

This phenomenon occurs in a certain percentage of the NS because it causes an intense pozzolanic reaction between the nanosilica and CH, accelerating the pozzolanic reactions between SIO2 and water molecules. Therefore, lower pore volume results in higher compression resistance and water absorption capacity of nanosilica-modified pastes.

CONCLUSIONS

The present study detailed the physical and mechanical performance of concrete with NS by weight of cement and LR by volume of coarse aggregate through analysis at different curing ages in specimens and beams; the results obtained allowed determining the following conclusions:

The inclusion of nanosilica (NS) affected the slump of the concrete, leading to a significant increase in the slump measurement as the NS dose increased, reaching a value of up to 8" with 1.4NS. On the contrary, the LR demonstrated, through this test, that it controlled the concrete's workability. Regarding the air content, it was observed that with the incorporation of NS percentages, the air was reduced to a minimum value of 0.7% with 0.8NS. On the other hand, with the LR, as its dosage is increased, the air content generated inside the concrete is higher due to the material's porosity, thus affecting its air content.

Concerning the mechanical properties, a significant increase in all strengths was determined with the incorporation of nanosilica (NS), and this effect was controlled by replacing LR with coarse aggregate. The most significant increase in concrete compression was observed with 1.4NS, reaching up to 37.19% for C-1 strength and 30.53% for C-2 compared to the standard models. This increase was also recorded with combined percentages of 1.4NS+6LR, where resistance increased by 21.85%. On the other hand, in traction, maximum increases of 24.10% were observed concerning pattern concrete (CP) when using 1.4NS and 16.57% when combining it with 6% LR. In flexion, a maximum increase of 18.84% was noted with the 1.4NS variable and up to 26.68% with the 1.4NS+8LR dose.

Based on the analysis of the mechanical performance results, it was concluded that the optimum addition of NS is 1.4% and 6% of LR, significantly increasing the concrete strengths concerning the control designs CP21 and CP28. Additionally, it is emphasized that their dosages do not exceed the proposed values; otherwise, such values would deteriorate.

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