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The Influence of Nano-Silica on the Properties and Microstructure of Lightweight Concrete: a Review

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Abstract. In recent years, the use of nanotechnology materials has increased in strengthening and enhancing the behavior of concrete and its mechanical properties. This is due to the special characteristic of these materials such as its tiny size that considerably improves the microstructure of concrete, which in return gives concrete new properties and dramatically enhances its behavior. The present study seeks to review several previous studies that investigated the effect of adding nano-silica on the mechanical properties, durability, transport properties, and microstructure of lightweight concrete. Based on the results, it has been noted that the addition of nano-silica material has a vital role in improving the properties of lightweight concrete. Moreover, it was observed that there is an increase in the compressive strength, tensile strength, and flexural strength due to the addition of nano-silica material. It has also been concluded that there is an improvement in the durability and transport properties of lightweight concrete.
Keywords. Nano-materials, Nano-silica, Mechanical properties, Durability, Microstructure, Lightweight concrete.

1. Introduction

1.1. Lightweight concrete
Concrete is known to be lightweight when its dry unit weight is less than (2000 kg/m3) [1]. The aforementioned type of concrete is versatile, and in the last few years, it has been used in a huge number of construction projects. Lightweight concrete is lighter than conventional concrete [2], and it can be classified into three types [3]:

- Lightweight concrete with lightweight aggregate has a low unit weight of less than 2.6, which is less than normal aggregate and this type of concrete is known as Lightweight Aggregate Concrete.
- Lightweight concrete is manufactured by producing voids that filled with air bubbles into the concrete. This type of lightweight concrete has different names, such as cellular concrete or colloidal concrete or gas concrete.
- Also, the concrete which is manufactured without using fine aggregate and use of normal weight coarse aggregate is known as no fine concrete.

Beyond that, lightweight concrete has different advantages including, reducing dead load which results in a reduction of structural elements and steel rebar [3], and it also plays a great role in fire resistance [4]. On the other hand, lightweight concrete has some drawbacks which include its sensitivity with water content in the mixtures, placing and finishing difficulty because of the porosity and angularity of the aggregate, and last but not least, it takes much more mixing time than conventional concrete to assure ideal mixing [5].

1.2. Nanotechnology

The amount of CO2 that manufactured for producing the Ordinary Portland Cement is estimated at 7% of the total atmospheric wastes [6]. The amount of CO2 produced from cement manufacturing can be controlled through the use of green concrete without affecting the quality of the final product. However, one of the solutions that has been used is adding supplementary cementitious materials [6]. Nano-materials are one of the aforementioned supplementary cementitious materials, it is characterized by its small size which is less than 100 nm [7], and because of this, it has physical and mechanical properties that make it different and special from the other conventional materials. As a result, those materials have been the focus of much concern and used in different fields in the last few years [8,9]. Also, the aforementioned materials are characterized by a large surface area which leads to a great enhancement in compressive strength and cement permeability [10]. A researcher [8] has found that increasing nano-particles proportion leads to an increase in the compressive strength of concrete, and the average corrosion ratio decreases with increasing the proportion of nano-particles which means that the nano-particles work properly with the conventional concrete. As many researchers have conducted that adding the nano-particles to concrete will make the concrete more homogenous and more compact microstructure [11]. There are many nano-materials used as a supplementary cementitious material including silica[12-14], nano-iron oxide[15,16], nano-titania[17-19], nano-clay[10,20-23], nano-alumina[24-26], Carbon Nanotubes[27,28], carbon nano fiber[29-32], nano-graphene oxide[33], nano-zinc oxide[34], nano-Zro2c[35], nano-metakaolin[36], modified montmorillonite clay nano-particles[37]. The benefits and drawbacks of using nano-materials can be summarized as follows [38]:

-Less maintenance.
-It reduces the rate of thermal transfer.
-It increases sound absorption.
-It inncreases glass reflection.
-It immproves segregation resistance.
-It repairs small cracks.
-It is rust resistant.
-Its life cycle is costeffective.
-It needs a lot of energy.
-It is costly.
-Nanotubes can cause problems with respiratory organs, but research is still in its early stages.

1.3. Research objective

The aim of the present review paper is to summarize the previous research works that focused on the effect of using nano-silica material on the properties of lightweight concrete as well as to clarify the most important results obtained from the previous experimental studies, and to embody the conclusions achieved based on their findings.

2. Literature review

2.1. Nano-silica effect on the mechanical properties of lightweight concrete

In this section, the studies which investigated the effect of nano-silica material on the compressive strength, splitting tensile strength, and flexural strength of lightweight concrete are reviewed. Shah and Pitroda (2012)[39] conducted an experimental study to investigate the effect of adding nano-silica material on the compressive strength of cellular lightweight concrete. Different samples of cellular lightweight concrete containing nano-silica material (5% by weight of cement) were prepared. For the sake of comparison, other samples without nano-silica material were also prepared. The samples were cast and tested for compressive strength with different ages (3, 7, and 28 days). The results showed that the addition of small amount of nano-silica material leads to an increase in the compressive strength as compared to the samples without nano-silica material as shown in figure 1. It was also noticed that the addition of this material increases compressive strength at early ages, which confirms that the nano-silica material has a pozzolanic activity.

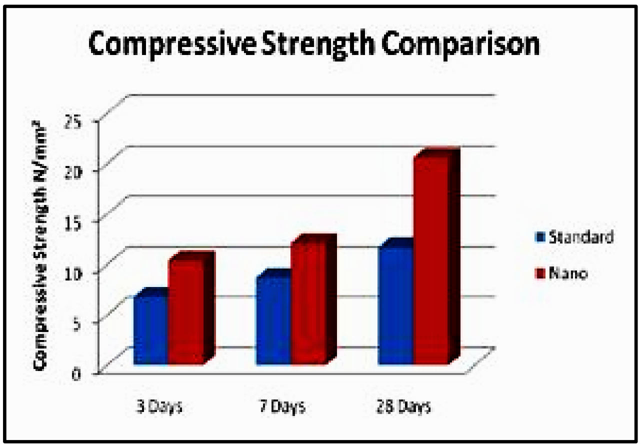
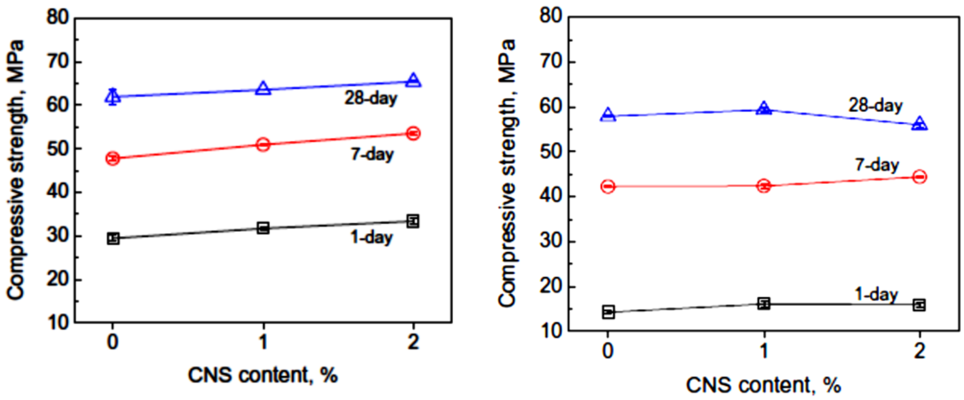


Figure 1. Compressive strength of all specimens [39].

Du et. al., (2015), [40] performed an experimental study to investigate the effect of nano-silica material on the compressive strength of lightweight concrete. Various concrete mixtures were prepared and casted including reference samples without nano-silica addition, mixtures containing pure cement and nano-silica with two percentages (1 and 2%), and other mixtures containing cement and slag at (60%) as an alternative of cement material in addition to the same percentages of nano-silica material. The study results showed that the compressive strength of both mixtures increased with increasing the percentage of nano-silica at different ages, but its effect appears more obvious in early ages than at later ages. Figure 2 demonstrates the compressive strength with varying nano-silica ratios at different ages.



(a) cement+nano silica (b) cement+slag+nano silica

Figure 2. Compressive strength of lightweight concrete [40].

Atmaca et al., (2017), [41] investigated the effect of nano-silica addition on mechanical properties of high-strength lightweight concrete. Two groups of concrete mixtures were made; the first group consisted of five mixtures whose variable was the ratio of replacing lightweight aggregate with normal aggregate with percentages of (0%, 10%, 20%, 30%, and 40%) and without nano-silica in the mixtures. The second group consisted of five mixtures with the same replacement of light aggregate with normal aggregate, but with the addition of nano-silica for all mixtures by (3%). The compressive strength of the two groups have been tested at different ages (3, 7, 28, and 90 days) and the results showed that the addition of nano-silica by (3%) increased the compressive strength of the mixtures compared to the non-containing group at the same replacement level of lightweight aggregate. The splitting tensile strength of the two groups was also examined at the ages of (28 and 90 days). It has also been observed that there is an increase in the tensile strength of lightweight concrete with the presence of nano-silica regardless of the percentages of light aggregates, as illustrated in figure 3.

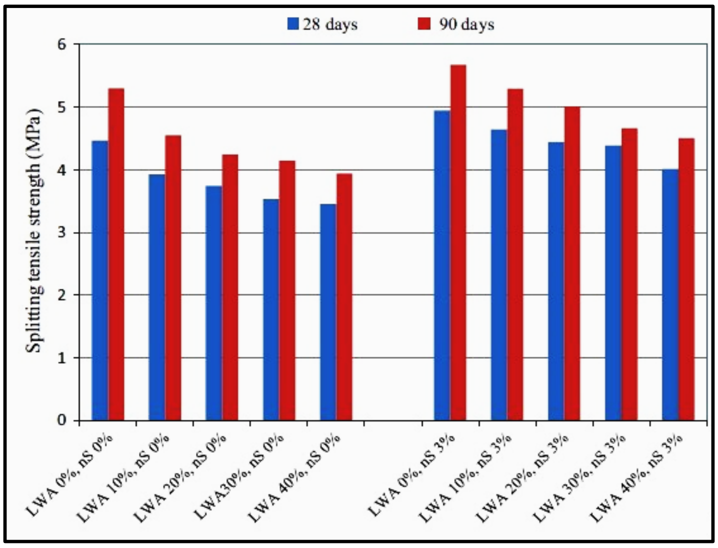


Figure 3. Splitting tensile strength of lightweight concrete [41].

Efforts were made by Zhang et. al., (2018), [42] to obtain a high-performance lightweight concrete using low doses of nano-silica material. Most of the studies that investigated the effect of using nano-silica on the behavior of lightweight concrete used to add this material in proportions ranging (3-10%) and due to its high cost that limits the use of it, the study tended to use nano-silica at rates of (0, 0.05, 0.1, 0.2, 0.5, and 1% by weight of cement) and evaluating the effect of these few percentages on the compressive and flexural strengths of concrete. The results showed that the relationship between compressive and flexural strengths and the doses of nano-silica material was nonlinear, and adding this material in small proportions improves both the flexural and compressive strengths of concrete. The results also revealed that the critical points were observed at a ratio of (0.1% by weight of cement) and when this ratio was exceeded, it turns out that adding nano-silica leads to a reduction in the strengthening of lightweight concrete properties. Wang et al., (2018), [43] observed an increase in the compressive strength of lightweight concrete when nano-silica material is added in variable proportion. They investigated the impact of adding nano-silica material in four ratios (0, 1, 2, and 3%) on the compressive strength, shrinkage, and sensitivity to early cracks of lightweight concrete which was prepared based on two types of lightweight aggregates. They concluded that the increase in the compressive strength continues with the age of concrete, and the average increase in the compressive strength is higher at an early age and then decreases at subsequent ages. It also has been observed that the larger values of compressive strength of the mixtures at all ages (3, 7, and 28 days) were during the addition of (3%) of nano-silica material. As for the shrinkage test, the results showed there was no clear effect of nano-silica addition with all ratios in the long-term period for the shrinkage of lightweight concrete, but there was an increase in the percentage of the shrinkage strain effect when increasing the doses of nano-silica material. The results also revealed that the use of nano-silica material reduced the area of early cracks of lightweight concrete.

Ismail et. al., (2018)[44] studied the effect of adding nano-silica material in different proportions on the properties of lightweight concrete containing lightweight aggregates as a complete alternate of normal aggregates. The researchers conducted their study on concrete with a density of (1400-1500 Kg/m3). The evaluation of nano-silica role on the behavior of lightweight concrete was made based on the results of the experiments, which include compressive strength and tensile strength. The ratios of nano-silica that were adopted in the study were (0, 0.75, 1.5, and 2%). The results revealed that the addition of nano-silica has a clear effect on compressive and tensile strength, and these values were higher than mixtures without nano-silica addition. The researchers also recorded that the compressive strength of mixtures containing nano-silica at ratios (0.75 and 2%) was higher than those containing a ratio of (1.5%), while the highest tensile strength was recorded when the percentage of nano-silica was (2%). Elrahman et. al., (2019)[45] investigated the effect of adding nano-silica on the compressive strength and flexural strength of concrete mixtures with densities ranging (900-1000 kg/m3). They added several percentages of nano-silica (0, 1, 2, and 4% by weight of cement). The results of the tests showed that there is a clear increase in the compressive strength of concrete when adding nano-silica material. It was also noticed that this material has the same effect on the flexural strength, and it increases especially at the two ratios (2 and 4% by weight of cement). Suliman et. al., (2019)[46] examined the effect of adding nano-silica material in different proportions (0, 1, 2, and 3%) on the compressive strength of lightweight concrete in which burnt bricks were used as coarse aggregates. The results showed that the compressive strength increases with the increase in the ratio of nano-silica, as the highest value of the compressive strength corresponded to the addition of nano-silica by 3%. Table1 summarizes the results of previous studies that examined the influence of nano-silica material on the compressive strength of mixtures.

Table 1. Relation between the ratio of nano-silica and its effect on lightweight concrete compressive strength.

References	Nano-silica ratio addition	Effect on compressive strength
Nakul Shah and Jayeshkumar Pitroda (2012) [39]	5%	Increase in strength
Du et. al., (2015) [40]	1 and 2%	Increase in strength
Atmaca et al., (2017) [41]	3%	Increase in strength
Zhang et. al., (2018) [42]	0.05, 0.1, 0.2, and 0.5%	Increase in strength
Wang et al., (2018) [43]	1, 2, and 3%	Increase in strength
Ismail et. al., (2018) [44]	0.75, 1.5, and 2%	Increase in strength
Elrahman et. al., (2019) [45]	1, 2, and 4%	Increase in strength
Suliman et. al., (2019) [46]	1, 2, and 3%	Increase in strength

2.2. Nano-silica effect on the durability and water sorptivity of lightweight concrete

Du et. al., (2015) [40] investigated the effect of adding nano-silica material with variety ratios (1 and 2%) on the penetration depth and transport properties of lightweight concrete. They observed that there is a reduction in the penetration depth, and this is due to the packing effect of nano-silica material. They also noticed that there is a decrease in the amount of water sorptivity associated with the addition of nano-silica, and this decreases steadily until (2%) of the nano-silica addition. In summary, the results showed that there is a decrease in the amount of chloride diffusion when adding nano-silica, and this reduction continued with the addition of nano-silica. Furthermore, Atmaca et al., (2017) [41] investigated a practical study on the effect of adding nano-silica on gas permeability and water sorptivity of lightweight high strength concrete. A ratio of (3%) nano-silica material was added to the concrete mixtures containing lightweight aggregates with variable proportions (0, 10, 20, 30, and 40%). The properties of these concrete mixtures were compared to the mixtures with the same ratio of aggregates but without addition of nano-silica material. The results revealed that nano-silica clearly reduces the effect of water sorptivity and gas permeability and this because of adding this material improves the pore structure of lightweight concrete.

Vargas et. al., (2018) [47] conducted an experimental study to examine the behavior of lightweight concrete containing nano-silica material under the influence of sulfur attack. They added nano-silica material with weight ratios of (0 and 10%), and then studied the effect of magnesium sulfate acid on the water absorption and the volumetric change of the concrete after exposure to this acid. It has been found that adding nano-silica by (10%) had an obvious role in reducing the expansion in concrete of the mixtures subjected to sulfur attack compared to the mixtures without nano-silica material. It also has been noted that the addition of this material leads to reduce the absorption and the pore volume in lightweight concrete. It was also concluded that the mixtures containing nano-silica have more surface degradation than the mixes without this material when exposed to magnesium sulfate acid, as it is known that nano-silica interacts with calcium hydroxide Ca (OH)2 and forming a C-S-H gel. As this gel increases, the magnesium sulfate acid reacts with it and forming the M-S-H on the surface, which causes clear deterioration on the mixtures surface, as the compound formed as mentioned earlier has a low cohesion. Elrahman et. al., (2019) [45] studied the effect of adding nano-silica in different proportions (0, 1, 2, and 4% by weight of cement) on the thermal conductivity and sorptivity of lightweight concrete. The results showed that there was a small decrease in the thermal conductivity of the samples in which high percentages of nano-silica were added. Generally, all the samples had a thermal conductivity of less than (0.35 W/m/K). It was also noticed that water absorption coefficient decreased significantly with the increase in the amount of nano-silica, and there was also a decrease in the amount of effective water porosity with the increase in the proportion of nano-silica material.

2.3. Nano-silica effect on microstructure of lightweight concrete

Zhang et al., (2018) [42] noticed that the use of nano-silica material in small proportions ranging from (0, 0.05, 0.1, 0.2, 0.5, and 1% by weight of cement) in lightweight concrete leads to form a new type of hydration compound in a shape of fibers at the interface between the lightweight aggregate and the cement paste. This contributes to the local toughening of lightweight concrete, as these compounds are in the form of fibers that bridge the small cracks in the cement paste which increases the strength and reduce the permeability. Figure 4 shows the microstructure of lightweight concrete containing nano-silica material. Energy dispersive X-ray spectroscopy also illustrated that the chemical composition of the formed fibers that contain nano-silica are Si, Ca and large quantities of Al, while the non-nano-silica samples contain only Si and Ca.

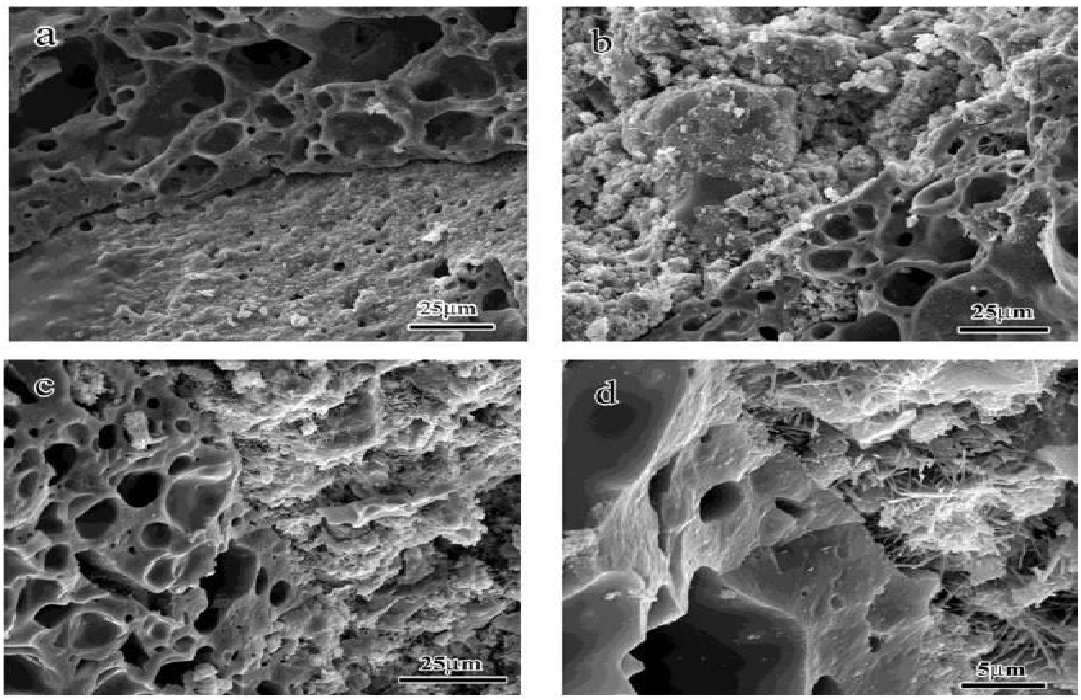


Figure 4. Scanning electron microscope image of lightweight concrete (a) without nano-silica addition, (b) with low nano-silica, (c) with relatively high dosage of nano-silica, (d) high magnification image of high dosage of nano-silica [42].

Ismail et. al., (2018)[44] concluded based on Scanning Electron Microscope test that has been performed on the mixtures of lightweight concrete containing variable ratios of nano-silica material (0, 0.75, 1.5, and 2%) that the voids in mixtures containing nano-silica were less compared to mixtures without nano-silica material. Moreover, the mixture containing (0.75%) had no cracks compared to mixtures containing (1.5 and 2%). This can be attributed to the pozzolanic activity of nano-silica material that leads to a formation of C-S-H gel which in turn fills the large voids in concrete and enhances the strength of concrete but after a long period of time, this gel gets dry, leaving small cracks in concrete that depends on nano-silica doses. Elrahman et. al., (2019)[45] investigated the effect of nano-silica addition with various proportions (0, 1, 2, and 4% by weight of cement) on the microstructure of lightweight concrete through conducting a Scanning Electron Microscope test. The study results indicated that the addition of nano-silica contributes to reducing the void diameters in the microstructure of lightweight concrete and the presence of nano-silica densified the microstructure. Furthermore, it also was recorded that adding large quantities of nano-silica material agglomerates the particles with the occurrence of small cracks around these agglomerates later, due to the volumetric change related to drought. These areas will be weak in the concrete, which negatively affects the mechanical properties.

3. Conclusion

The following points can be inferred from the thorough analysis of the literature which examined in particular the impact of nano-silica addition on mechanical characteristics, transport properties, durability and microstructure of lightweight concrete:

1. Nano-silica improves the behavior and durability of lightweight concrete because the small size of these materials reduces the size of voids within the concrete structure and significantly reduces the voids between the aggregates. This is due to the filling effect [48,49] of this material, which makes the concrete more uniform and homogeneous. It also makes the concrete denser, which allows it to improve its strength and avoid leakage and penetration of gas and chemicals with an negative effect on concrete behavior. Moreover, it also reduces water permeability and thermal conductivity of lightweight concrete. It should also be mentioned that adding nano-silica in high proportions does not enhance the behavior of lightweight concrete, because including these small materials in high ratios contributes to the collection of these particles. As a result of the volumetric change resulting from the drought, these agglomerated particles may have small cracks, which will make this area weak and thus impact the durability of lightweight concrete negatively.
2. Nano-silica contributes to the pozzolanic reactions as these materials reduce the calcium hydroxide Ca (OH)2 component located in the Interfacial Transition zone ITZ between the aggregate and cement paste by interacting with it and forming an additional C-S-H gel. Nevertheless, it increases the strength of lightweight concrete as it fills the voids and improves the microstructure of the concrete.
3. Better nano-silica molecules diffusion allows and accelerates the process of hydration [14], and it also works on the fluctuations of the pores. Improper diffusion of nano-silica particles decreases the durability of lightweight concrete. When small nanoparticles do not disperse efficiently, their collecting areas in the form of voids will also be weak, typically when the water-cement ratio is low [50].

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