INGENIERIA CIVIL

Combined effect of nano-silica and silica fume to improve concrete workability and compressive strength: a case study

CIVIL ENGINEERING

Efecto combinado de nano-sílice y humo de sílice para mejorar la trabajabilidad del concreto y la resistencia a la compresión: un estudio de caso

Yineth García-Díaz[1], Ramon Torres-Ortega [2], Manuel Saba[2,] §, Edgar Quiñones-Bolaños[2], Jesús Torres-Sanchez[3]

[1] Universidad Politécnica de Cataluña, department of construction engineering, Barcelona, Spain

[2] Civil engineering Program, Universidad de Cartagena, Cartagena, Colombia

[3]Engineer at Arquitec, INGUETO LTDA, Cartagena, Colombia

ygarciad1@unicartagena.edu.co, rtorreso@unicartagena.edu.co, § msaba@unicartagena.edu.co, equinonesb@unicartagena.edu.co, jedatos.95@gmail.com

García-Díaz Y, Torres-Ortega R, Saba M, Quiñones-Bolaños E, Torres- Sánchez J. Efecto combinado de nano-sílice y humo de sílice para mejorar la trabajabilidad del concreto y la resistencia a la compresión: un estudio de caso. Ingeniería y Competitividad, 25(1)2023; e-21612201. https://doi.org/10.25100/iyc.v25i1.12201

Recibido: 09 de julio de 2022 – **Aceptado:** 22 de noviembre de 2022

Abstract

Several types of amorphous silica generate pozzolanic reactions at micro- and nano-scale improving concrete macro-structural characteristic. However, their addition can raise the viscosity of the mixture, thus decreasing its workability. In the present work is proposed an experimental setup to determine concrete compression and manageability performance adding Silica Fume (SF), 0.0, 6.5, 8.5, 10.0% w/b, colloidal silica (nSi), 0.0, 0.5, 1.0, 1.5, 2.0, 2.5% w/b and SF-nSi combined, 0.0-0.0, 0.2-8.5, 0.2-10% w/b (by weight), and an extensive overview of the literature for concrete mixtures with SF, nSi and SF-nSi combined. The results show that the addition of SF can increase compressive strength by 12%, nevertheless, can also lead to decreases in manageability of the sample (e.g., a decrease by 67% for a dosage of 10.0% w/b). On the other hand, nSi can increase compressive strength by up to 25% with a dosage of 2.5% and can increase the manageability by 78% for dosages greater than 0.5% w/b. When combining the two materials, an increase in compressive strength was observed, along with a loss of workability. A statistical analysis of the data found in literature is proposed using MATLAB, highlighting interesting trends of behavior between SF and nSi with workability and compressive strength, as well as a lack of research for slump outcomes and for the effects of combined additives in concrete. Finally, a short cost-benefit analysis of the mixtures is proposed.

Keywords: Mechanical improvement of concrete; Cost-benefit analysis; nSi and macro-silica; workability and compressive strength.

Resumen

Varios tipos de sílice amorfa generan reacciones puzolánicas a escala micro y nano, que pueden mejorar las características macroestructurales del concreto. Sin embargo, su adición puede aumentar la viscosidad de la mezcla, disminuyendo así su trabajabilidad. En el presente trabajo se propone un montaje experimental para determinar el comportamiento de compresión y manejabilidad del concreto agregando Humo de Sílice (SF), 0.0, 6.5, 8.5, 10.0% p/b, sílice coloidal (nSi), 0.0, 0.5, 1.0, 1.5, 2.0, 2.5 % p/b y SF-nSi combinados, 0.0-0.0, 0.2-8.5, 0.2-10 % p/b (por peso), y una amplia descripción de la literatura para mezclas de concreto con SF, nSi y SF-nSi combinados. Los resultados muestran que la adición de SF puede aumentar la resistencia a la compresión en un 12%, sin embargo, también puede conducir a una disminución en la manejabilidad de la muestra (por ejemplo, una disminución del 67% para una dosis de 10,0% p/b). Por otro lado, el nSi puede aumentar la resistencia a la compresión hasta en un 25% con una dosificación del 2,5% y puede aumentar la manejabilidad en un 78% para dosificaciones superiores al 0,5% p/p. Al combinar los dos materiales, se observó un aumento en la resistencia a la compresión, junto con una pérdida de trabajabilidad. Se propone un análisis estadístico de los datos encontrados en la literatura usando MATLAB, destacando tendencias interesantes de comportamiento entre el SF y el nSi con la trabajabilidad y la resistencia a la compresión, así como la falta de investigación sobre los resultados del asentamiento y los efectos de los aditivos combinados en el concreto. Finalmente, se propone un breve análisis costo-beneficio de las mezclas.

Palabras clave: *Mejoramiento mecánico del concreto; Análisis coste-beneficio; nSi y macro-silica; trabajabilidad y resistencia a la compresión.*

1. Introduction

Silica fume (SF) is a type of amorphous silica with a higher specific surface than cement (SF, 19,800 m^2/kg; cement, 314 m^2/kg) (1). This led to its wide use in concrete for mechanical behavior improvement (2–5), despite its high cost (6). SF is composed of SiO_2 and is characterized by high-purity spherical particles with a very fine size and high pozzolanic activity, which contribute to the improvement of cement-based compounds (7,8). SF also improves resistance and can be used advantageously when good quality aggregates are not available (9).

In recent years, interest in SiO_2, ZnO_2, Al_2O_3, CuO, $CaCo_3$, Fe_2O_3, and TiO_2 nanotechnological products, processes, and applications has raised for their advantages in many aspects of material science, among which improvement of the antimycotic behavior of the materials and air-purifying purposes (10,11). Furthermore, they provide greater durability of concrete by modifying the micro-structural, mechanical, and durability properties of concrete and mortar, (12,13). Nano-SiO_2 (nSi) has been one of the most widely used materials, compared to other nanomaterials (14–16), as it is a very effective concrete additive, improving its strength, flexibility, and durability (17). Furthermore, it can be used as an additive to improve the workability and strength of high-performance and self-compacting concrete (18). Research has shown that the use of 1 kg of SF, in particular, can save 4 kg of cement (19). Additionally, 1% of nSi is equivalent to 10% of SF (20).

SF, or micro-silica, is a byproduct of the industrial production of silicon (21), having particle sizes within the submicrometric range. In concrete, amorphous silica presents a pozzolanic reaction, wherein SF reacts with portlandite ($Ca(OH)_2$, CH) as a result of alite hydration (22). Subsequently, amorphous silica fills the gaps between the cement particles and other constituent materials (which is called the filler effect), thus densifying the concrete (23). Another principle of the filler effect is that the nucleation of calcium silicate hydrate (C–S–H) phases (formed from alite hydration) occurs at the surface of the fillers. This effect accelerates cement hydration and is known as the sowing effect (24,25). Due to its extreme fineness and high content of amorphous silicon dioxide, silica fume is a highly reactive pozzolanic material. The mechanism of silica fume in concrete is basically due to three functions: Pore refinement and matrix densification, reaction with free limestone (from cement hydration), and interfacial refinement of paste-aggregate, (26).

Colloidal silica is a liquid nano-silica (nSi) of uniform shape and particle size between 1–1000 nm (19). It is produced from a sodium silicate solution. The solution is subject to an ion exchange to partially remove sodium ions, thus forming a silica suspension. Subsequently, the pH is adjusted to control the particle size. The appearance of nSi is a suspension of fine silica particles in an aqueous medium. Its main applications are as a binder in investment casting, paper processing and coating, and as a binder in refractories and construction materials (27). Regarding hydration, nSi is superior to SF, as it accelerates the process and leads to a compaction of the concrete microstructure at early stages of curing, as well as increasing the hydration heat produced, due to the fast formation of CH crystals during the settlement of the cement paste. nSi particles react with CH and result in an additional amount of NSIH gel in the matrix. Therefore, there is an enhancement in the mechanical properties of the mixtures prepared with nSi, as related to the dosage (28). However, the dispersion of nanoparticles in the concrete is vital for the enhancement of the macro-, micro-, and nano-cementing properties. Additionally, there is a lack of data on the reaction mechanism of nSi (19). Combination of the two additives shows a great potential to improve concrete workability and compressive strength, because they are a complement, nSi works at nanoscale, while Sf works at macroscale. Furthermore, as mentioned by (29), nSi and SF supplied the voids in the micron size of cement particle and formed a denser concrete which leads to improving the concrete mechanical properties compared to conventional concretes.

In this study, an experimental procedure was carried out to evaluate the effect of the individual and combined additions of SF and nSi (in the form of a colloidal suspension) on the concrete workability and compressive strength. The most and relevant studies in the last decade are discussed and compared to see the international trends in the matter. Finally, an overview of the economic aspects of those mixture is proposed emphasizing the context of a developing country like Colombia.

2. Methodology

In this research, for all tests, a high early strength cement (HESC) was used, according to American Society for Testing and Materials (ASTM) (2020a). HESC means that the required compressive strength of the concrete can be reached significantly before the 28 standard days. This was used in all mixtures of the present work, in order to streamline laboratory times. This will not affect the final results of the work, as has been shown in the literature (31,32). Additionally, it was used a superplasticizer type F additive based on polycarboxylates, a fractured boulder-type coarse aggregate from old river channels of the Colombian Caribbean area with nominal maximum size of 9.53 mm, and natural siliceous sand. The characteristics of the aggregates are given in Table 1 y Table 2.

Table 1. Features of the aggregates used in the preparation of the mixture.

Parameter	Sand	Coarse aggregate
Wear (M. Angels) maximum (%)	-	12.48
Clay lumps maximum (%)	-	0.71
Fractured faces minimum (%)	-	75.70
Absorption (%)	2.35	1.00
Dry density (Kg/m^3)	2512	2462.66
Saturated density (Kg/m^3)	-	2487.29
Apparent density (Kg/m^3)	-	2525.00
Humidity (%)	3.08	0.20
Fineness module (%)	3.28	-

The silica fume utilized (SiO2) had a percentage >95% by weight, specific surface area of 30,000 m^2/kg, humidity of 3–5%, and colloidal silica density of 1.14 kg/l.

Table 2. Grading of aggregates with ASTM-C33 limits

Sieve No. (mm)	% Passing
25.4	100.00
19.0	100.00
12.5	100.00
9.5	99.18
4.8	26.95
2.4	0.95

2.1. Mixture proportions

For the compression tests, binary mixtures of three concrete specimens were prepared: 1) for three SF dosages: 6.5, 8.5, and 10.0% w/b; 2) binary mixtures (from three test tubes) for each NSI dosage: 0.5, 1.0, 1.5, 2.0, and 2.5% w/b; 3); and, finally, ternary mixtures were prepared with combinations of the two materials and cement, with a single dose of colloidal silica (0.2% w/b) and two dosages of silica fume (8.5 and 10.0% w/b). Additionally, three standard cylinders were prepared, which did not contain SF or NSI. The mix design is detailed in Table 3.

Table 3. The mix design of the present study

The above-mentioned percentages and combinations were set after an extensive experimental work taking as starting point the ranges found in literature (Table 4).

Table 3. The mix design of the present study

Sample	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	SP (% w/b)	Silica fume (SF) (kg/m^3)	Colloidal Silica (% w/b)
SF0-NSI0	448.25	210.0	568.24	1021.76	0.6	0	0
SF6.5-NSI0	448.25	224.7	568.24	1021.76	0.6	31.38	0
SF8.5-NSI0	448.25	228.9	568.24	1021.76	0.6	40.34	0
SF10-NSI0	448.25	233.1	568.24	1021.76	0.6	49.31	0
SF0-NSI0.5	448.25	210.0	568.24	1021.76	0.6	0	0.5
SF0-NSI1	448.25	210.0	568.24	1021.76	0.6	0	1
SF0-NSI1.5	448.25	210.0	568.24	1021.76	0.6	0	1.5
SF0-NSI2	448.25	210.0	568.24	1021.76	0.6	0	2
SF0-NSI2.5	448.25	210.0	568.24	1021.76	0.6	0	2.5
SF 8.5 NSI0.2	448.25	228.9	568.24	1021.76	0.6	40.34	0.2
SF 10-NSI0.2	448.25	233.1	568.24	1021.76	0.6	49.31	0.2

Colloidal silica is a liquid nano-silica (nSi)

2.2. Preparation and testing of mixtures

The mixtures were made in a 35-rpm piece of rotating equipment. Aggregates, cement, and silica fume were mixed for 2 minutes, followed by the addition of water containing pre-mixed additives (mixing time of 10 min). As for the SC procedures, a mixture with water was previously made.

For each mixture, three 10 x 20 cm cylinders were prepared, in order to carry out the compressive strength tests. The mixtures were compacted inside molds in three layers, applying 25 strokes. All specimens were settled for 24 h at room temperature and were subjected to curing under water up to the 7th day.

After the mix was completed, the workability level was assessed using the Abrahams cone test, according to the ASTM C143/C143M - 20 Standard Test Method for Slump of Hydraulic-Cement Concrete, (2020). The procedure to determine the f_c was performed in accordance with the ASTM C39 / C39M - 20 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, (2020), using a hydraulic press of *Rosemberg-Laboratory Equipment*, Model 3100-PE-D of 2019 with 0.1 kN sensitivity.

Furthermore, an overview of the literature is proposed, to oversee the research trend at an international level regarding the addition of SF and nSi to improve concrete workability (Slump) and compressive strength (fc) and compare with the case study.

Finally, a short discussion regarding the cost–benefit analysis is presented below.

3. Results and Discussion

3.1. Workability

Figure 1 shows a loss of workability resulted when incorporating SF, considering the difference in the slump values of the mixes. When SF was used, there was a 67% reduction in manageability, from 9 to 3 cm. The surface area of SF increases the attraction forces between its siliceous particles, which results in the clustering of particles and, thus, decreases the mixture's slump and workability. An increase in slump occurred only with the addition of nSi (Figure 1 b) to the mixtures, with a 78% increase from 9 to 16 cm, while the combination of nSi and SF led to a total reduction in workability, carrying the slump back to zero (Figure 1c). The loss of workability in the latter sample may have been due to the small particle size capturing a significant amount of water from the original mixture, as well as the excess of pozzolanic materials preventing the complete chemical reaction from occurring.

Table 4 and Figure 2 show the slump results of some of the most relevant studies around the word in recent years. The relationship between the slump of the mixture with SF, nSi and SF+nSi, respectively, with the slump of the base mixture without additives (Slump base). The ratio "Slump/Slump base" allows to normalize the data found in the literature and compare different studies. In the literature can be observed that slump for SF addition in concrete is less studies than nSi, while the SF+nSi addition is the least studied. Due to multiple variables in play in each mixture, such as different types of aggregate, water/binder ratio, superplasticizer, among others, it is difficult to find a proper mathematical model to describe slump variation in function of SF, nSi and SF+nSi concentrations valid worldwide. Nevertheless, it is observed a trend in the data found, suggesting that for higher SF percentages the mixtures shown a loss of slump ratio (Figure 2), with values lower than 1, according to the present study experimental part.

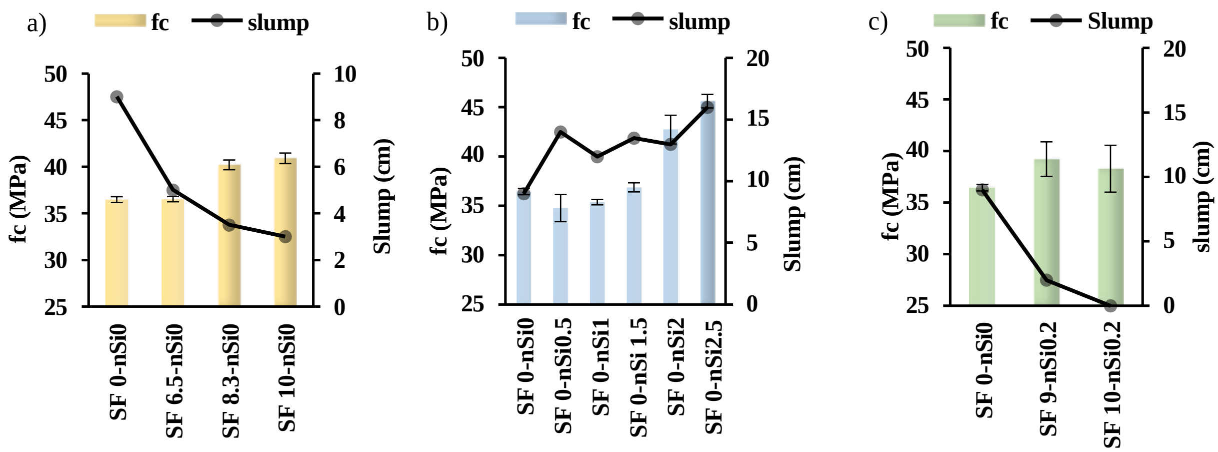

Figure 1. *Behavior of settlement flow and compressive strength of mixtures when using: a) SF; b) nSi; and c) SF+nSi. Standard deviation for fc results is reported. Slump data is based on one measurement.*

Table 4. *Literature studies using silica fume (SF) addition in concrete.*

w/b	SF (%)	fc (MPa)	fc (Base) (MPa)	fc/fc base (MPa)	Slump (mm)	Slump (Base) (mm)	Slump / Slump (Base)	Reference
0.50	7.00	36.50	36.47	1.00	35.00	90.00	0.39	PS
0.51	8.50	40.10	36.47	1.10	35.00	90.00	0.39	PS
0.52	10.00	40.90	36.47	1.12	30.00	90.00	0.33	PS
0.28	5.00	79.27	76.52	1.04	740.00	790.00	0.94	(35)
0.28	10.00	88.25	76.52	1.15	690.00	790.00	0.87	(35)
-	3.00	-	-	-	129.00	137.00	0.94	(36)
-	5.00	-	-	-	110.00	137.00	0.80	(36)
-	8.00	-	-	-	105.00	137.00	0.77	(36)
	10.00				100.00	137.00	0.73	(36)
0.40	8.00	71.70	59.25	1.21	30.00	40.00	0.75	(37)
0.35	8.00	77.90	64.95	1.20	30.00	35.00	0.85	(37)
0.30	5.00	113.20	105.70	1.07	140.00	140.00	1.00	(38)
0.30	5.00	106.20	97.30	1.09	128.00	157.00	0.82	(38)
0.30	5.00	80.50	68.10	1.18	181.00	181.00	1.00	(38)
0.30	5.00	62.80	44.70	1.40	115.00	125.00	0.92	(38)
0.36	3.00	33.00	37.20	0.88	135.00	135.00	1.00	(39)
0.36	5.00	39.50	37.20	1.06	140.00	135.00	1.04	(39)
0.36	3.00	35.00	37.20	0.94	140.00	135.00	1.04	(39)
0.36	5.00	42.00	37.20	1.12	135.00	135.00	1.00	(39)
0.79	5.00	30.00	27.50	1.10	-	-	-	(40)
0.79	10.00	32.00	27.50	1.16	-	-	-	(40)
0.79	15.00	33.00	27.50	1.20	-	-	-	(40)
0.79	20.00	33.50	27.50	1.22	-	-	-	(40)
0.65	5.00	41.50	37.00	1.12	-	-	-	(40)
0.65	10.00	45.00	37.00	1.22	-	-	-	(40)
0.65	15.00	47.00	37.00	1.27	-	-	-	(40)
0.65	20.00	48.00	37.00	1.30	-	-	-	(40)
0.60	5.00	46.50	41.00	1.13	-	-	-	(40)
0.60	10.00	50.50	41.00	1.23	-	-	-	(40)
0.60	15.00	52.50	41.00	1.28	-	-	-	(40)
0.60	20.00	54.00	41.00	1.33	-	-	-	(40)
0.52	5.00	57.00	50.00	1.14	-	-	-	(40)

0.52	10.00	62.00	50.00	1.24	-	-	-	(40)
0.52	15.00	64.00	50.00	1.28	-	-	-	(40)
0.52	20.00	66.00	50.00	1.32	-	-	-	(40)
0.45	5.00	68.00	59.00	1.15	-	-	-	(40)
0.45	10.00	74.50	59.00	1.26	-	-	-	(40)
0.45	15.00	77.00	59.00	1.31	-	-	-	(40)
0.45	20.00	79.00	59.00	1.34	-	-	-	(40)
0.36	2.50	63.79	60.33	1.06	787.00	645.00	1.21	(41)
0.36	5.00	65.01	60.33	1.08	820.00	645.00	1.26	(41)
0.36	7.50	68.86	60.33	1.14	795.00	645.00	1.22	(41)
0.35	11.00	43.70	39.35	1.11	700.00	720.00	0.97	(42)
0.45	11.00	31.50	28.80	1.09	755.00	785.00	0.96	(42)
0.31	8.00	57.27	43.93	1.30	150.00	170.00	0.88	(43)
0.31	10.00	70.32	43.93	1.60	110.00	170.00	0.65	(43)
0.31	12.00	70.53	43.93	1.61	70.00	170.00	0.41	(43)
0.38	10.00	56.50	51.80	1.09	650.00	750.00	0.87	(44)
0.38	10.00	63.40	52.50	1.21	760.00	840.00	0.90	(44)
0.50	5.00	46.20	46.70	0.98	180.00	180.00	1.00	(45)
0.50	10.00	47.50	46.70	1.01	180.00	180.00	1.00	(45)
0.38	10.00	56.50	51.80	1.09	650.00	750.00	0.87	(46)
0.38	10.00	58.30	52.00	1.12	700.00	800.00	0.88	(46)
0.38	10.00	63.40	52.50	1.21	760.00	840.00	0.90	(46)

w/b water/binder ratio; fc= Compressive strength of the mixture with SF; fc (Base)= Compressive strength of the mixture without SF; Slump= Slump of the mixture with SF; Slump (Base)= Slump of the mixture without SF. In light blue are highlighted the mixtures where slump flow was measured instead of standard slump. PS= Present Study

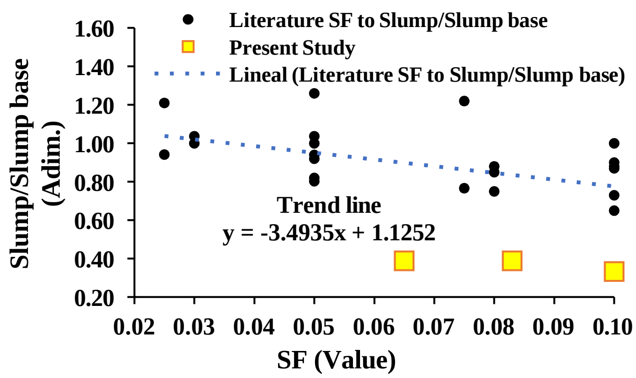

Figure 2. *Slump behavior in the literature for SF*

On the contrary, for nSi, a sightly increasing trend in the slump ratio was observed in the literature as an overall behavior (Figure 3). Notwithstanding, most of the cases found in literature show a slump ratio lower than 1, indicating a general decrease in slump when using this additive.

The increase in workability with nSi is probably due to the material's suspension features. Nevertheless, in some cases in the literature is observed a loss of the material's workability with the incorporation of nano-silica (47,48), while other authors have observed increases in workability with dosages greater than 0.5% w/b (49). Therefore, to confirm these results, the same dosages were tested with another type of cement and aggregate, a plasticizer dose of 0.3% w/b, and nSi in different proportions (named nSi2). Figure 1 shows that an increase in workability was maintained by incorporating nSi2, similar to that seen in Figure 1 b). This confirms the trend towards an increase in slump ratio by incorporating nSi with the same w/b ratio.

Furthermore, more than 60 mixtures with the addition of nSi were found in the recent literature specifically studying workability. Most of the studies focused on a range between 0.5% and 3% of nSi. Workability is found proportional to nSi percentages in this range, nevertheless, for percentages higher that 3% fewer studies were found and with not a clear trend (Table 5, Figure 3).

Table 5. *Literature studies using nano sílica (nSi) addition in concrete.*

w/b	nSi (%)	fc (MPa)	fc MPa) (Base)	fc/ fc Base(MPa)	Slump (mm)	Slump (Base) (mm)	Slump / Slump (Base)	Reference
0.47	0.00	36.47	36.47	1.00	90.00	90.00	1.00	PS
0.47	0.50	34.80	36.47	0.95	140.00	90.00	1.56	PS
0.47	1.00	35.60	36.47	0.98	120.00	90.00	1.33	PS
0.47	1.50	36.90	36.47	1.01	135.00	90.00	1.50	PS
0.47	2.00	42.80	36.47	1.17	130.00	90.00	1.44	PS
0.47	2.50	45.60	36.47	1.25	160.00	90.00	1.78	PS
0.51	3.00	43.12	38.11	1.13	92.00	109.00	0.84	(39)
0.47	6.00	44.70	38.11	1.17	73.00	109.00	0.67	(39)
0.47	8.00	40.52	38.11	1.06	81.00	109.00	0.74	(39)
0.40	0.50	45.10	42.70	1.06	80.00	85.00	0.94	(50)
0.40	1.00	47.40	44.70	1.06	71.00	85.00	0.84	(50)
0.41	1.50	50.80	42.90	1.18	66.00	85.00	0.78	(50)
0.41	2.00	52.60	42.50	1.24	61.00	85.00	0.72	(50)
0.31	0.50	60.10	56.50	1.06	39.00	43.00	0.91	(47)
0.31	1.00	63.60	56.50	1.13	32.00	43.00	0.74	(47)
0.31	1.50	65.70	56.50	1.16	38.00	43.00	0.88	(47)
0.31	2.00	68.30	56.50	1.21	42.00	43.00	0.98	(47)
0.31	2.50	66.60	56.50	1.18	45.00	43.00	1.05	(47)
0.31	3.00	64.70	56.50	1.15	47.00	43.00	1.09	(47)
0.31	1.01	62.80	58.80	1.07	170.00	170.00	1.00	(43)
0.31	2.04	67.10	58.80	1.14	160.00	170.00	0.94	(43)
0.31	3.09	63.90	58.80	1.09	140.00	170.00	0.82	(43)
0.48	0.50	57.50	56.30	1.02	100.00	110.00	0.91	(25)
0.48	1.00	60.00	56.30	1.07	80.00	110.00	0.73	(25)
0.48	3.00	63.00	56.30	1.12	60.00	110.00	0.55	(25)
0.48	5.00	52.00	56.30	0.92	20.00	110.00	0.18	(25)
0.36	2.50	65.73	59.06	1.10	720.00	650.00	1.11	(41)
0.36	5.00	66.12	59.06	1.12	635.00	650.00	0.98	(41)
0.36	7.50	71.65	59.06	1.21	565.00	650.00	0.87	(41)
0.38	10.00	71.30	51.80	1.38	740.00	750.00	0.99	(44)
0.38	10.00	82.10	52.50	1.56	820.00	840.00	0.98	(44)
0.38	2.04	56.50	51.80	1.09	740.00	750.00	0.99	(46)
0.38	2.04	58.30	52.00	1.12	790.00	800.00	0.99	(46)
0.38	2.04	63.40	52.50	1.21	820.00	840.00	0.98	(46)
0.35	1.01	43.80	39.35	1.11	750.00	720.00	1.04	(42)
0.35	3.09	46.90	39.35	1.19	690.00	720.00	0.96	(42)
0.35	5.26	46.00	39.35	1.17	625.00	720.00	0.87	(42)
0.45	1.01	32.40	39.35	0.82	750.00	785.00	0.96	(42)
0.45	3.09	34.85	39.35	0.89	770.00	785.00	0.98	(42)
0.45	5.26	33.80	39.35	0.86	650.00	785.00	0.83	(42)
0.30	2.40	110.90	105.70	1.05	158.00	140.00	1.13	(38)
0.30	4.78	113.00	105.70	1.07	130.00	140.00	0.93	(38)
0.35	2.23	102.40	97.30	1.05	160.00	157.00	1.02	(38)

0.35	4.42	105.40	97.30	1.08	150.00	157.00	0.96	(38)
0.40	2.07	72.00	68.10	1.06	175.00	181.00	0.97	(38)
0.40	4.12	75.90	68.10	1.11	169.00	181.00	0.93	(38)
0.45	1.94	50.90	44.70	1.14	120.00	125.00	0.96	(38)
0.45	3.85	59.60	44.70	1.33	110.00	125.00	0.88	(38)
0.37	0.50	44.13	34.32	1.29	46.00	32.00	1.44	(51)
0.37	1.00	46.48	34.32	1.35	76.00	32.00	2.38	(51)
0.37	1.50	49.13	34.32	1.43	97.00	32.00	3.03	(51)
0.37	2.00	52.46	34.32	1.53	106.00	32.00	3.31	(51)
0.60	2.50	29.28	29.28	1.00	108.00	108.00	1.00	(52)
0.60	5.00	30.33	29.28	1.03	185.00	108.00	1.71	(52)
0.60	7.00	29.80	29.28	1.02	235.00	108.00	2.17	(52)
0.55	2.50	35.80	35.80	1.00	102.00	102.00	1.00	(52)
0.55	5.00	37.07	35.80	1.03	210.00	102.00	2.05	(52)
0.55	7.00	38.34	35.80	1.07	241.00	102.00	2.36	(52)
0.50	2.50	39.65	39.65	1.00	121.00	121.00	1.00	(52)
0.50	5.00	44.26	39.65	1.11	210.00	121.00	1.73	(52)
0.50	7.00	47.63	39.65	1.20	235.00	121.00	1.94	(52)
0.38	1.00	39.29	34.32	1.14	215.90	440.00	0.49	(53)
0.38	1.50	41.17	34.32	1.20	234.90	600.00	0.39	(53)
0.38	2.00	44.45	34.32	1.30	234.90	680.00	0.35	(53)
0.38	2.50	40.95	34.32	1.19	241.30	720.00	0.34	(53)
0.38	3.00	36.15	34.32	1.05	241.30	740.00	0.33	(53)
0.28	0.50	87.24	76.52	1.14	720.00	790.00	0.91	(35)
0.28	1.50	91.87	76.52	1.20	685.00	790.00	0.87	(35)

w/b water/binder ratio; fc= Compressive strength of the mixture with SF; fc (Base)= Compressive strength of the mixture without SF; Slump= Slump of the mixture with SF; Slump (Base)= Slump of the mixture without SF. In light blue are highlighted the mixtures where slump flow was measured instead of standard slump. PS= Present Study

Regarding the mixtures SF8.5-nSi0.2 and SF10.0-nSi0.2 of the present study, the manageability condition was critical, blocking good compaction of the sample and allowing an increase of the air content, therefore, leading to a reduction of the final resistance. Although the pozzolanic material can react in smaller spaces to densify on a smaller scale, if the mixture has larger internal cavities due to the lack of workability of the mixture, the generated matrix does not have enough density to reflect the effect of pozzolanic additions.

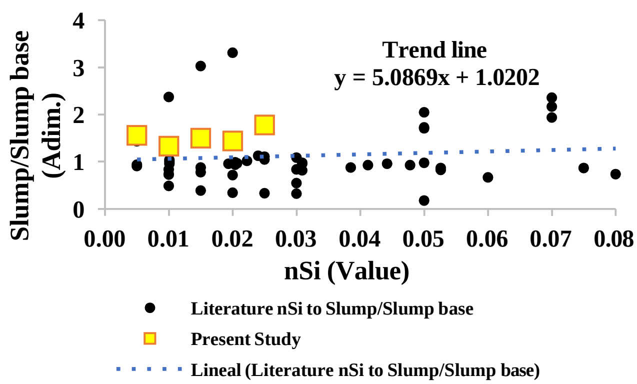

Figure 3. *Slump behavior in the literature for nSi*

Table 6. *Literature studies using SF+nSi addition in concrete.*

Mixture	w/b	% of SF	% of nSi	fc (MPa)	fc with only SF (MPa)	fc with only nSi (MPa)	fc (Base) (MPa)	Slump (mm)	Slump with only SF	Slump with only nSi	Slump (Base) (mm)	Reference
SF8.5-nSi0.2	0.50	8.50%	0.20%	39.23	40.10	42.80	36.47	20.00	35.00	130.00	90.00	PS
SF10-nSi0.2	0.50	10.00%	0.20%	35.44	40.90	42.80	36.47	0.00	35.00	130.00	90.00	PS
SF5-nSi0.5	0.28	5.00%	0.50%	95.25	79.27	87.24	76.52	690.00	740.00	720.00	790.00	(35)
SF5-nSi0.5	0.30	5.00%	0.50%	118.10	113.20	110.90	105.70	122.00	140.00	158.00	140.00	(38)
SF5-nSi1	0.30	5.00%	1.00%	121.40	113.20	113.00	105.70	110.00	140.00	130.00	140.00	(38)
SF5-nSi0.5	0.35	5.00%	0.50%	108.50	106.20	102.40	93.70	145.00	128.00	160.00	157.00	(38)
SF5-nSi1	0.35	5.00%	1.00%	111.60	106.20	105.40	93.70	129.00	128.00	150.00	157.00	(38)
SF5-nSi0.5	0.40	5.00%	0.50%	84.90	80.50	72.00	68.10	188.00	181.00	175.00	181.00	(38)
SF5-nSi1	0.40	5.00%	1.00%	90.60	80.50	75.90	68.10	187.00	181.00	169.00	181.00	(38)
SF5-nSi0.2.5	0.45	5.00%	0.50%	65.40	62.80	28.70	44.70	169.00	115.00	120.00	125.00	(38)
SF5-nSi1	0.45	5.00%	1.00%	73.30	62.80	39.70	44.70	166.00	115.00	110.00	125.00	(38)
SF2.5-nSi5	0.36	2.50%	5.00%	69.26	63.79	68.73	60.33	670.00	765.00	605.00	645.00	(41)
SF2.5-nSi2.5	0.36	2.50%	2.50%	82.17	63.79	65.73	60.33	685.00	765.00	695.00	654.00	(41)
SF5-nSi2.5	0.36	5.00%	2.50%	71.15	65.01	65.73	60.33	705.00	820.00	695.00	645.00	(41)
S10-nSi3	0.35	10.00%	3.00%	51.70	43.70	46.90	39.35	605.00	615.00	610.00	720.00	(42)
S10-nSi3	0.35	10.00%	3.00%	37.10	31.50	34.85	28.80	650.00	635.00	640.00	785.00	(42)
SF10-nSi5	0.35	10.00%	5.00%	33.90	31.50	33.80	28.80	625.00	635.00	580.00	785.00	(42)
SF10-nSi5	0.45	10.00%	5.00%	47.15	43.70	46.00	39.35	560.00	615.00	560.00	720.00	(42)
SF10-nSi1	0.45	10.00%	1.00%	34.70	31.50	32.40	28.80	715.00	635.00	645.00	785.00	(42)
SF10-nSi1	0.45	10.00%	1.00%	48.50	43.70	43.80	39.35	710.00	615.00	600.00	720.00	(42)
SF10-nSi2	0.38	10.00%	2.00%	87.90	63.40	82.10	52.50	740.00	760.00	820.00	750.00	(44)
SF10-nSi2	0.38	10.00%	2.00%	78.80	56.50	71.30	51.80	640.00	650.00	740.00	750.00	(44)
SF10-nSi2	0.38	10.00%	2.00%	78.80	56.50	71.30	51.80	640.00	650.00	740.00	750.00	(46)
SF10-nSi2	0.38	10.00%	2.00%	83.50	58.30	80.40	52.00	700.00	700.00	790.00	800.00	(46)
SF10-nSi2	0.38	10.00%	2.00%	87.90	63.40	82.10	52.50	740.00	760.00	820.00	840.00	(46)

w/b water/binder ratio; fc= Compressive strength of the mixture PS= Present Study

It is worth mentioning that all samples had the same content of plasticizer material. Table 6 and Figure 4 show an interesting comparison between 25 mixtures of SF+nSi found in literature. It is observed that other authors found similar trends (35,38).

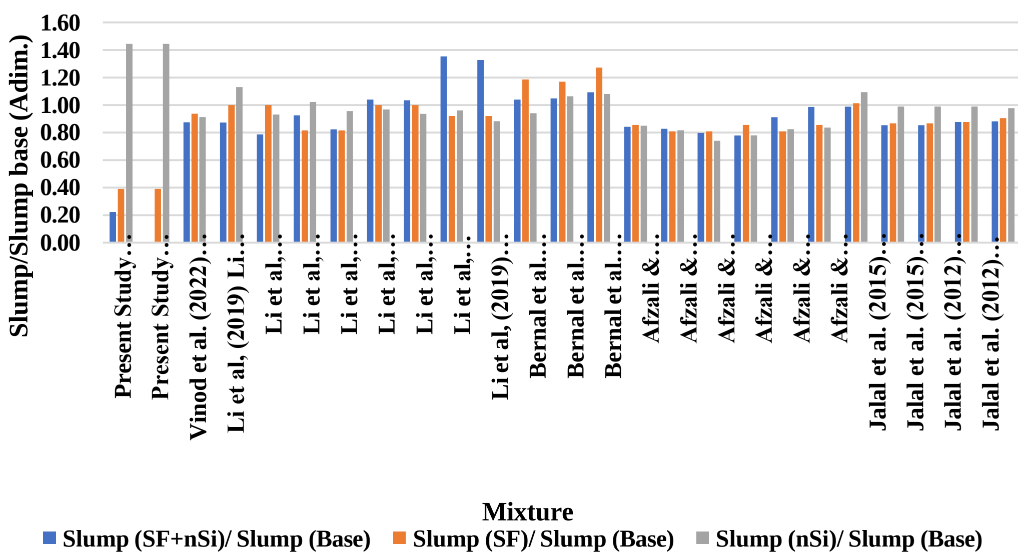

Figure 4. *Slump behavior in the literature for a) SF, b) nSi, c) SF+nSi mixtures*

3.2. Compressive strength

In the first stage, the compressive strength results (in Figure 1 a) show an increase with the addition of SF (from 36.47 MPa to 40.90 MPa). However, this was tangible only with dosages above 6.5%, reaching an increase in resistance up to 12.2%, compared to the standard mixture (see Figure 5). The increase in f_c was due to the formation of C–S–H bonds, during the hydration of the mixture, between the particles of cement and the silicon of SF, according to the literature (18,50).

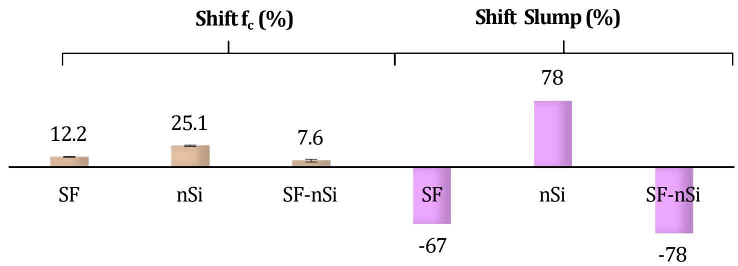

Figure 5. *Percent variation of the standard sample containing no pozzolanic addition in a) Compressive strength; and b) Slump for higher values of compressive strength, compared to plain mix. Data includes standard deviation where applicable.*

On the other hand, as can be seen in Figure 1 b) in the case of nSi, an increase in compressive strength was observed with dosages from 2%, reaching an improvement in f_c up to 25% with the addition of nSi1 (Figure 5), in accordance with Gesoğlu et al., (2012), (54). The initial increase in compressive strength with the addition of nSi was attributed to the increase in the dimensions and rigidity of CSH chains during hydration of the mixture's components, which can be produced by the presence of active nucleation sites from the pozzolanic reaction. This contributed to the densification of the microscale concrete structure by diminishing the concrete's porosity and improving the properties of the interfacial transition zone (17,22). In advanced stages, nSi modifies the internal structure of the C–S–H gel, increasing the average chain length, which leads to a denser structure. Hence, it is advisable to study this behavior at latter stages. The amount of CH drops, due to the pozzolanic reaction, while the large pores are partially or completely filled with hydration products (especially secondary C–S–H), (55).

As a decline in resistance was not achieved with the dosages utilized to confirm the results. In the literature (56), the same dosages were tested with another type of cement and aggregate, a plasticizer dose of 0.3% w/b, and nSi (named nSi 2). Figure 6 shows a drop in f_c, (56). This may have been because, for high SC dosages, the content of chemically combined water increases through the pozzolanic reaction of the nSi and, therefore, there is no free water to provide complete settlement. On the other hand, the excessive presence of nSi particles fills the pores and prevents Ca $(OH)_2$ crystals from growing and increasing the resistance, as has been shown previously, (57).

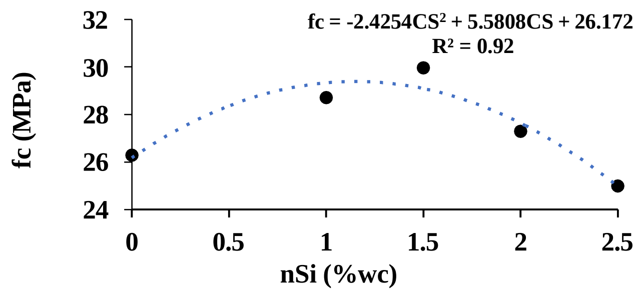

Figure 6. *f_c results from second mix with nSi for the present study (PS). Adapted from* (56).

Figure 7 shows the results found in the literature, compared with the present study. It is noted that for percentages lower than 3% of nSi there are exponential increases in compressive strength, according to the literature. However, for higher percentages no more significant increases are observed.

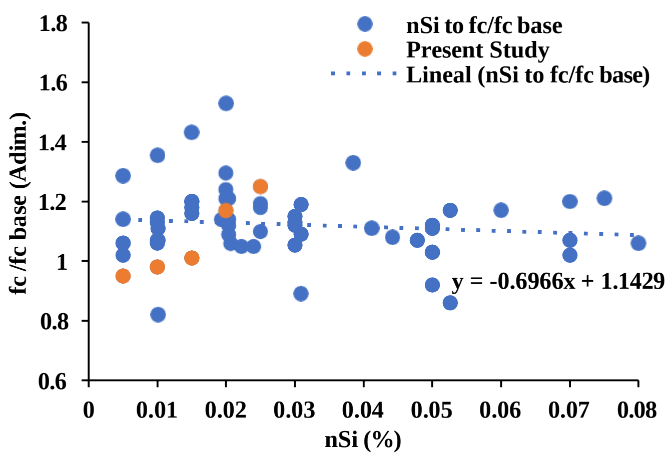

Figure 7. *fc (MPa) Improved/fc (MPa) results of other studies in the literature with nSi addition compared with the present study.*

With the results using nSi 2, the materials affected the optimum dosage point, propitiating a decline in resistance for high dosages of SC. Previous research on the microstructure of concrete has revealed that an increase in the dose of nano-silica from 3% to 6% did not increase CH consumption, suggesting that the overall improvement in performance associated with the increased addition of high nano-silica may be mainly due to the effect of the physical filler in the cement-based matrix (58).

With the addition of both siliceous compounds, a 7.6% increase in f_c was observed (Figure 5); the combined effect of siliceous pozzolanic additions increased the amount of SiO_2 particles, which are very fine and have a high surface area-to-volume ratio. Therefore, when the amount of SiO_2 is greater than a critical value, the clustering of particles occurs and, so, they cannot be dispersed well in the mix, as has been reported previously (25). On the other hand, the amount of SiO_2 may have exceeded the amount necessary to deplete the $Ca(OH)_2$ required during the hydration reaction to form the gel that gives rise to the C–S–H bonds, (24). Consequently, it is impossible to conform the homogeneous and dense microstructure of the materials, as the de-clustering of the nanoparticles is essential to achieve an improvement in concrete properties (59).

Although SF and nSi pozzolanic materials were added in this study, the results of the optimal ranges found for SF (10.0%) and NSI (1.5–2.0%) were consistent with those found in the

Table *5* and Table 6. It is feasible that, with higher doses of SF, there may still be an increase in f_c as found in the literature.

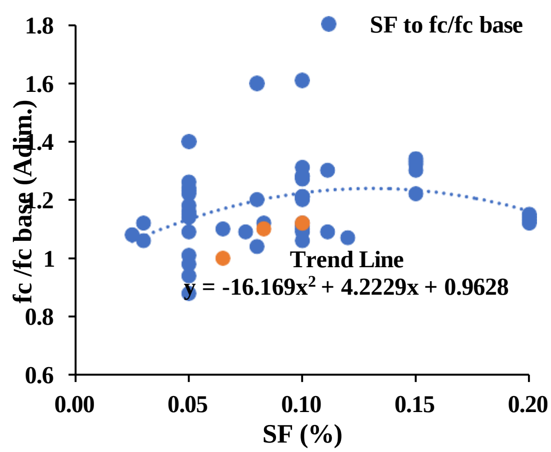

Figure 8. *fc (MPa)/fc base (MPa) results of other studies in the literature with SF addition compared with the present study.*

Table 5 and Table 6). The main purpose of this analysis was to fit each *fc* data set to a probability distribution model, considering SF, nSi and SF+nSi. This analysis was performed using MATLAB R2013a (The MathWorks Inc., Natick, Massachusetts, US), in which all statistical inferences assumed a confidence level of 95% (α= 0.05). The goodness of normal fitted distributions for each addition type (SF, nSi and SF+nSi) was assessed using a procedure based on the log likelihood ratio test, which results showed values between 5.55 and 39.75, meaning that the normal distribution is a good estimator of the data. Figure 9 a) and b) shows the normal and the cumulative distributions of the data.

However, the workability of the mixture must be improved. By combining the optimal doses without adding more superplasticizer, the resistance dropped dramatically, leading to results opposite to those observed in Table 4. This means that, in ternary mixtures, dosing of the additive at an important amount is vital to promoting the capacity to generate a compact matrix, thus improving the resistance.

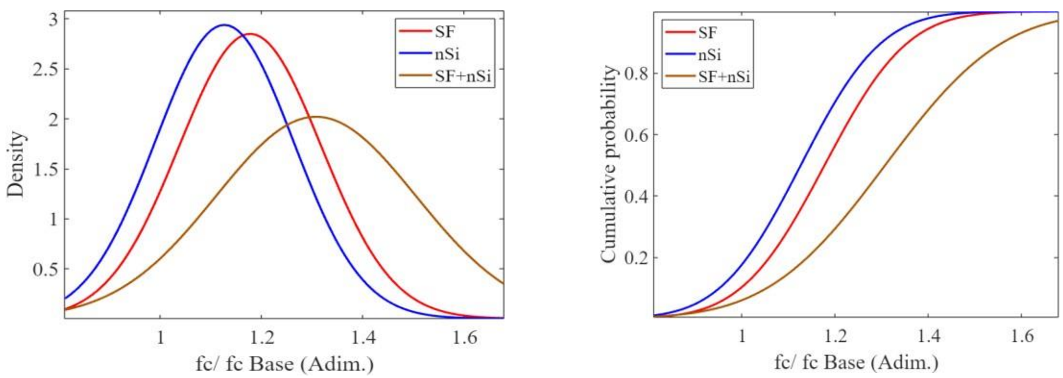

Figure 9. *a) fc/fc base Normal Distribution; b) fc/fc base Cumulative distribution, for SF, nSi and SF+nSi.*

When investigating the properties of high-performance self-compacting concrete with SF, they significantly improve for ternary samples whose agglomerate is cement, SF, and nSi. Increasing the SF content greatly increases the compressive strength, especially at latter stages. In comparison with control samples, when replacing up to 10% of SF in binary mixtures (with cement binder and SF), compressive strength was increased by 21.0% after 28 days. In contrast, 2% replacement of nSi in binary mixtures increased the compressive strength by 56% after 28 days, while 10% replacement of SF and 2% of nSi in ternary mixtures increased the compressive strength by 67% after 28 days. In binary mixtures, the enhancement in compressive strength was greater in mixtures containing 2–3.5% nSi and the highest occurred in ternary mixtures. When cement fractions are substituted by amorphous silicas at the microscopic scale, a more refined and packaged pore structure of the concrete can be observed, which can lead to an increase in the concrete strength and durability properties (44,46,60). Aside from the compressive strength (f_c), the rheological, thermal, and transport properties have been shown to improve in mixtures containing nSi and SF. However, when replacing high quantities of SF (beyond 15%) or nSi (beyond 3.5%), the yield decreases (60).

The rheological properties of the mixtures containing 2% of nSi have shown workability levels close to those of the mixtures without additives (44). The maximum contraction without restriction increased by about 80% for mortars with nSi at 7 days and by 54% at 28 days, compared to mortars with SF within the same periods (60).

Table 5 and Table 6 show the results of the optimum compressive strength tests at 28 days in which a percentage of cement with SF, nSi (in colloidal or powder form), and/or a combination of both was used. Furthermore, Table 3-4 and 5 show the mixtures where the individual and joint behavior of SF and nSi in concrete were assessed simultaneously. In that group, when a comparison was made with the mixtures in which the SF was replaced by nSi, there was a 30% increase in f_c, and a 41% increase when adding both materials as a replacement for cement. The average values taken as optimal in the studies were 10.3% of SF and 2.3% of nSi.

In studies where high amounts of nSi were used, the amount of additive added is generally above 3.5 % w/b (42,60), even as high as 5% w/b (20). In investigations, such as those of Behfarnia and Rostami, (2017) or Bernal et al., (2018), where the percentage of nSi was high, the concretes were made with special procedures, through the addition of other materials that require alkaline activation with Na (OH) or the implementation of curing with limestone water. Alkaline activation occurs with the reaction between solid aluminosilicate powders, such as fly ash, blast furnace slag, or metakaolin, and an alkaline solution. Pozzolanic materials are combined with hydrated calcium hydroxide (CH) to form hydrated calcium silicate (C–S–H), which is responsible for the strength of hydrated cement pastes (61). In the same line, it is worth mentioning that Jalal et al., (2012) have achieved the highest values of f_c in concrete, using limestone aggregate and siliceous sand with partial replacement of limestone filler. These materials provide a higher content of calcium carbonate, which allows for greater CH formation and helps to complete the pozzolanic reaction. Furthermore, lime filler has been shown to accelerate the hydration of C_3S, thus increasing early compression resistance (62). On the other hand, Jalal et al., (2012) ensured good manageability by using a high dose of superplasticizer (3.12% w/b), a viscosity modifying agent, a maximum size of low coarse aggregate (12.5 mm), and established values close to the optimum ones seen in

The different contents of nSi, with values approaching 2% nSi, also improved the modulus of elasticity, flexure resistance, load and displacement behavior, and fracture energy after 90 days. Ternary samples of cement, nSi, and SF seem to yield better results than concrete samples that only contain nSi (20).

Table ***5*** and Figure 3 (i.e., 0% SF and 2% nSi) for their mixture.

The aggregate of the material significantly defines the final resistance values. For example, the f_c values of Afzali Naniz & Mazloom, (2018) were much lower than the others, as their coarse aggregate was light. Mortar f_c values are generally higher, as the fineness of the material leaves less pores in the mixture; however, it is also necessary to emphasize the fact that mortar mixtures incorporate higher dosages of SF and a lower w/b ratio. In the research reported in the literature shown above, mixing water was kept constant, as part of the cement was replaced by pozzolan. Another way of combining amorphous silicas is as an addition; that is, maintaining a constant weight of the cement and changing the amount of water in the mixture to maintain the w/b ratio.

Additionally, the authors found in the literature numerous applications of nSi and SF also in mortars although it is not the object of this study. It was noted that with the addition of nSi up to 2% there is agreement in the literature on the benefits over f_c. However, as for concrete, when the percentages exceed 3% the benefits in terms of f_c are the object of discussion, having contrasting results in the literature. Furthermore, with the addition of SF, a minor increase in f_c is noted in the literature. Nevertheless, percentages greater than 6% - 8% show there may still be an increase in f_c as found for the concrete.

3.3. Cost–benefit analysis

The present study shows concrete mixtures with the addition of SF and nSi with an overview in the literature. However, in developing countries, there is a significant lack of research on this issue and an almost total absence of cost–benefit analyses.

Therefore, even though it was not the main objective of this study, a simplified cost–benefit analysis is presented in, considering only direct costs and applied to the Colombian context. The cost of concrete was calculated per m^3, according to material local prices (in Cartagena) from quarries and cement makers, including labor costs. Therefore, the costs were calculated in Colombian pesos (COP) and converted to USD by applying the exchange of COP 4,392.00 for 1 USD (rate at September 2022).

Cost variation was found to range between +17.9% and +72.2%, while strength variation was between -4.6% and +25%. This means that a cost increase does not always correspond to a strength improvement. Furthermore, unit cost per MPa of strength showed that the lower rate corresponded to the control sample, 3.03 (USD/MPa), while the most convenient between the other mixtures proposed was SF0-NSI2.5, with 3.11 (USD/MPa). In fact, the latter, with the 2.5% nSi addition to the standard mixture, reached up to a 25% strength (f_c) increase.

Table 7. *Cost–benefit analysis*

SF (%)	nSi (%)	Cost (USD)/m^3	f_c (MPa)	Δ f_c (MPa)	Δ Cost (%)	Δ Strength (%)	Cost (USD)/f_c (MPa)	Cost (USD)/f_c Improved (MPa)
0.0	0.0	87.7	36.47	-	-	-	2.40	-
6.5	-	134.2	-	0.03	53.1	0.1	-	3.68
8.5	-	142.4	-	3.63	62.4	10.0	-	3.55
10.0	-	150.1	-	4.43	71.2	12.1	-	3.67
-	0.5	103.3	-	-1.67	17.9	-4.6	-	2.97
-	1.0	105.6	-	-0.87	20.4	-2.4	-	2.96
-	1.5	107.8	-	0.43	23.0	1.2	-	2.92
-	2.0	110.0	-	6.33	25.5	17.4	-	2.57
-	2.5	112.3	-	9.13	28.1	25.0	-	2.46
8.5	0.2	144.1	-	2.76	64.4	7.6	-	3.68
10.0	0.2	150.9	-	-1.03	72.2	-2.8	-	4.25

Cost = cost of one m^3 of concrete in (USD); USD = United States of America Dollar; Δ Cost = Cost variation between f_c Improved and f_c (per m^3); Δ Strength = Strength variation between improved mixture and standard mixture; f_c Improved= $f_c + \Delta f_c$.

Further studies should progressively increase the nSi rate, which appears to be the most promising mixture, as well as carrying out sustainability assessments. In the literature, encouraging results can be found in this regard. Gunasekara et al., (2020) proposed a sustainability assessment of High-Volume Fly Ash (HVFA) concrete and Portland Concrete (PC) with and without nano-silica. They estimated the emissions factor considering the manufacturing processes, which corresponds to the energy consumption and emission activities during raw material extraction, transportation to production plant, and production processes. They finally found that the addition of nSi into the mix design caused a cost increment in HVFA concrete, corroborating what was found in the present work. However, cost reductions could be achieved by reducing transport costs and through efficient manufacturing techniques and procurement strategies.

The addition studied in this study can be considered cost-effective compared to other additives with similar effects found in literature such as nano iron (64), nano-metakaolin (NMK) (65) and nano-clay (66).

4. Conclusion

The main objective of this study was to evaluate the concrete compression behavior at various SF, nSi, and combined SF-nSi dosages, keeping constant the plasticizer dosages, w/b ratio, and the stone aggregates. Under the proportions studied and with the materials used, it can be concluded that SF dosages between 6.5% and 10.0% w/b can increase the compressive strength from 36.47 MPa to 40.90 MPa (12%), but significantly decrease the workability of the sample, generating a spike in viscosity that could hinder the compaction of the mixture in the formwork.

In contrast, nSi raised the compressive strength from 36.47 MPa to 45.63 MPa (25%) with doses above 1.5–2% w/b and increased the workability at dosages greater than 0.5% w/b, which may be due to the liquid suspension state of the nanomaterial. Improvements in strength can be attributed to the augmented production of C–S–H gels during the hydration and densification of the microstructure.

The results achieved suggest the need to optimize the SF and nSi dosage, when used simultaneously, in order to find the balance between workability and mechanical performance, given the fact that, within the proportions studied (nSi 0.2% and SF 10.0%), the loss of workability was up to 100%. This may be due to the sizes of the micro- and nanoparticles and their reactivity, which prevents the proper setup of the fresh mixture within the important molds, as well as their porosities, which limit the increase in mechanical resistance. A 2% nSi dosage can achieve the same effect as a 10% SF dosage; however, the optimum dosage points to reach a higher f_c may vary with the type of materials used.

The extensive literature review confirms that for higher SF percentages it is observed a loss of workability, while for nSi is observed a slightly positive trend for Slump/Slump base. However, most of the studies focus on nSi percentages lower than 3%. For future research is suggested an extensive experimental campaign considering SF percentages from 1% to 20% and nSi from 0.5% to 10%, whit intervals of 0.5% expanding the physicochemical and mechanical parameters to be monitored.

Finally, a cost–benefit analysis was proposed, which has rarely been studied worldwide for such concrete additions. Authors did not wish to be exhaustive, in this regard. However, it should be noted that there is enormous potential in adding these types of fibers. Decreases in the unit cost of these materials could progressively lead to the entry of such mixtures into the construction market in the near future. For future research Life-Cycle Assessment (LCA) is suggested to clearly evaluate and identify environmental impact of the solution studied.

Acknowledgement

The authors thank the Fund for the Promotion of Technological Innovation which, through the "*Fomento IDT 2015-2017- Mipymes Proceso 2*" campaign, provided financial support to the "New high-strength hydraulic pavement for mobile loads with natural stone aggregates and the addition of superficially modified fibers" project, in collaboration INGUETO and Cia ltda, and the University of Cartagena (Colombia). The authors thank the students of the ESCONPAT and GEOMAVIT research group of the University of Cartagena, Colombia, for the extensive help with the literature review.

5. References

1. Xuan DX, Shui ZH, Wu SP. Influence of silica fume on the interfacial bond between aggregate and matrix in near-

surface layer of concrete. Constr Build Mater. 2009;23(7):2631–5.

2. Ahmed MM. Study on Durability Properties of Concrete Using Silica Fume With Addition of Polypropylene Fibre. 2017;3(11):21–5.

3. Fidjestøl P, Lewis R. Microsilica as an Addition. Lea's Chem Cem Concr. 1998 Jan;679–712.

4. Sanjuán MÁ, Argiz C, Gálvez JC, Moragues A. Effect of silica fume fineness on the improvement of Portland cement strength performance. Constr Build Mater. 2015;96:55–64.

5. Siddique R. Utilization of silica fume in concrete: Review of hardened properties. Resour Conserv Recycl. 2011;55(11):923–32.

6. Damineli BL, Pileggi RG, John VM. Lower binder intensity eco-efficient concretes. Eco-Efficient Concr. 2013;26–44.

7. Paiva H, Silva AS, Velosa A, Cachim P, Ferreira VM. Microstructure and hardened state properties on pozzolan-containing concrete. Constr Build Mater. 2017 Jun;140:374–84.

8. Aggarwal P, Singh RP, Aggarwal Y. Use of nano-silica in cement based materials—A review. Cogent Eng. 2015;2(1).

9. Almusallam AA, Beshr H, Maslehuddin M, Al-Amoudi OSB. Effect of silica fume on the mechanical properties of low quality coarse aggregate concrete. Cem Concr Compos. 2004;26(7):891–900.

10. Bhattacharyya S, Akhtar S, Chaudhuri A, Mahanty S, Chaudhuri P, Sudarshan M. Affirmative nanosilica mediated approach against fungal biodeterioration of concrete materials. Case Stud Constr Mater. 2022 Dec 1;17:e01258.

11. Castro-Hoyos AM, Rojas Manzano MA, Maury-Ramírez A. Challenges and Opportunities of Using Titanium Dioxide Photocatalysis on Cement-Based Materials. Coatings 2022, Vol 12, Page 968 [Internet]. 2022 Jul 7 [cited 2022 Nov 21];12(7):968. Available from: https://www.mdpi.com/2079-6412/12/7/968/htm

12. Wongkeo W, Thongsanitgarn P, Ngamjarurojana A, Chaipanich A. Compressive strength and chloride resistance of self-compacting concrete containing high level fly ash and silica fume. Mater Des. 2014 Dec;64:261–9.

13. Muhd Norhasri MS, Hamidah MS, Mohd Fadzil A, Megawati O. Inclusion of nano metakaolin as additive in ultra high performance concrete (UHPC). Constr Build Mater. 2016 Nov;127:167–75.

14. Di Maida P, Sciancalepore C, Radi E,

Bondioli F. Effects of nano-silica treatment on the flexural post cracking behaviour of polypropylene macro-synthetic fibre reinforced concrete. Mech Res Commun. 2018;88:12–8.

15. Janković K, Stanković S, Bojović D, Stojanović M, Antić L. The influence of nano-silica and barite aggregate on properties of ultra high performance concrete. Constr Build Mater. 2016;126:147–56.

16. Du H, Du S, Liu X. Effect of nano-silica on the mechanical and transport properties of lightweight concrete. Constr Build Mater. 2015 May;82:114–22.

17. Balapour M, Ramezanianpour AA, Hajibandeh E. An investigation on mechanical and durability properties of mortars containing nano and micro RHA. Constr Build Mater. 2017;132:470–7.

18. Balapour M, Joshaghani A, Althoey F. Nano-SiO2contribution to mechanical, durability, fresh and microstructural characteristics of concrete: A review. Constr Build Mater. 2018;181:27–41.

19. Khan MI. Nanosilica/silica fume. Waste and Supplementary Cementitious Materials in Concrete. Elsevier Ltd; 2018. 461–491 p.

20. Gesoglu M, Güneyisi E, Asaad DS, Muhyaddin GF. Properties of low binder ultra-high performance cementitious composites: Comparison of nanosilica and microsilica. Constr Build Mater. 2016 Jan;102:706–13.

21. Sarkar SL, Aimin X, Jana D. Scanning-Electron-Microscopy-X-Ray-Microanalysis-of-Concretes_2001_Handbook-of-Analytical-Techniques-in-Concrete-Science-and-Technology.pdf. In: Ramachandran VS, Beaudoin JJ, editors. Handbook of Analytical Techniques in Concrete Science and Technology. 2001. p. 231–74.

22. Reches Y. Nanoparticles as concrete additives: Review and perspectives. Constr Build Mater. 2018 Jun;175:483–95.

23. Alkaysi M, El-Tawil S, Liu Z, Hansen W. Effects of silica powder and cement type on durability of ultra high performance concrete (UHPC). Cem Concr Compos. 2016;66:47–56.

24. Ghafari E, Costa H, Júlio E, Portugal A, Durães L. The effect of nanosilica addition on flowability, strength and transport properties of ultra high performance concrete. Mater Des. 2014;59:1–9.

25. Behfarnia K, Rostami M. Effects of micro and nanoparticles of SiO2on the permeability of alkali activated slag concrete. Constr Build Mater.

2017;131:205–13.

26. Siddique R, Chahal N. Use of silicon and ferrosilicon industry by-products (silica fume) in cement paste and mortar. Resour Conserv Recycl. 2011;55(8):739–44.

27. Satish Chandra LB. Use of silica fume in concrete (multiple letters). Indian Concr J. 2002;76(2):131–2.

28. Ardalan RB, Jamshidi N, Arabameri H, Joshaghani A, Mehrinejad M, Sharafi P. Enhancing the permeability and abrasion resistance of concrete using colloidal nano-SiO2 oxide and spraying nanosilicon practices. Constr Build Mater. 2017;146:128–35.

29. Qasim OA, Al-Ani SA. Effect of nano-silica silica fume and steel fiber on the mechanical properties of concrete at different ages. AIP Conf Proc. 2020 Mar 25;2213.

30. American Society for Testing and Materials (ASTM). ASTM C1157/C1157M - 20 Standard Performance Specification for Hydraulic Cement [Internet]. 2020. Available from: https://www.astm.org/Standards/C1157.htm

31. Yasin AK, Bayuaji R, Susanto TE. A review in high early strength concrete and local materials potential. In: IOP Conference Series: Materials Science and Engineering. 2017.

32. Srinivasan CB, Lakshmi Narasimhan N, Ilango S V. Development of rapid-set high-strength cement using statistical experimental design. Cem Concr Res. 2003;33(9):1287–92.

33. American Society for Testing and Materials (ASTM). ASTM C143/C143M - 20 Standard Test Method for Slump of Hydraulic-Cement Concrete [Internet]. 2020. Available from: https://www.astm.org/DATABASE.CART/HISTORICAL/C143-78.htm

34. American Society for Testing and Materials (ASTM). ASTM C39/C39M - 20 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [Internet]. 2020. Available from: https://www.astm.org/TRAIN/filtrexx40.cgi?+-P+ID+174+traindetail.frm

35. Vinod Kumar G, Narendra Kumar B. Effect on mechanical, durability and micro structural properties of high strength self compacting concrete with inclusion of micro and nano silica. Mater Today Proc [Internet]. 2022;(xxxx). Available from: https://doi.org/10.1016/j.matpr.2022.02.064

36. Luo T, Hua C, Liu F, Sun Q, Yi Y, Pan X. Effect of adding solid waste silica fume as a cement paste replacement on

the properties of fresh and hardened concrete. Case Stud Constr Mater. 2022;16(April):e01048.

37. Nili M, Ramezanianpour AA, Sobhani J. Evaluation of the effects of silica fume and air-entrainment on deicer salt scaling resistance of concrete pavements: Microstructural study and modeling. Constr Build Mater [Internet]. 2021;308(September):124972. Available from: https://doi.org/10.1016/j.conbuildmat.2021.124972

38. Li LG, Zheng JY, Ng PL, Zhu J, Kwan AKH. Cementing efficiencies and synergistic roles of silica fume and nano-silica in sulphate and chloride resistance of concrete. Constr Build Mater J. 2019;223:965–75.

39. Wang Y, Hughes P, Niu H, Fan Y. A new method to improve the properties of recycled aggregate concrete: Composite addition of basalt fiber and nano-silica. J Clean Prod. 2019 Nov 1;236:117602.

40. Meddah MS, Ismail MA, El-Gamal S, Fitriani H. Performances evaluation of binary concrete designed with silica fume and metakaolin. Constr Build Mater [Internet]. 2018;166:400–12. Available from: https://doi.org/10.1016/j.conbuildmat.2018.01.138

41. Bernal J, Reyes E, Massana J, León N, Sánchez E. Fresh and mechanical behavior of a self-compacting concrete with additions of nano-silica, silica fume and ternary mixtures. Constr Build Mater. 2018 Jan;160:196–210.

42. Afzali Naniz O, Mazloom M. Effects of colloidal nano-silica on fresh and hardened properties of self-compacting lightweight concrete. J Build Eng. 2018 Nov;20:400–10.

43. Fallah S, Nematzadeh M. Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume. Constr Build Mater. 2017 Feb;132:170–87.

44. Jalal M, Pouladkhan A, Harandi OF, Jafari D. Comparative study on effects of Class F fly ash, nano silica and silica fume on properties of high performance self compacting concrete. Constr Build Mater. 2015;94:90–104.

45. Çakır Ö, Sofyanlı ÖÖ. Influence of silica fume on mechanical and physical properties of recycled aggregate concrete. HBRC J. 2015;11(2):157–66.

46. Jalal M, Mansouri E, Sharifipour M, Pouladkhan AR. Mechanical, rheological, durability and microstructural properties of high performance self-compacting concrete containing SiO2micro and

nanoparticles. Mater Des. 2012;34:389–400.

47. Chithra S, Senthil Kumar SRR, Chinnaraju K. The effect of Colloidal Nano-silica on workability, mechanical and durability properties of High Performance Concrete with Copper slag as partial fine aggregate. Constr Build Mater. 2016;113:794–804.

48. Ghafari E, Costa H, Júlio E, Portugal A, Durães L. The effect of nanosilica addition on flowability, strength and transport properties of ultra high performance concrete. Mater Des. 2014 Jul;59:1–9.

49. Khaloo A, Mobini MH, Hosseini P. Influence of different types of nano-SiO2 particles on properties of high-performance concrete. Constr Build Mater. 2016 Jun;113:188–201.

50. Najigivi A, Khaloo A, Iraji zad A, Abdul Rashid S. Investigating the effects of using different types of SiO2 nanoparticles on the mechanical properties of binary blended concrete. Compos Part B Eng. 2013 Nov;54:52–8.

51. Carrasco Vasques DJ, Fernandez Herrera LH. Influencia del Nano-sílice en las propiedades de un concreto de F'c= 350 kg/cm2 para obtener un concreto de alta resistencia [Internet]. Universidad Cesar Valejo; 2019. Available from: https://repositorio.ucv.edu.pe/handle/20.500.12692/52543

52. Dongo G P, Saavedra P O. Influencia de la adición de nanosílice en la permeabilidad del concreto. Veritas. 2021;21:29–38.

53. Mendoza Almonte H. Influencia de la Nanosílice por sustitución parcial al cemento en el diseño del mezcla de concreto de alta resistencia, en la ciudad de Puno. Universidad Nacional del altipiano, Perú; 2021.

54. Gesoğlu M, Güneyisi E, Kocabağ ME, Bayram V, Mermerdaş K. Fresh and hardened characteristics of self compacting concretes made with combined use of marble powder, limestone filler, and fly ash. Constr Build Mater. 2012 Dec;37:160–70.

55. Kontoleontos F, Tsakiridis PE, Marinos A, Kaloidas V, Katsioti M. Influence of colloidal nanosilica on ultrafine cement hydration: Physicochemical and microstructural characterization. Constr Build Mater. 2012;35:347–60.

56. Cardona Acuña JD, Márquez Cárcamo LA. Adición de nanopartículas de óxido de sílice y su incidencia en las propiedades físicas y mecánicas del concreto. University of Cartagena; 2018.

57. Abd.el.aleem S, Heikal M, Morsi WM. Hydration characteristic, thermal

expansion and microstructure of cement containing nano-silica. Constr Build Mater. 2014;59:151–60.

58. Said AMM, Zeidan MSS, Bassuoni MTT, Tian Y. Properties of concrete incorporating nano-silica. Constr Build Mater. 2012;36:838–44.

59. Rong Z, Sun W, Xiao H, Jiang G. Effects of nano-SiO2 particles on the mechanical and microstructural properties of ultra-high performance cementitious composites. Cem Concr Compos. 2015 Feb;56:25–31.

60. Senff L, Hotza D, Repette WL, Ferreira VM, Labrincha JA. Mortars with nano-SiO2and micro-SiO2investigated by experimental design. Constr Build Mater. 2010;24(8):1432–7.

61. Song HW, Pack SW, Nam SH, Jang JC, Saraswathy V. Estimation of the permeability of silica fume cement concrete. Constr Build Mater. 2010;24(3):315–21.

62. Medjigbodo G, Rozière E, Charrier K, Izoret L, Loukili A. Hydration, shrinkage, and durability of ternary binders containing Portland cement, limestone filler and metakaolin. Constr Build Mater. 2018;183:114–26.

63. Gunasekara C, Sandanayake M, Zhou Z, Law DW, Setunge S. Effect of nano-silica addition into high volume fly ash–hydrated lime blended concrete. Constr Build Mater. 2020 Aug 30;253:119205.

64. López-Carrasquillo V, Hwang S. Comparative assessment of pervious concrete mixtures containing fly ash and nanomaterials for compressive strength, physical durability, permeability, water quality performance and production cost. Constr Build Mater. 2017;139:148–58.

65. Diab AM, Elyamany HE, Abd Elmoaty AEM, Sreh MM. Effect of nanomaterials additives on performance of concrete resistance against magnesium sulfate and acids. Constr Build Mater [Internet]. 2019;210:210–31. Available from: https://doi.org/10.1016/j.conbuildmat.2019.03.099

66. Mohamed AM. Influence of nano materials on flexural behavior and compressive strength of concrete. HBRC J [Internet]. 2016;12(2):212–25. Available from: http://dx.doi.org/10.1016/j.hbrcj.2014.11.006