Research Article

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Effect of nano-silica on the mechanical properties of LWC

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Abstract: Nanotechnology has made significant inroads across various sectors, augmenting properties and economic impacts. Its pivotal role extends notably to the realm of construction and building. This study focuses on the tangible consequences of incorporating nano-silica (NS) into lightweight concrete (LWC) and its influence on mechanical attributes. The primary aim is to illustrate how NS impacts the mechanical properties of LWC, specifically its effects on compressive strength, flexural strength, and tensile strength in comparison to conventional LWC. The research encompassed the casting and examination of seven distinct concrete mixtures, including a reference mix, in laboratory settings. The study findings highlight that the utilization of lightweight Iraqi porcelanite stone resulted in a one-third reduction in the weight of standard concrete. Furthermore, the introduction of varying quantities of NS into structural LWC yielded enhancements in compressive, tensile, and flexural strength when contrasted with the reference mix, albeit at the expense of workability. Remarkably, The results showed an introduction of varying quantities of NS into structural LWC yielded enhancements in compressive, tensile, and flexural strength when contrasted with the reference mix, albeit at the expense of workability. The findings demonstrated that when doses of 1, 3, 5, 10, 15, and 20% NS were applied, the rate of three models for determining compressive strength at 90 days old rose by 19, 45, 62, 32, 15, and 37%, respectively. On the other hand, when dosages 1, 3, 5, 10, 15, and 20% were added, the percentage of improvement in tensile strength at 28 days of age was 77, 75, 84, 51, 55, and 53%. Additionally, while employing the same above doses, the bending strength at 28 days of age improved by 141, 140, 171, 115, 114, and 108%, respectively. Remarkably, the results also underscored the sustained efficacy of NS, particularly during the later stages of concrete maturation.

Keywords: compressive strength, flexural strength, splitting tensile strength, porcelanite lightweight aggregate, structural lightweight concrete

1 Introduction

One of the most widely consumed commodities in the world, Portland cement, has the excellent advantages of being inexpensive, fire-resistant, and able to be cast into any desired shape. Cement does, however, have several drawbacks, such as brittleness, volume instability, and porous systems. Lately, scientists and engineers have been working harder to investigate the possible uses of nanotechnology as a means of enhancing the performance of conventional cement-based materials. Using nanoparticles, such as nano-SiO_2 for increased strength and durability, cement composites' bulk engineering qualities may be altered [1]. Moreover, cement-based materials can be endowed with certain intelligent qualities that are needed for certain purposes, such as self-cleaning and discoloration resistance by nano-TiO_2 to combat the air pollution problem [2].

A form of concrete known as lightweight concrete (LWC) has an air-dry unit weight of 400–2,000 kg m^{-3}. In contrast to conventional weight concrete, which has a unit weight of 2,400 kg m^{-3}, structural LWC has a unit weight between 1440 to 1920 kg m^{-3}. Because of their decreased self-weight, the structures can have more efficiently utilized spaces thanks to lower cross-sectional structural

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components [3]. Because less water can collect near the aggregate particle, it has been shown that the interfacial zone (ITZ) thickness will decrease as the lightweight aggregate's absorption capacity increases. In addition, LWC with lightweight aggregates benefits from internal curing, which can lessen permeability and stop shrinkage cracking. It is evident from earlier studies that nano-silica (NS) can strengthen the LWC's defenses against water and chloride ion intrusion [4].

With its small particle size and high surface area, NS has drawn a lot of attention for its potential to improve the mechanical properties of concrete. Being a highly reactive material, it can affect the hydration process and microstructure of the cementitious matrix, improving the strength, durability, and other mechanical characteristics of concrete. The use of nanomaterials has revolutionized many industries, including the construction industry [5].

The mechanical characteristics of concrete, including its tensile strength, flexural strength, and compressive strength, are important factors in determining how well structures and infrastructure function structurally and are reusable. A lot of research has been done to find out how NS affects these characteristics, especially when it comes to LWC. Gaining insight into how NS affects LWC's mechanical behavior is crucial to improving its functionality and broadening its uses [6].

Through a number of methods, NS can improve the mechanical characteristics of LWC. It serves as a nucleation site, which lowers the porosity of the cementitious matrix and encourages the development of more hydration products. Reduced permeability and increased strength are the results of this densification. Second, by strengthening the interfacial transition zone and binding strength, NS particles can cover the spaces left by bigger aggregate particles. Furthermore, NS has the ability to alter the cement paste's microstructure, which can affect the hydration products' connectivity and dispersion [5].

The incorporation of NS in LWC holds significant potential for various applications. The enhanced mechanical properties can lead to the development of lightweight structural elements with improved load-bearing capacity, reduced thickness, and increased resistance to environmental factors. Furthermore, the reduced cement content achieved through NS additions contributes to sustainable construction practices by minimizing carbon emissions and resource consumption [7].

Many investigations have been done to look at the interaction between LWC and NS and how it affects mechanical qualities [8], given the relevance of LWC and the promising potential of NS. The objective of this study is to add to the current corpus of knowledge by providing a thorough examination of the effect of NS on the mechanical properties of LWC. For engineers, researchers, and business experts engaged in the design and development of cutting-edge LWC materials, the study's conclusions will offer insightful information [9].

It is important to note that numerous studies have been conducted to look into the characteristics of LWC, and to the best of the author's knowledge, a small number of experimental investigations look into the impacts of NS in combination with LWC. This study aims to explore the impact of varying concentrations of NS on the fresh and hardened properties of LWC, specifically 0, 1, 3, 5, 10, 15, and 20%. The LWC specimens' mechanical properties (compressive strength, splitting tensile strength, flexural strength, and microstructure) as well as their workability qualities (slump) have been established for this reason. It should be mentioned that the workability is reduced because of the high surface areas and absorb the mixing of water, but the mechanical properties have been improved.

In conclusion, adding NS to LWC provides a technique to improve its performance and mechanical qualities. Researchers and practitioners can harness the potential of nanotechnology to develop novel and sustainable construction materials that improve structural performance and have positive environmental effects by understanding the effects of NS on the mechanical behavior of LWC.

2 LWC

LWC is a term given to concrete with a density between 300 and 2,000 kg m^{-3} [10]. This type of concrete was used in many parts of buildings because of its lightweightness compared to traditional concrete [11]. Two kinds of LWC exist based on the uses for which it is intended. The first type of concrete is known as structural lightweight concrete, and it is categorized in accordance with American Code ACI No. 211.2, which states that the concrete's density must not exceed 2,000 kg m^{-3}, and its compressive strength must not be less than 17 MPa after 28 days. This kind of concrete is frequently used for load-bearing surfaces like ceilings and walls. Non-structural LWC is the second variety, which is primarily utilized for partition floors or non-load-bearing walls. There are actually three ways to make LWC. This study will describe the first method, which is to employ lightweight aggregates in place of traditional aggregates. The second technique is called light-foamed or cellular concrete, and it is made by creating tiny, air-filled pores in the cement mixture. Lastly, the third technique yields light concrete that only contains coarse aggregate and cement as a binder. This type of concrete is made without the use of fine aggregate [12]. LWC has great advantages, including lightweight, thermal insulation, fire resistance, and heat storage capacity [13]. Nevertheless, this concrete has several flaws, such as being sensitive to water, hard to polish, and challenging to finish because of the aggregate's porosity and angle. Lastly, it takes longer to achieve optimum mixing than it does with regular concrete [14]. The main difficulty for designers using LWC is that it has a low compressive strength, which limits the usage of concrete in certain areas. The researchers looked for numerous ways to increase LWC's compressive strength without changing its density [15]. Some researchers have succeeded in finding new solutions, such as using additives or fibers. After the emergence of nanomaterials, the researchers focused most of their interest on using them to improve the mechanical properties of concrete to increase its applications in buildings.

In this study, LWAC was produced using the sedimentary rock porcelanite. It has been known by a variety of names, several of which are trademarks used in commerce (*e.g.*, diatomite, filtac, diatomaceous earth, cellite, kieselguhr). Its unique qualities that qualify it for the sector are reflected in its texture, chemical makeup, and mineral makeup [16].

In Iraq, porcelanite is found in the Iraqi Western Desert. Two types of porcelanite were noted; the first one with a SiO_2 content of more than 70%, and the second one with a SiO_2 content of 60–69%. Manufactured LWA costs a lot of money which is why porcelanite rock is a very important source of LWA [17].

3 Nanotechnology

Cement production emits waste estimated at 7% of the total atmospheric waste [18]. Through the use of green concrete, it became possible to reduce the amount of carbon dioxide emission, but without affecting the quality of the cement. Scientists found that the use of complementary cement materials is one of the solutions that reduce the amount of cement produced and thus reduce the amount of carbon dioxide in the atmosphere [18]. One of the best of these supplementary cement materials is nanomaterials. They are nanoparticle materials that have a large surface area and unique mechanical and physical properties [19]. Nanomaterials have been and still are of interest to many researchers and have been used in various fields in the past few years [20,21]. Through their investigations and research, the researchers discovered that adding more nanoparticles to concrete boosts its compressive, tensile, and bending resistance while lowering its average corrosion rate. This leads us to the conclusion that nanoparticles are more beneficial than conventional materials. The ability of nanoparticles to improve the cohesiveness and homogeneity of concrete was demonstrated by the researchers [22]. A variety of nanomaterials have been employed to improve the characteristics of concrete: the most well-known ones are NS, iron oxide nanoparticles, metakaolin, alumina, carbon nanotubes, graphite oxide nanoparticles, zinc oxide nanoparticles, and modified montmorillonite clay nanoparticles [5,23–36].

4 Literature review

In this part, previous studies on the effect of NS on the compressive, flexural, tensile strength, and microstructure of normal and LWC will be reviewed.

Shah and Pitroda [24] in an experimental study to demonstrate the effect of NS on the compressive strength of lightweight cellular concrete. Different doses of NS were replaced by the weight of the cement. Several mixtures were prepared, some containing NS and others free of it, and a comparison was made between them. All samples were examined at the age of 3, 7, and 28 days. The results showed that the addition of a small dose of NS increased the compressive strength of the mixtures containing NS. It was also observed that the strength in the early stage of solidification increases as a result of the pozzolanic activity of the NS. Figure 1 shows the effect of NS on concrete's compressive strength.

Du *et al.* [25] conducted an experimental study to investigate the effect of NS on the compressive strength of LWC. Various concrete mixtures have been prepared. Some of the cast samples included NS, others with slag, and others without any additives. The results showed that both mixtures improved their compressive strength when increasing the dose of NS at different ages. The effect of NS was on all mixtures at an early age shown in Figures 2 and 3.

Atmaca *et al.* [26] have investigated the addition of NS to structural lightweight concrete. Two groups of concrete mixtures were prepared. The first group consisted of five mixtures, each of which was variable in the lightweight coarse aggregate, which was replaced by the traditional aggregate, knowing that all mixtures are free of NS. The

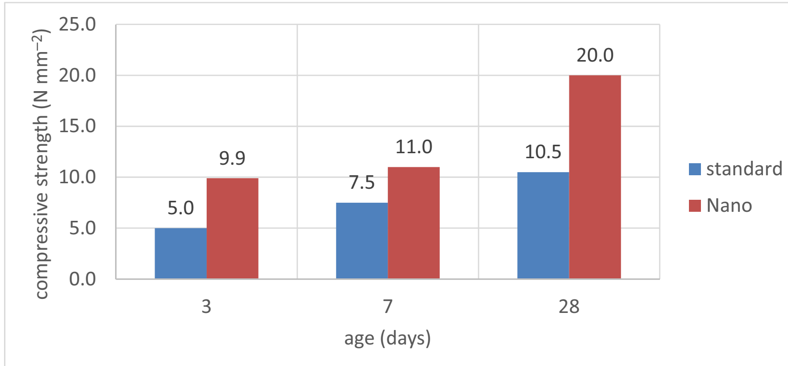

Figure 1: The compressive strength [24].

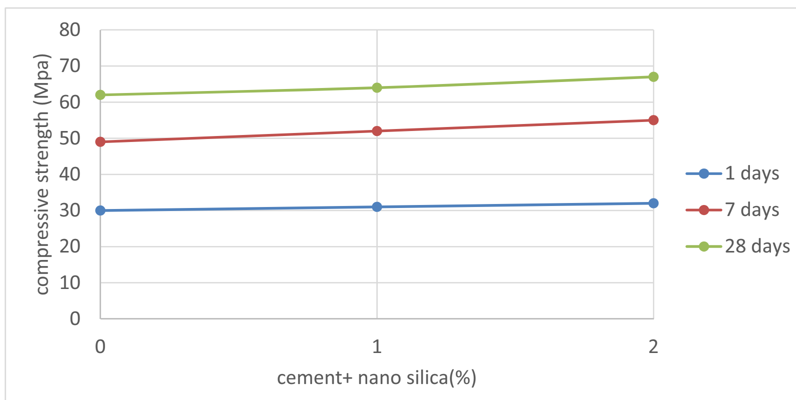

Figure 2: Compressive strength with different percentages of NS.

second group also consists of five mixtures similar to the mixtures in the first group, but NS is added to it. The compressive strength test was conducted at different ages 3, 7, 28, and 90 days. The compressive strength of the second group containing NS showed a significant increase when compared with the first group. It was noted that the tensile strength of the mixtures containing NS showed an increase when compared to the concrete without NS, regardless of the percentage of light aggregate. Figure 4 shows the effect of NS on compressive strength of LWC.

Zhang *et al.* [27] attempted to obtain lightweight yet high-performance concrete using NS. The researchers moved away

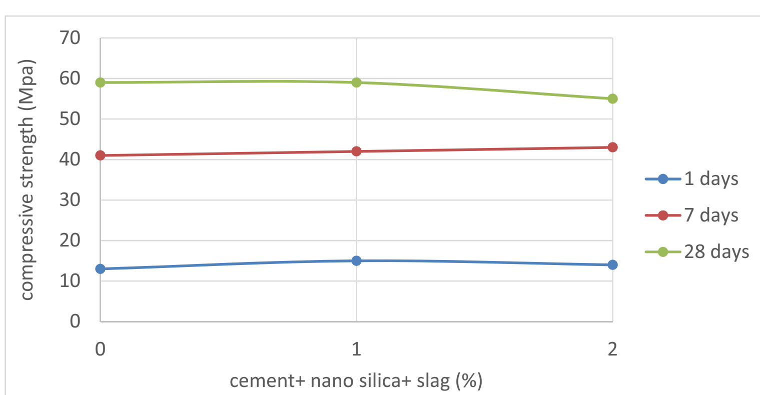

Figure 3: Compressive strength with different percentages of NS + slag [25].

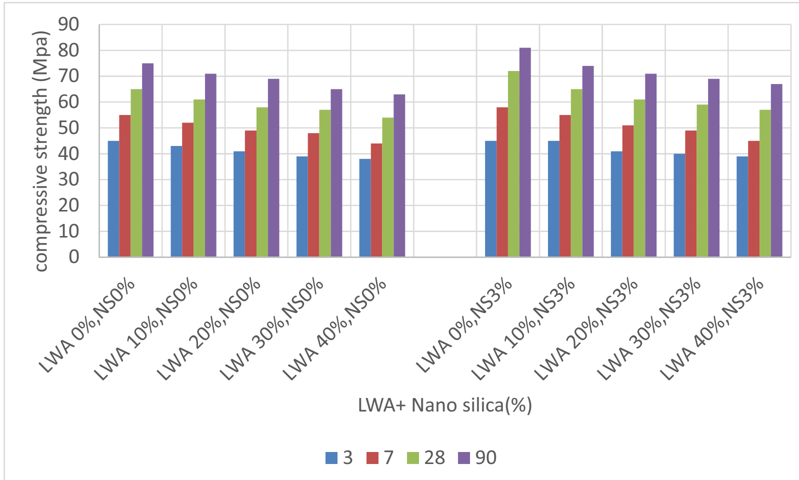

Figure 4: Compressive strength with different percentages of NS [26].

from the previous ratios used by previous researchers and used lower doses of NS because of its high cost. The doses used were less than 1% of the weight of the cement and their effect on LWC was evaluated. The results showed that the addition of small doses of NS leads to strengthening the properties of concrete in terms of flexural and compressive strength. 0.1% was the critical ratio, and increasing it leads to a decrease in flexural and compressive strength.

Wang *et al.* [28] observed that the addition of NS in proportions of 1, 2, and 3% increased compressive strength and decreased shrinkage. The study showed that compressive strength continues to increase to late age. The early increase was very large, but it decreased in later ages. The highest compressive strength was recorded at all ages at a replacement rate of 3% with NS. It was observed that NS reduced the premature cracking of LWC.

Ismail *et al.* [29] conducted a study on the effect of NS in different proportions on LWC that contains lightweight aggregates instead of normal aggregates. The density of the concrete on which the study was conducted was between 1,400 and 1,500 kg m^{-3}. The researchers evaluated the role of NS based on the results obtained from the compressive and tensile strength tests. The researchers used a ratio of 0.75, 1.5, and 2% NS. The results showed that the addition of NS had a clear effect on compressive and tensile strength when compared with the reference mixture free of NS. The results recorded the highest compressive strength at the dose of 0.75 and 2% NS. While the tensile strength recorded the highest value at a 2% dose.

Abd Elrahman *et al.* [30] published a study on the effect of NS on the flexural and compressive strength of light concrete, whose density ranges between 900 and 10,000 kg m^{-3}. The researchers used replacement ratios 1, 2, and 4% of the cement weight. The laboratory results showed a significant increase in the compressive and flexural strength of light concrete. The study showed that the best results were obtained at the ratio of 2 and 4%.

Suleiman *et al.* [31] added ratios 1, 2, and 3% NS. The researchers examined the effect of adding nanomaterials on the compressive strength of LWC. The lightweight aggregate was the fired brick. The results showed that increasing the dose of NS increases the compressive strength. The highest compressive strength was recorded when substituting a dose of 3% NS.

Zahid and Mohammadi [32] studied the effect of nanomaterials on the mechanical properties of concrete. The use of 5 NS as a substitute for cement showed an improvement in the corrosion resistance of concrete by 16% when compared with the reference mixture. Also, it was observed during the study that adding NS to concrete containing fly ash increased the compressive strength by 15% at the age of 90 days when compared with the control mixture.

Abdalla *et al.* [33] studied the effect of nanomaterials on concrete workability and compressive strength. The study showed that adding carbon nanotubes increased the compressive strength by 50% when compared with the reference mixture. At the same time, the results showed that all the nanomaterials used (NS, nano-aluminum, nano-titanium, nano-iron oxide, nano-metakaolin, and nano-clay) reduced workability.

Chakravarty *et al.* [34] used NS to investigate its effect on the strength of concrete. The results of the study showed that replacing 3% gave the best improvement in compressive strength, with an increase of 7% when compared with the reference mixture. The researchers also noted that the

Table 1: The improvement of compressive strength with different types of nanomaterials

No.	Nanomaterials used	Replacement % of nanomaterials	Compressive strength before adding nanomaterials	Compressive strength after adding nanomaterials	% of improvement	Ref.
1	NS and macro-silica	2, 4, 6	16.96	25.8	+22–52	[41]
		1, 2	61	68.9	+(7.7–13.3)	[25]
		1, 2, 3, 4, 5	12.9	19.8	+53	[42]
		0.05, 0.1, 0.2, 0.5	28	35	+25	[43]
		1, 2, 3	23	35	+52	[28]
		1, 2, 4	100	125	4–25	[30]
		1, 2, 3	35	46.35	21.49–32.45	[44]
		1,2, 3	49.50	60.45	+22	[34]
		1, 2, 3	—	—	+15	[32]
		0.5–2	—	—	+20.14	[37]
		2	—	—	32	[45]
		2.5 + 4	—	—	+37	[33]
2	Nano-metakaolin	5, 10	30	46	+53	[46]
		2–14	35	48	12–37	[47]
3	NS + metakaolin	5	33	41.7	+25.4	[47]
		19	28.45	48	+69	[48]
		NS1-2 + MK 5-10	90	105	+17	[49]
4	Nano-Al_2O_3	1.5	—	—	+49	[50]
5	carbon	—	—	—	+50	[33]
	nanotubes CNTs	—	—	—	+(10–50)	[39]
6	NS + CNTs	—	—	—	Increase	[40]
7	NS + nano-clay	2 + 5	—	—	1 and 4	[38]

bending resistance also increased due to the improvement of the microstructure of the mixture after incorporating NS into it. The workability of concrete decreased due to water absorption by NS particles.

Nuri Turkmenoglu *et al.* [35] published a study on the effect of NS and macro-silica on the strength and flexibility of concrete and its microstructure. The combination of NS and micro-silica at a rate of 2.5%, +4%, increased the compressive strength by 37% at the age of 28.

Oh *et al.* [36] observed through a study conducted to demonstrate the effect of combining NS with silica fume on the performance of high-performance concrete. Replacing 10–20% NS and silica fume resulted in a 6% improvement in compressive strength. The highest compressive strength was recorded when replacing 10% NS. However, by increasing the NS content to 30%, self-shrinkage increases.

Arif *et al.* [37] published a paper on the effect of NS on the strength and permeability of concrete. The percentages that the researchers utilized as a cement substitute ranged from 0.5 to 2%. The research revealed that while the compressive strength increased with the model, age, and permeability decreased. Furthermore, at 28 days, the maximum reduction in permeability and the greatest percentage gain in compressive strength (20.14%) happened at a concentration of 1.5% NS.

Dahish and Almutairi [38] studied the effect of NS and nano-clay on compressive strength at high temperatures. According to the study, the compressive strength rose by 1% and 4%, respectively, with 2 and 5% NS and nano-clay. The researchers also looked at how different materials affected compressive strength at high temperatures. It was discovered that combining the two nanomaterials with the concrete mix produced the greatest results.

Du and Korjakins [39] demonstrated the effect of nanomaterials on the mechanical properties and microstructure of LWC. Researchers discovered that these substances, which include NS and CNTs, enhanced the general strength of concrete by between 10 and 50% and its bending strength by 89%. Furthermore, the investigation demonstrated that nanomaterials had a favorable impact on the microstructure, augmenting the concrete's strength.

Hwangbo *et al.* [40] studied the effect of carbon nanotube and NS on the properties of concrete incorporated with graphene oxide. The results showed that the combination of NS, nano-carbon tube, and graphene oxide improved the mechanical properties and also improved the bond strength between the cement paste and the rebar significantly when compared with the control mixture.

Zhao *et al.* [45] studied the effect of NS on the mechanical properties of concrete containing recycled aggregate. Studies have shown that compressive, bending, and tensile strength improve by 32, 33, and 89.6%, respectively, when compared with the reference mixture if 2% NS is incorporated (Table 1).

Several studies examined the influence of NS on the compressive strength of LWC. The findings suggest that the addition of NS at an optimal dosage can enhance compressive strength, with improvements ranging from 10 to 40% compared to conventional LWC. The enhanced strength is attributed to the pozzolanic reaction between the NS particles and the cementitious matrix, resulting in increased hydration products and a denser microstructure.

The literature review also discusses the impact of NS on the flexural strength of LWC. It reveals that the incorporation of NS can significantly improve the flexural strength, with reported increases ranging from 15 to 50% compared to control specimens. The improved flexural strength is attributed to the enhanced bonding between the cementitious matrix and the porcelanite aggregate particles, resulting in a more efficient load transfer mechanism.

Overall, the literature review demonstrates that the addition of NS positively impacts the mechanical properties of LWC containing porcelanite aggregate. The inclusion of NS leads to improved compressive strength, flexural strength, and durability, making it a promising additive for enhancing the performance of LWC in construction applications. However, further research is still needed to optimize the dosage and understand the long-term effects of NS on the properties of LWC.

This article’s aim is to investigate how NS can increase the strength of LWC with lightweight porcelanite aggregate. Compared to other LWC mixes such as aerated concrete or concrete without fine aggregate, concrete composed of lightweight porcelanite aggregate is considered easy to design and process and does not require careful monitoring. It is also cheap and can be used in important parts of the building, such as roofs, bridges, and foundations, after combining them with nanomaterials and turning them into lightweight structural concrete, unlike other types of light concrete which cannot be used because their weakness, expensive, and require monitoring and follow-up from the design stage to the casting and hardening. Furthermore, the following have been cited as the secondary aims of the current paper.

5 Experimental program

5.1 Materials

The structural LWC consists of cement, porcelanite stone, fine sand, and water. Superplasticizers are added to increase concrete workability. NS is to enhance hardening properties. Iraqi OPC used in this work satisfied the limit of Iraq specification No. (5)_1984 as tabulated in Table 2 and its chemical composition in Table 3.

Aggregates constitute between 60 and 85% of the volume of concrete, with the coarse aggregate amount being twice the fine aggregate. Porcelanite stone (Figure 1) is used as coarse aggregate, while for the fine aggregate, the normal fine aggregate is used. Porcelanite, a sedimentary stone, is characterized by its lightweight and hardness, which can give good resistance to concrete if it is treated with correct engineering methods. This stone is found in abundance in western Iraq and has a mineral and chemical composition that reflects the unique properties that make it suitable for industry. The second major component of the concrete mix is fine aggregate or sand. This component constitutes approximately 42% of the concrete volume in normal mixtures and is used to fill the voids within the mixture and increase the bonding strength of the components.

Table 2: Physical properties of cement (type I)

Physical properties	Test results	Limit of Iraq specification No. (5)_1984
Specific surface area ($m^2\ kg^{-1}$)	240	≥230
Setting time		
Initial setting time (h:min)	2:10	≥45 min
Final setting time (h:min)	8:10	≤10 h
Compressive strength		
3 days (MPa)	22.1	≥15
28 days (MPa)	33.46	≥23

Table 3: Chemical oxide analysis, weight %, for type I cement

Oxide	% by weight	Limit of Iraq specification No. (5)_1984
CaO	61.52	—
SiO_2	21.8	—
Al_2O_3	6.5	—
Fe_2O_3	2.2	—
MgO	1.403	<5
SO_3	2.5	<2.8
Na_2O	0.28	—
K_2O	0.51	—
Insoluble residue (IR)	0.544	<1.5
Loss of ignition (LOI)	I 2.4	<4.0
Main compounds		
C3S	42.527	—
C2S	30.505	—
C3A	13.507	—
C4AF	6.688	—

5.1.1 Aggregate

Aggregates are one of the main components in all concrete mixtures and have a direct effect on most of the mechanical, physical, and chemical properties of concrete. Aggregate is divided into two types, coarse aggregate, and fine aggregate. Usually, aggregates (both types) constitute between 60 and 85% of the volume of concrete. coarse aggregate twice that of fine aggregate. In this paper, porcelanite stone is used as coarse aggregate. As for the fine aggregate, the normal fine aggregate will be used. Specifications for each subject will be presented in this part [51].

Porcelanite stone is one of the alternatives that will be used instead of normal aggregates for the production of LWC. Porcelanite, a sedimentary stone, is characterized by its lightweight and hardness, which can give good resistance to concrete if it is treated with correct engineering methods. This stone is found in abundance in western Iraq and there are many places where it appears on the surface, which is an important source for many types of research related to the production of light concrete with certain specifications. It is a mineral and chemical composition that reflects the unique properties that make it suitable for industry. Porcelanite was defined by Al-Jubouri as a sedimentary stone containing 50% opal-CT, which has the feel of unglazed porcelain and is an advanced product of bio-silica. Figure 5 shows the porcilanite lightweight aggregate (Tables 4 and 5).

The second major component of the concrete mix is fine aggregate or sand. This component constitutes approximately 42% of the concrete volume in normal mixtures and is used to fill the voids within the mixture and increases the bonding strength of the components and has a direct impact on many properties of concrete such as resistance to compression, bending, tensile, and absorption (Table 6).

Figure 5: Porcelanite stone.

5.1.2 Mineral admixture

Pozzolana is a natural or artificial material containing silica or alumina (mainly silica) in a reactive form. By themselves, pozzolanas have little or no cementitious properties. However, in a finely divided form and in the presence of moisture they will chemically react with alkalis to

Table 4: The test was done at the State Company of Geological Survey and Mining, Baghdad, IRAQ

Chemical compositions	%
SiO_2	62.02
CaO	11.55
MgO	7.20
Al_2O_3	2.71
Fe_2O_3	0.87
TiO_2	0.18
SO_3	0.30
LOI	13.86

Table 5: Physical properties of coarse porcelanite

Property	Test result
Absorption	32%
Saturation	3.6%
Loose bulk density (SSD) (kg m^{-3})	891

form cementing compounds. The silica and alumina in a pozzolana have to be amorphous, or glassy, to be reactive [52].

The main purpose for the use of Pozzolana is to substitute cement and to reduce the consumption of energy and raw materials and thus to reduce the CO_2 emission relatively less than the original production.

Pozzolans reduce bleeding because of fineness and reduce the maximum rise in temperature when used in large amounts (more than 15% by mass of cementitious material) because of the slower rate of chemical reactions, which reduce the rise in temperature.

Pozzolanic materials are divided into three categories. The first is the natural pozzolanic materials. It is always more common in plain areas and is in the form of ineffective clays containing silica oxides and alumina oxides. It is not cement, but in the presence of water, it reacts with calcium hydroxide (CH) present in the concrete in the presence of water and becomes a cement material with good effectiveness and environmental friendliness [52].

The second type is the industrial pozzolanic materials, and these materials are ineffective, but by using some chemicals, they turn into effective ones, such as mortar and plaster [53].

The third type is the pozzolanic materials resulting from industrial waste such as furnace slag and the remains of burnt paper after grinding others.

The use of small percentages of pozzolan nanomaterials contributes to ensuring an integrated interaction with the cement paste and the non-agglomeration of these materials, which causes weak concrete. As well as an economic factor, it reduces the cost of the nanomaterials used [54].

The effect of the remaining unreacted pozzolanic materials is directly on the durability of the concrete through the continuation of interaction with these materials to form CH in the presence of water, which improves the microstructure of the concrete [54].

NS is one of the most abundant materials in the world. Its chemical composition is similar to a diamond. It is a white crystalline substance. NS is one of the most used materials with concrete. NS is found as a pozzolanic material in solid or liquid form. It is widely used in the concrete industry, through which it determines the viscosity and the condition of filling the pores in the concrete. NS can be dispersed with water in the form of a dry powder. NS is a very active pozzolanic material in concrete and plays an important role in it. NS maintains the strength of concrete during chemical and physical reactions and when the particles are compressed [41]. NS can accelerate the hydration of cement when added to concrete, which is very useful for obtaining early strength [43]. Previous studies showed that a certain dose of NS increased the production of hydrated calcium silicate and ettringite crystals gradually when the content of NS was increased. NS has the ability to reduce the diffusion of chloride ions, as well as improve the porosity of concrete [49]. Singh *et al.* compared the effect of colloidal NS and NS powder on the mechanical properties of concrete, where they found that NS powder was more effective in producing C–S–H gel. On this basis, NS powder is considered more effective for enhancing the mechanical properties of concrete [55]. Zahid *et al.* showed that NS can reduce the size of the pores in the cement paste when replacing it with a part of the weight of the cement, and it does not affect the permeability and porosity of concrete [49].

Finally, it is important to note the effects of nanoparticles on concrete. The effects of NS on concrete may vary depending on several factors, including nano-dose, particle size, curing conditions, cement type, and concrete mix design. Also, NS provides important and different benefits to concrete, and its incorporation into its paste provides the best results, but on the condition that the work is accurate and compatible with the research requirements [42].

5.1.3 Superplasticizer

The use of superplasticizers in this research is very, very important for structural lightweight concrete. After adding the nanomaterials, the water of the mixture is absorbed by it, due to the high softness and large surface area of the nanoparticles, which leads to the rapid interaction of the pozzolanic material with the concrete components in the presence of water. Superplasticizers help to reduce the effects of nanomaterials. In the stage of hardened concrete, superplasticizers help to increase compressive strength.

From this point of view, the importance of adding superplasticizers to structural LWC came to enhance the mechanical properties without negatively affecting the rest of the concrete properties.

6 Mix design

In this research, seven concrete mixtures have been designed as shown in Table 1. A reference mixture refers to a LWC of 17.3 MPa without NS. The design of the reference mix included the selection of certain proportions of cement, fine aggregate, porcelain stone as coarse aggregate, water, and superplasticizer to achieve the requirements of structural lightweight

Table 6: Grading and soluble material for fine aggregate used in this work

	Sieve size (mm)	% passing sand	% passing (3) limit sand
Grading	9.5	100	100
	4.75	92.0	90–100
	2.36	82.8	85–100
	1.18	76.1	75–100
	0.6	63.4	60–79
	0.3	35.9	12–40
	0.15	9.8	0–10
	Clay material (%)	4.6%	5%
	Organic material (%)	0.69%	3%

concrete with a density of not more than 2,000 kg m^{-3} and a compressive strength of not less than 17 MPa. Materials were estimated and experimental mixtures were designed until the required density and strength were obtained, according to Table 7. Figure 6 shows the experimental flowchart.

7 Test program

After choosing the suitable lightweight aggregate, the effect of adding NS by the different dosages (0, 1, 3, 5,10, 15, 20%) has been studied on the suitable LWC mixture by testing fresh and hardened concrete.

7.1 Fresh concrete behavior

The slump test based on ASTM No. C 143 [56] is applied to measure the concrete plastic viscosity and workability. The slump height is measured from the top of the cone to the top of the slump as in Figure 7. According to the code, the allowable slump height is between 25 and 160 mm.

7.2 Hardened test

- Density test: The density of concrete is an important parameter as it affects the strength, durability, and other engineering properties of the material. The density is typically expressed in kilograms per cubic meter (kg m^{-3}) or pounds per cubic foot (lb ft^{-3}). To find the dry density, 84 samples – three samples for each concrete mix – were collected after the mixture had cured for 28 days. The density measurement was conducted in accordance with Specification No. C642 [57]. After being in the water and left in a basin for 28 days at room temperature (20–25°C), the samples were dried in an oven set at 110°C for 24 h. To determine the density, the average of three samples was used.
- Compression test was conducted on specimens at 7, 28, 56, and 90 days. For each variable, three repetitive samples were tested. In total, there are 84 samples. The test was conducted according to ASTM C109 [58] using a compression machine of 2,000 kN capacity. The loading rate used is (3 MPa s^{-1}). Figure 8 shows the compressive tester.

7.2.1 Splitting tensile strength test

Splitting tensile strength was tested by three specimens for one age at 7 and 28 days of curing on Ø 150 mm × 300 mm cylindrical according to ASTM C 496-97 [59]. The splitting tensile strength test has been carried out according to ASTM C496-2004, using an ELE machine at the rate of loading (2.1 MPa s^{-1}). Figure 9 shows a splitting tensile strength tester.

Table 7: Groups of the LWC mix

Groups	Cement (kg m^{-3})	LWA porcelanite gravel (kg m^{-3})	Fine aggregate (kg m^{-3}) normal sand	% NS	Water (L m^{-3})	Superplasticizer (L m^{-3})
Control	500	525	525	0	175	10
NS 1	495	525	525	1	175	10
NS 3	485	525	525	3	175	10
NS 5	475	525	525	5	175	10
NS 10	450	525	525	10	175	10
NS 15	425	525	525	15	175	10
NS 20	400	525	525	20	175	10

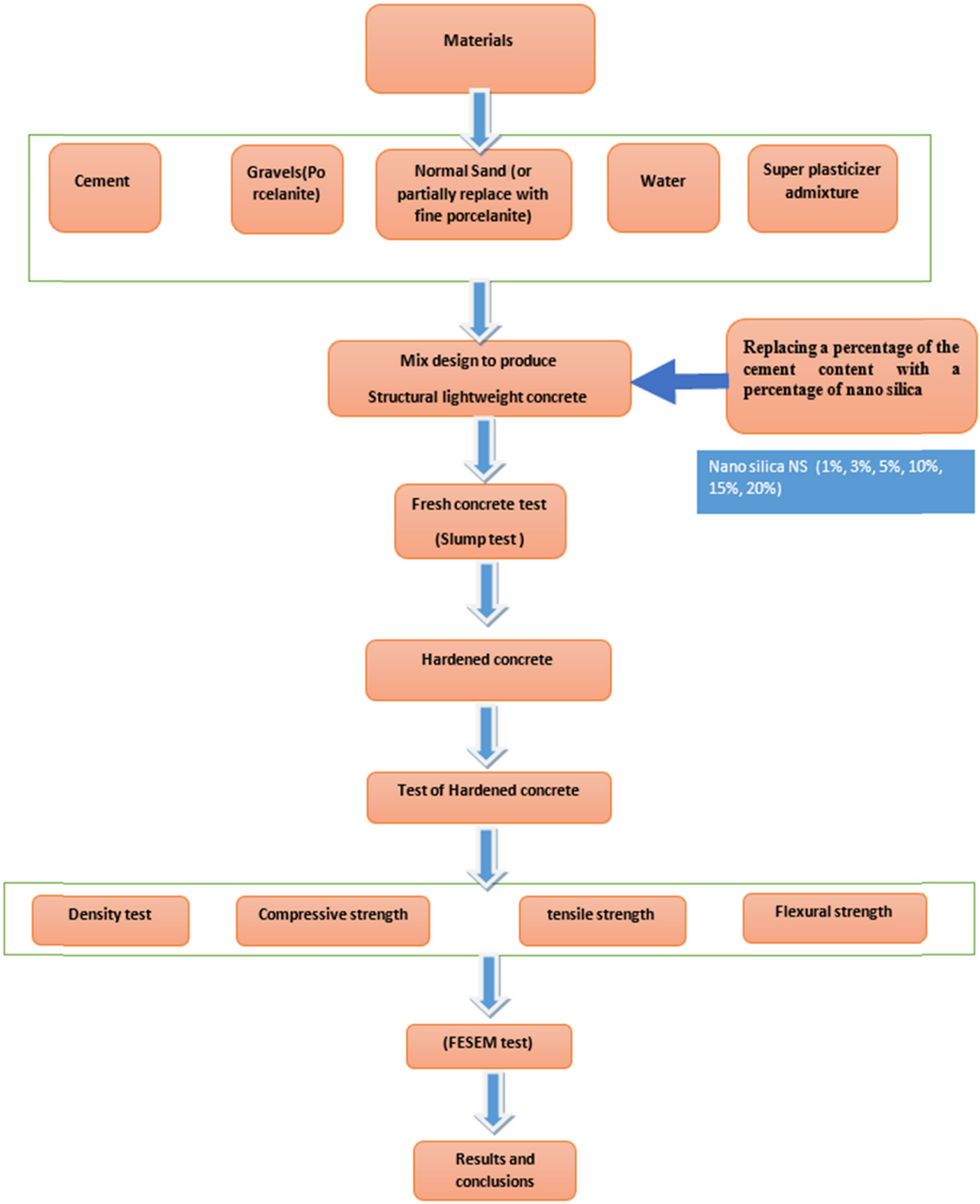

Figure 6: Experimental flowchart.

Figure 7: Slump test.

7.2.2 Flexural strength

The flexural test of concrete is one of the tests that are no less important than the compression strength test, as most of the important joints of the concrete structure are directly or indirectly exposed to the bending load, so the designed concrete must be ensured that it has good flexure strength and according to the required strength. The bend is checked by pouring concrete with dimensions of 10 cm × 10 cm × 50 cm into iron molds and leaving it for 24 h, the iron mold is opened and immersed in water to be examined at the age of 7 days and the age of 28 days. The examination was conducted in accordance with Standard Specification No. C1161 [60]. Forty-two samples were examined, three samples for each concrete mix, at 28 days of age to verify flexural resistance. The load was applied at a rate of 0.9–1.2 MPa s^{-1}. Figure 10 shows the flexural strength tester.

7.2.3 Microstructure test (field emission scanning electron microscope [FESEM])

FESEM is a test conducted to examine the microstructure of NS and on LWC with and without NS. The test examines the internal structure and characteristics of the concrete at a microscopic level. It provides insights into the composition, distribution, and connectivity of the various components within the concrete matrix. The examination was performed after reducing the image to a size of 50 nm. The research included taking seven samples, one for each mixture.

8 Fresh properties

The slump test gives indicators of the workability of LWC and an indirect indicator of compressive strength. Figure 11 shows the slump height of 7 mixes. The results showed a gradual decrease in the slump height as the NS content

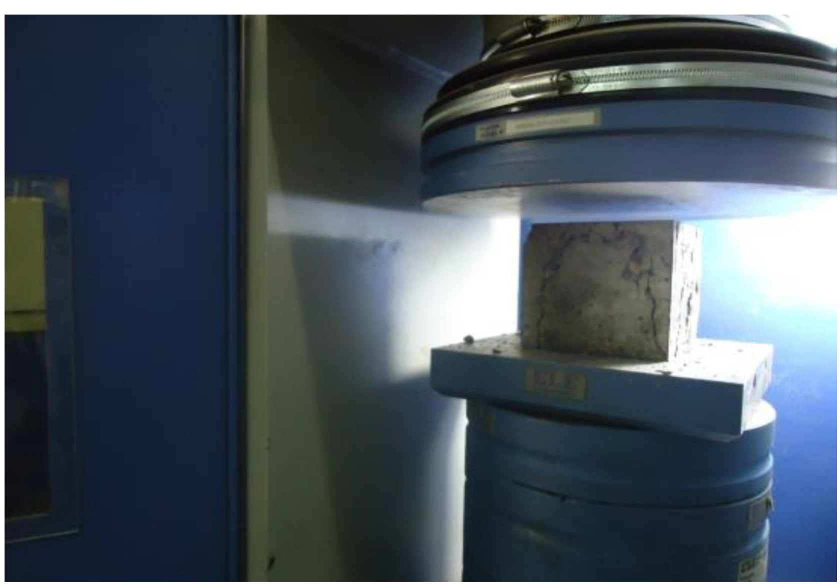

Figure 8: Compressive strength tester.

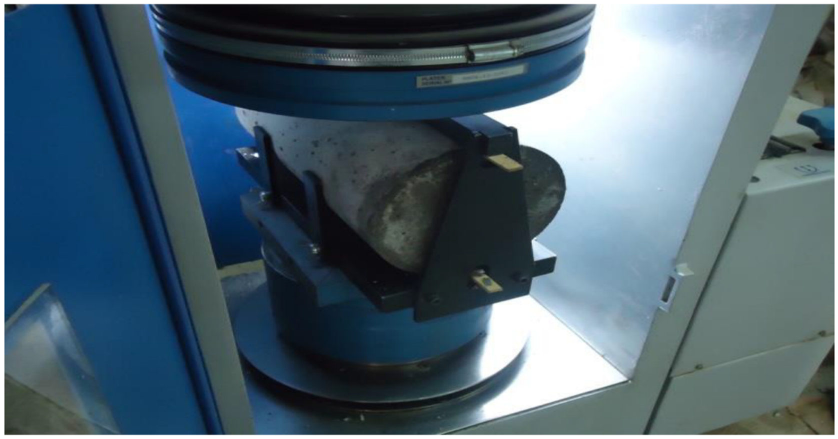

Figure 9: Splitting tensile strength tester.

increased. The reason for this is due to the attraction of water molecules towards NS particles due to their large surface area, which led to the absorption of part of the water of the mixture due to the high interaction and limited surface area [31]. Consequently, the amount of free water needed to improve the fluidity of the mixture decreases. This problem was overcome by adding a superplasticizer to achieve appropriate fluidity.

Figure 11 shows the results decrease in the slump height after adding NS to the concrete mixture. The decrease in slump height was from 48 to 35 mm. The reason for this is due to the attraction of water molecules towards NS particles due to their large surface area, which led to the absorption of part of the water of the mixture due to the high interaction and limited surface area. Consequently, the amount of free water needed to improve the fluidity of the mixture decreases. This problem was overcome by adding doses of superplasticizer to achieve appropriate fluidity.

To facilitate the flow of concrete after adding NS doses to it, superplasticizers were used to enhance the dispersion properties of NS to help isolate cement particles to preserve the water of the mixture.

Figure 12 shows the clear difference in the height of the slump after adding a dose of superplasticizer. as it helped increase the workability and flow of the concrete between 150 and 315% by dispersing the cement particles and maintaining the water of the mixture.

9 Hardened properties

The second stage of concrete is the hardened concrete stage. This stage represents the most important part of this research, in which hardened samples of structural LWC are examined to demonstrate their mechanical and

Figure 10: Flexural strength tester.

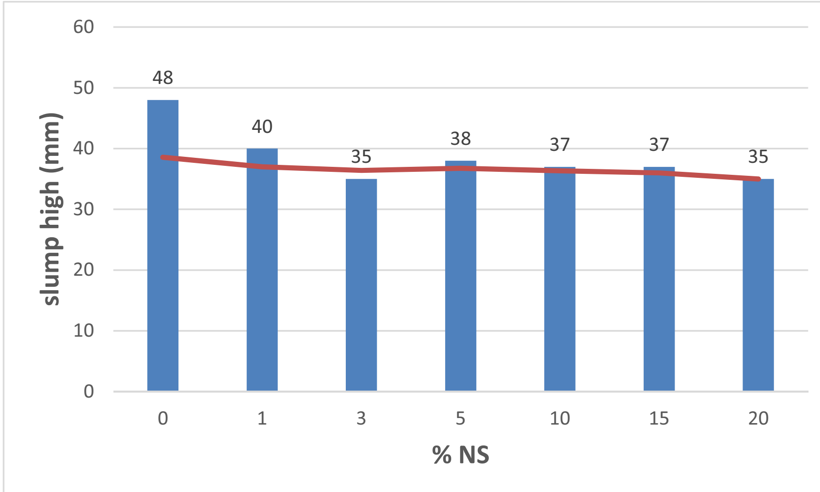

Figure 11: Slump test results.

physical properties. The mechanical tests (compression, bending, tensile strength, and dry density) were carried out for hardened concrete.

9.1 Density test results

The results of using NS to reinforce LWC are displayed in Figure 13. After 7 and 28 days of water cure, the outcomes were assessed. The graphic clearly shows that the density of the concrete increases with an increase in the dose of NS. The fact that the increase was gradual is also evident. The use of NS in LWC has been shown to increase its density, which explains the variation in concrete density. Because of its small particle size, NS may pack particles more tightly, which can help fill the spaces between the lightweight aggregate particles. This allows for an increase in the LWC's overall density. More efficiently, lightweight aggregate particles' interstitial gaps can be filled by NS. This improved filling of voids can lead to a denser concrete matrix, thereby increasing the density of the LWC.

9.2 Compressive strength results

Adding NS has been shown in many tests to improve LWC's compressive strength. Because of their high reactivity and vast surface area, NS particles facilitate the nucleation and production of more hydration products inside the cementitious matrix. Improved interparticle bonding and a

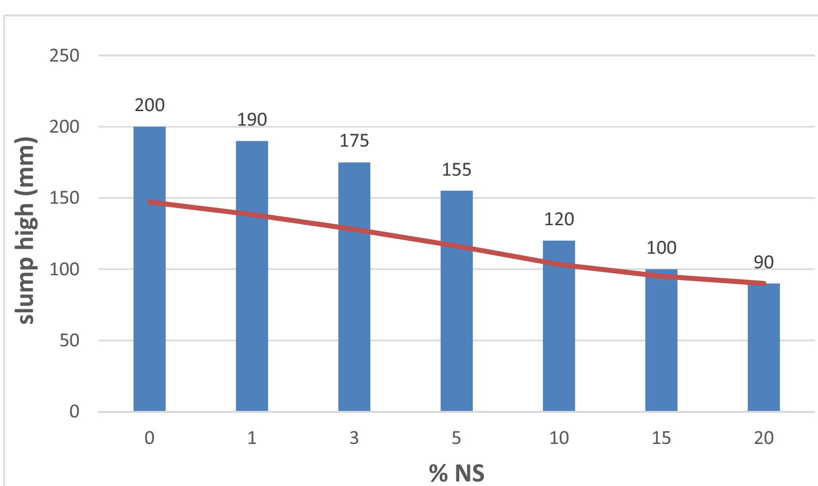

Figure 12: Slump high after adding superplasticizer.

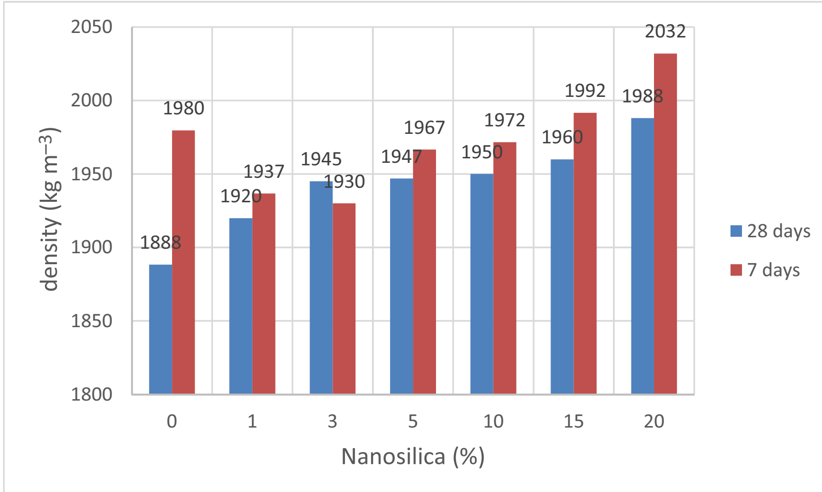

Figure 13: Results of oven dry density test (NS) 7 and 28 days.

decrease in pore size are the outcomes of this densification effect, which raises compressive strength [49].

Because NS has pozzolanic qualities, it can combine with CH, which is created when cement hydrates, to create new cementitious compounds. These molecules, which include calcium aluminate silicate hydrates (C–A–S–H) and calcium silicate hydrates (C–S–H), form and help LWC gain strength. Compressive strength is increased as a result of the pozzolanic activity of NS, which also improves the cementitious matrix's microstructure and general performance [39].

The samples were tested at 7, 28, 56, and 90 days. The results are shown in Figure 14 and the improvement in compressive strength compared with the reference in Table 8. It has been noted that adding NS to the mixture has an impact on the concrete's compressive strength. The addition of an NS dosage after a week increased the compressive strength by 58–140%. Additionally, introducing NS improved compressive strength by a significant margin (55–140%). Depending on the degree of NS addition, there was very little improvement in CS after the curative age of 56 days, ranging from 1 to 17%. Reaching the age of the models to 90 days increased the improvement rate for all mixtures from 15 to 62% higher than that recorded at the age of 56 days. This is confirmed by previous studies that showed that the effect of NS is noticeable at later ages. This increase can be attributed to the interaction of nanomaterial with CH $Ca(OH)_2$ crystals in the ITZ between the hardened cement paste and porcelanite aggregate, which creates packing of C–S–H gels and nanoparticles and dense microstructures. study proves that the

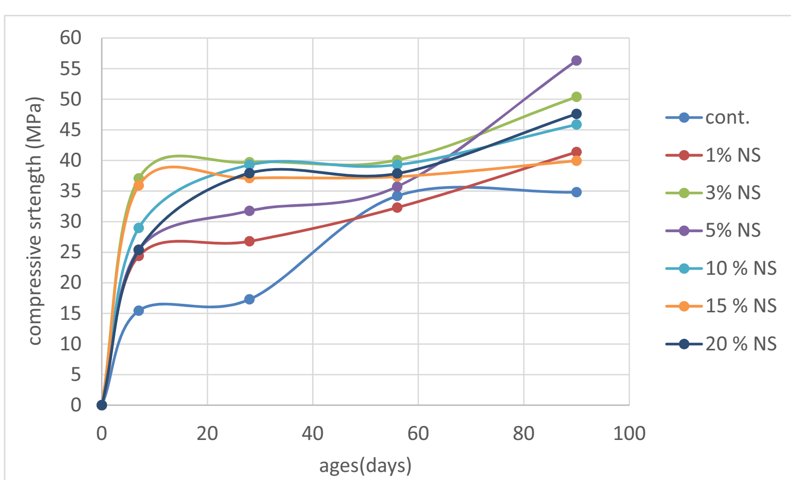

Figure 14: Compressive strength results for mixes with nano-SiO_2.

Table 8: Improving compressive strength with different dose of nano

Mix	% improving in compressive strength at 7 days	% improving in compressive strength at 28 days	% improving in compressive strength at 56 days	Improving in compressive strength at 90 days
1% NS	58	55	1	19
3% NS	40	130	17	45
5% NS	65	84	4	62
10% NS	87	127	15	32
15% NS	32	115	9	15
20% NS	64	119	11	37

compressive strength of LWC with NS is increased due to accelerated C–S–H gelation rather than Due to the increased amount of crystalline $Ca(OH)_2$ early years.

In conclusion, the compressive strength of LWC is improved by the addition of NS. Increased compressive strength is a result of the high reactivity of NS particles, their pozzolanic activity, the effects of particle packing, and the densification of the cementitious matrix. In LWC applications, optimizing the augmentation of compressive strength while preserving other desired attributes requires careful consideration of synergistic effects, dosage, and dispersion.

Table 9: Splitting tensile strength results

Mix	% improvement of splitting tensile strength at 7 days	% improvement of splitting tensile strength at 28 days
1% NS	0.70	77
3% NS	54	75
5% NS	0.93	84
10% NS	11	51
15% NS	35	55
20% NS	32	53

9.3 Splitting tensile strength results

When investigating the use of nanomaterials in concrete technology, it is crucial to take into account how NS affects the splitting tensile strength of LWC. This paper will explore how NS affects LWC's splitting tensile strength and what it means for building applications.

According to studies [28,61,62], adding NS can improve LWC's splitting tensile strength. Better interparticle bonding and a denser cementitious matrix result from the creation of extra hydration products, which are facilitated by the high reactivity and pozzolanic qualities of NS. The LWC's tensile and crack resistance are improved by this improved microstructure, which raises the splitting tensile strength.

The inclusion of NS has increased the splitting tensile strength of the various concrete mixtures, as shown in Figure 15 and Table 9, which displays increases in splitting tensile strength of 75, 77, and 84% for the 1, 3, and 5% NS at 28 days, respectively. As the amount of nanoparticles in concrete increases, the enhanced degree of its splitting tensile strength diminishes. This could be because there

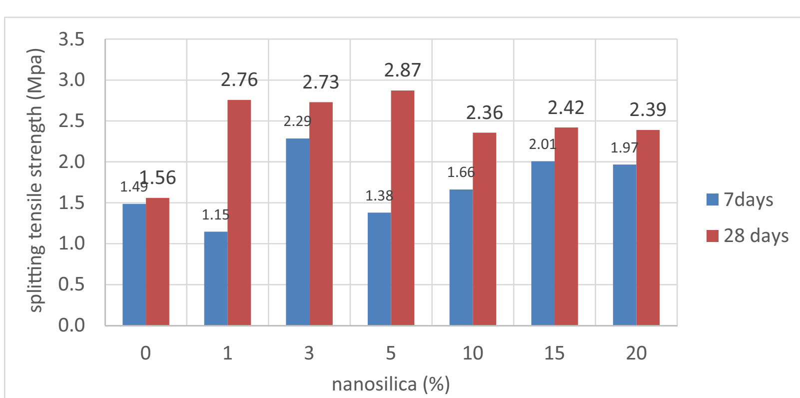

Figure 15: Splitting tensile strength results.

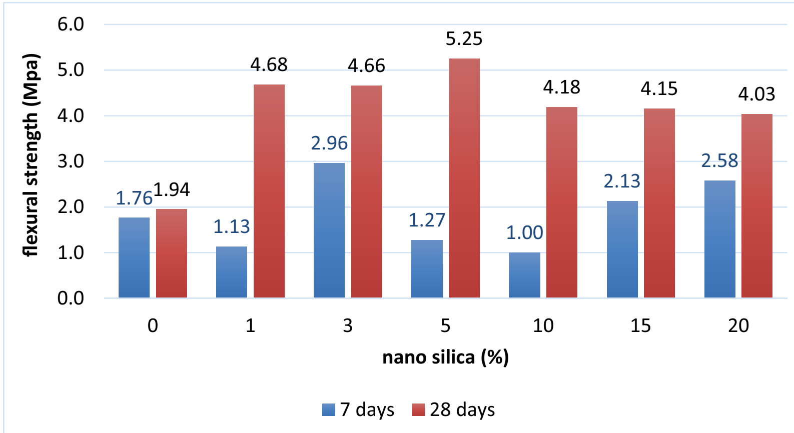

Figure 16: Flexural strength.

Table 10: Flexural strength results

Mix	% improvement of flexural strength at 7 days	% improvement of flexural strength at 28 days
1% NS	0.64	141
3% NS	68	140
5% NS	0.72	171
10% NS	0.57	115
15% NS	21	114
20% NS	47	108

are more nanoparticles in the mix than are needed to combine with the released lime during the hydration process. As a result, excess silica leaks out and causes a strength deficit because it replaces some of the cementitious material but adds nothing to it.

In conclusion, the splitting tensile strength of LWC is improved by the addition of NS. The increased tensile and crack resistance is a result of the high reactivity, pozzolanic qualities, better cohesiveness, and frictional resistance. In LWC applications, it is essential to maximize the splitting tensile strength enhancement while retaining other desired qualities. This involves optimum dosage, dispersion, and consideration of synergistic effects, particularly with fibers.

9.4 Flexural strength results

NS has been shown in several experiments to improve the flexural strength of LWC [30,63,64]. Because of their high reactivity and pozzolanic qualities, NS particles encourage

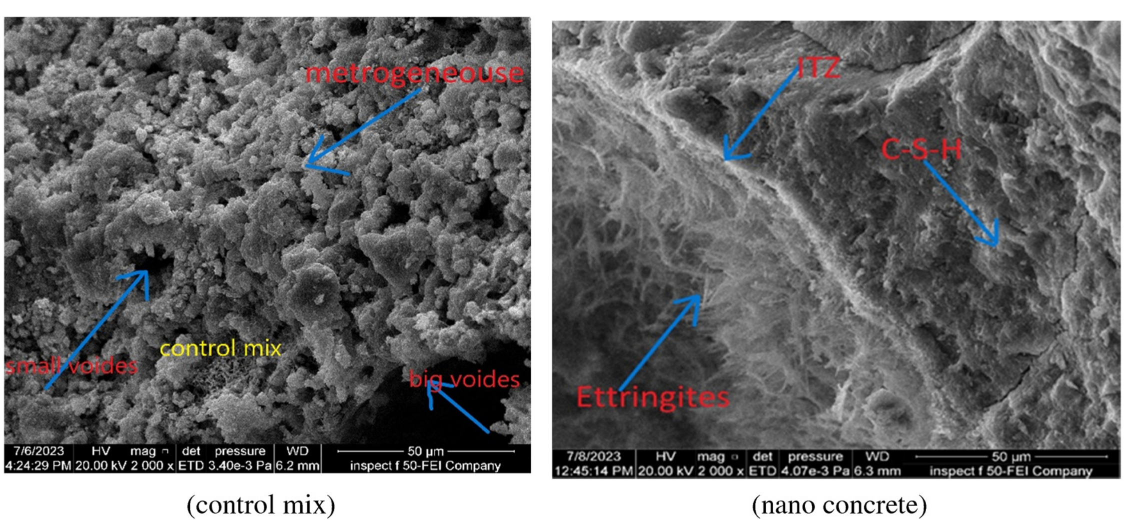

Figure 17: FESEM test results.

the creation of more hydration products inside the cementitious matrix. Flexural strength is raised as a result of the densification action, which also strengthens the cementitious matrix and enhances interparticle bonding.

The flexural strength results are shown in Table 9. Similar to the tensile strength, the flexural strength of the specimens increases with NS up to 5% replacement and then it decreases, although the results of 10,15, and 20% replacement are still higher than those of the control mix. The improvement in bending resistance recorded an increase of 141, 140, 171, 115, 114, and 108% when replacing NS with 1, 3, 5, 10, 15, and 20%, respectively. Again, the increase in the flexural strength is due to the rapid consumption of $Ca(OH)_2$ which was formed during the hydration of Portland cement especially at early ages related to the high reactivity of nanoparticles.

In conclusion, the flexural strength of LWC may be improved by adding NS. Overall flexural strength has improved because of the high reactivity, pozzolanic characteristics, enhanced bonding, load transmission, and crack resistance. When using LWC, it is important to take into account the synergistic effects of the dose, dispersion, and fibers in particular to maximize the augmentation of flexural strength while preserving other desired attributes (Figure 16, Table 10).

9.5 Microstructure results

When investigating the integration of nanoparticles in concrete technology, it is crucial to take into account the impact of NS on the microstructure of LWC. The possible effects and ramifications of including NS on the microstructure of LWC will be covered in detail in this paper. NS particles have a high surface area and reactivity, which promotes the nucleation and formation of additional hydration products within the cementitious matrix of LWC. This densification effect leads to a more compact microstructure with reduced voids and improved interparticle bonding. The increased hydration product formation contributes to a denser and stronger cementitious matrix, enhancing the overall microstructure of LWC. The addition of NS in LWC can help reduce the porosity of the cementitious matrix. The high reactivity of NS particles contributes to the further hydration of cementitious materials, resulting in a more refined pore structure. The reduction in pore size and overall porosity enhances the connectivity of the hydration products, improving the strength and durability of the LWC microstructure. Because of their small size, NS particles can more easily disperse evenly throughout the cementitious matrix of LWC. Appropriate dispersion methods guarantee uniform dispersion of NS particles, resulting in improved microstructure uniformity. A more uniform distribution of hydration products is facilitated by enhanced homogeneity and dispersion, which creates a cohesive and well-connected microstructure.

Through the images shown below, the NS material improved the material's density and the sample's internal coherence. Figure 17(a) and (b) shows that incorporating NS into concrete improved the interfacial transition zone between cement and aggregate. The added NS was mainly filled in the ITZ of cement and sand and some capillaries in the matrix as ultrafine aggregates. As a result, the compressive strength of the concrete increases.

10 Conclusion

The use of nanomaterials to enhance the mechanical and physical properties of LWC has shown significant promise and potential. This conclusion is based on the following observations and findings:

1. The slump flow test results show that the mixtures containing NS had lower slump flow than the reference mixture.
2. As the age of the sample, their oven-dry densities decrease. However, when NS is added, their densities increase because the nanomaterial fills in voids due to its high surface area, acting like pozzolanic material and making the samples containing it denser.
3. Compressive strength has increased in all mixtures when adding NS, but at 90 days, the greatest results (62%) were obtained by replacing a percentage of 5%.
4. All mixtures containing NS showed a clear improvement, but the best improvement rate (313%) occurred when a dose of 5% was added at 28 days of treatment.
5. The splitting tensile strength increases significantly when adding NS compared to the reference mixture without addition. Clearly, the highest splitting (84%) was obtained when replaced of NS percentage by 5% at the 28 days of curing.
6. The results of the FESEM test showed that the concrete mixture's microstructure had improved and that the interface between the light aggregate and the cement paste had grown needle-shaped growths, which strengthened the binding between the aggregate and the paste. In contrast to the control mixture, which displayed wide gaps, capillary pores, and a heterogeneous mixture, the results also demonstrated that the cement paste containing NS was less porous, had fewer gaps, and was homogeneous.

7. The studies on hardened concrete revealed that 5% replacement of NS produced the best results.

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Conflict of interest: Authors state no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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