The Influence of Nano-Silica on Some Properties of Light Weight Self-Compacting Concrete Aggregate

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Abstract. Lightweight concrete (LWC) has been used successfully in building constructions for many years due to its physical properties and its lightweight with high thermal insulation and durability. Recently, this work was done on a new type of concrete: lightweight self-compacting concrete (LWSCC) that combines the feature of lightweight and self-compacting concrete simultaneously. In this study, light expanded clay aggregate (LECA) was used as coarse aggregate in (LWSCC) mixtures, using nano-silica as a partial replacement of cement with three percent (0.5, 0.75, and 1%) by mass of cement. They were tested to evaluate these values of fresh characteristics through slump flow time and diameter, L-box, and segregation tests. The results of the fresh concrete tests showed a decrease in the workability of the concrete in the mixtures containing nano-silica due to the increase in fine materials in the mixture. The effects of nano-silica on the hardened properties of (LWSCC) such as compressive strength, flexural strength, splitting tensile strength, oven-dry density, and scanning electron microscopy (SEM), have improved. The mixtures containing nano-silica were investigated and compared with the reference mixture, where the results of the tests showed a significant improvement in the mechanical properties by (17.35, 16.27, 11.73, and 3.82%) for each of the compressive strength, flexural strength, splitting tensile strength and oven dry density respectively. In the presence of nano-silica, the replacement percentage of 1% recorded the best results in all tests at 90 days of curing.

Keywords: Leca, lightweight self-compacting concrete, Nano silica, compressive strength, flexural strength.

1. INTRODUCTION

Lightweight concrete is produced in several methods, and one of these methods is the use of lightweight aggregate. The purpose of resorting to this type of concrete is for several reasons, although this concrete is less strong and durable than traditional concrete [1]. Recently, with the development of high-rise buildings and buildings with tall sections, the demand for a special type of concrete that is light in weight, with strength and durability. The benefit of using lightweight concrete is to reduce the total weight of the structure and reduce the cross-section area of the structural members [2]. One such lightweight aggregate is Light Expanded Clay Aggregate (LECA), made by heating clay in a rotating kiln to 1200°C. LECA is a spherical organism with a continuous network of pores. LECA may make lightweight blocks, concrete, partition panels, thermal insulating tiles, and thermally roofing plaster. Abbas [3] investigated the production of expanded clay aggregate and the effects of processing variables on the material's mechanical and physical properties. Additionally, it examines auxiliary elements that can be used to enhance the properties of concrete with expanded clay aggregates. Further, the impact of expanded clay aggregate quantity on fresh, hardened, and durable concrete properties is investigated. Concrete's workability, fire resistance, sound insulation, and thermal insulation are all improved by expanded clay aggregates. Contrarily, its addition reduces the density, strength, elastic modulus, and resistance to the freeze-thaw action of concrete. Self-compacted concrete (SCC) can be spread into place by filling the structure's framework and permeating the reinforcement without any compaction or mechanical consolidation, according to ACI 237R-14 [4]. It is high-flowable concrete that has no segregation [5].

Self-compacting concrete is a novel type of concrete that doesn't require vibration for placement or compaction. Even when reinforced with a lot of other material, it can still flow under its weight, filling the forms and achieving full compaction [6]. Self-compacting concrete (SCC) has recently undergone a major evolution due to numerous studies showing the series of advantages SCC offers. The effects of micro silica (MS) (10%, used as a reference) and colloidal nano-silica (CNS) (2.5%, 5%, 7.5%, and 10%) on the fresh and hardened properties of SCC. Micro and nanomaterials used as mineral additives in SCC offer several high-performance properties. All mixtures' hardened properties, including compressive strength, elastic modulus, and tensile strength, were calculated. Compared to the reference mixture, the use of CNS increased compressive strength overall by an average of 41% over 28 days [7]. LWSCC (lightweight self-compacting concrete) is expected to provide great workability without segregation and high durability while being lighter. The usage of aggregates is essential to the production of high-quality (LWSCC). Expanded clay aggregate combined with additional high-quality supplementary cementing elements (such as fly ash and silica fume) can provide workable and hard concrete (LWSCCs). Preceding research shows that the addition of nanoparticles changes fresh and hardened state characteristics, even when compared to traditional mineral additions. Colloidal amorphous silica particles appear to influence the C_3S hydration process [8] significantly. The manufacturing procedure determines the primary properties of nano-silica, such as particle size distribution, specific density, specific surface area, pore structure, and reactivity. Due to their tiny size, nanoparticles can spread in hot environments due to their high specific surface area, high activity, and high solar radiation absorption. While a conglomerate may form at low temperatures, this does not affect the product's density. In addition, nanoparticles made of gray silicon and yellow gold are colored red. In order to create new construction materials with distinctive properties. In addition, one of the key components of buildings is Portland cement. Despite the existence of several research documenting the primary qualities and characteristics of concrete incorporating nano-silica particles, the majority of their concentration on the use of nano-silica as an anti-bleeding and compressive strength increase as well [9]. The performance of these cementitious-based materials is heavily reliant on nano-sized solid particles, such as calcium–silicate–hydrates (C–S–H) particles, or nano-sized porosity in the interfacial transition zone between cement and aggregate particles. Strength, durability, shrinkage, and steel bond are some of the few attributes that nano-sized particles or voids can affect [10-12]. In this paper, nano silica will be used with lightweight self-compacting concrete that has a density between (1800-1950) kg/m^3, which is nano-silica where this part of the cement is replaced with this material in three proportions, which are (0.5, 0.75, and 1%) and tests are conducted to find out the physical changes as a result of the replacement and compare it with the reference mixture.

2. EXPERIMENTAL WORK

2.1 Ordinary Portland Cement (type V)

The chemical and physical properties of cement used in this study are shown in Tables 1 and 2, which are satisfied with Iraqi specifications (IQS No.5, 2019) [13].

Table 1: The chemical properties of cement.

Oxide composition	% by weight	Limits of (IQS No.5, 2019).
SiO_2	21.62	Not limited
Al_2O_3	5.94	Not limited
Fe_2O_3	3.32	Not limited
CaO	61.55	Not limited
L.S.F	0.86	Not limited
MgO	2.85	Max (5)
SO_3	2.25	Max (2.8)
Loss on ignition	1.07	Max (4)
Insoluble residue	0.88	Max (1.5)
Main compounds(Bogue's equation)% by mass of cement		
C3S	35.11	Not limited
C2S	35.07	Not limited
C3A	10.13	Not limited
C4AF	10.09	Not limited

Table 2: The physical properties of cement.

Physical properties		Test results	Limits of (IQS No.5, 2019)
Setting time (Vicate method)	Initial (min) Final (hrs)	106 4.83	Min (45) Max (10)
Compressive strength (MPa)	2 days 28 days	11.25 33.31	Min (10) Min (32.5)

2.2 Fine Aggregate

Sieve analysis of fine aggregate is shown in Table 3, and the properties of fine aggregate which are satisfied to Iraqi specification No.45/1984 [14] are shown in Table 4.

Table 3: Sieve analysis of fine aggregate.

Sieve size (mm)	Accumulated percentage passing (%)	Limit of Iraqi specification No. 45/1984 (Zone 2)
4.75	92	90 -100
2.63	80	75-100
1.18	64	55-90
0.60	40.3	35-59
0.30	10	8-30
0.15	2	0-10

Table 4: The properties of fine aggregate.

Property	Results	Iraqi specification limits I.Q.S 45/1984

Grading Zone	second	------
Fineness Modulus	2.73	------
Apparent Specific Gravity	2.58	------
Bulk Density(kg/m^3)	1670	-----
Absorption (%)	3	------
Sulfate Content (SO_3) %	0.21	≤ 0.5

2.3 Light Expanded Clay Aggregate (LECA)

In this study, Leica was used as a coarse aggregate with a size between (4-10) mm. It is sourced from the quarries of southern Iraq. As shown in Figure 1. Leca should be immersed in water for 24 hours before mixing. The properties of light-expanded clay aggregate are shown in Table 5**.**

Figure 1:Light expanded clay aggregate (LECA).

Table 5: The properties of light-expanded clay aggregate.

Properties	**Experimental value**
Fineness modules	3
Density (kg/m^3)	320
Specific gravity	2.6
Water absorption %	21.6

2. 4 Silica Fume

The production of elemental silicon or alloys containing silicon in electric arc furnaces results in the by-product known as silica fume, according to ASTM C1240 [15]. It physically optimizes particle packing of the concrete or mortar mixture and chemically as a highly reactive pozzolan. Typical properties of silica fume at 25°C are shown in Table 6.

Table 6: Typical properties of silica fume at 25°C*.

Property	**Value**
Color	Grey to medium grey powder
State	Sub-micron powder
Specific gravity	2.2
Bulk density	500 to 700 kg/m^3
Chemical Requirements Silicon Dioxide (SiO_2) Moisture Content (H_2O) Loss on Ignition (LOI)	 89 2.6 4.9
Physical Requirements Specific Surface Area Pozzolanic Activity Index, 7 days Oversize particles retained on a 45-micron sieve	 > 15 m^2/g 99 8.6

*the properties according to the manufacturer

2. 5 High-Range Water Reducing Admixture (BETONAC®-1030)

It improves workability and provides unique properties to concrete surface finishings as it reduces leaching and segregation when poorly graded sand is used in concrete mixes. The additive can also provide the amount of cement in the mixtures within limits (15-20) % and does not affect the compressive strength of the concrete results. The properties of the superplasticizer are shown in table 7.

Table 7: The properties of superplasticizer.

Property	Value
Density	1.14 gm./ml ± 0.02
Color	light yellow
Calcium chloride (%)	There is no
pH	7.5 at 20 c°

2.6 Silicon Dioxide Nano Powder SiO_2

The chemical reaction of hydrophobic fumed silica with reactive silanes such as chlorosilane or hexamethyldisiloxide produces hydrophobic silica. It is hydrophobic (waterproof) and cannot be dispersed in water. The properties of nano-silica are shown in Table 8.

Table 8: The properties of Nano Silica*.

Property	Value
Form	Powder
Size	20-30 nm
Purity	99.8 %
Color	White
Odor	Odorless
Melting point	1610-1728 c°
Boiling point range	2230
Density	At 20 c (2.17-2.66 g/cm3)
Water	Insoluble

*The properties of nano-silica according to manufacture

2.7 Mix Design

EFNARC [16] was used to design the mixtures of this work. For SCC to achieve the target slump flow of (650-750) mm. Multi-trail mixtures were tried for this purpose, with the proportions of the materials modified to satisfy both the requirements of structural LWC and compacting concrete. Four mixes were used in this research the reference mix and three mixes with nano silica. Nano silica was used with three partial replacements (0.5, 0.75, and 1%). Powder content, fine aggregate content, SP dosages, coarse aggregate content, and W/p ratio were all held constant for all mixtures. Table 9 provides information about the mixtures used in this study.

Table 9: The details of mixes by weight (kg/m3).

Mix	Cement kg/m^3	Leca kg/m^3	Sand kg/m^3	Water kg/m^3	Silica fume kg/m^3	Lime powder kg/m^3	S.P %	Nano percent%	Nano Silica kg/m^3
M0	480	150	800	194.7	80	30	1.7	-	……
MS1	477.6	150	800	194.7	80	30	1.7	0.5	2.4
MS2	476.4	150	800	194.7	80	30	1.7	0.75	3.6
MS3	475.2	150	800	194.7	80	30	1.7	1	4.8

3. EXPERIMENTAL RESULTS

3.1 Fresh Properties

3.1.1 Slump Flow Test

It is defined as assessing a concrete's capacity to be mixed, handled, transported, and—most importantly—installed with minimal loss of homogeneity. The slump of the mixes used in this study is displayed in Figure 2 and Table 10 according to BS EN 12350-8 [17]. The results of the slump flow test indicate a decrease in slump flow in the mixtures containing nano-silica compared with the reference mixture. As a result of adding nano-silica, the slump flow diameter was smaller. Small-particle, high-surface-area nano silica contains these elements. Concerning concrete production, this nano silica feature raises the water demand. The water content was held constant for the duration of this study. Despite this, it was still found that the slump flow diameter decreased as nano silica content increased. The percentage of replacement of nano silica 1% recorded the highest rate of decrease by 20%.

Table 10: Slump flow.

Mix	Slump (mm)
M0	750
MS1	680
MS2	630
MS3	600

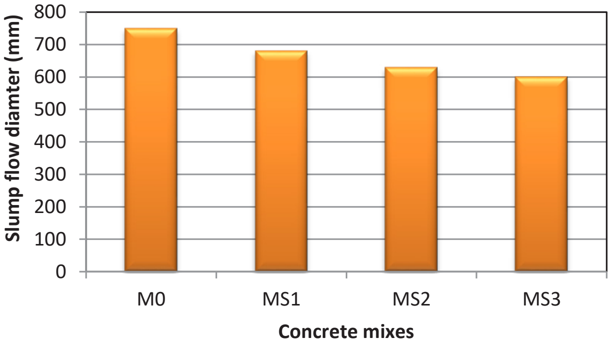

Figure 2: Slump flow diameter for all concrete mixes.

3.1.2 Segregation Test

The sieve segregation test is used to evaluate the anti-segregation performance of self-compacting concrete according to BS EN 12350-11 [18]. The test results in Table 11 and Figure 3 show that the segregation decreases when adding nano silica compared to the reference mixture. This is because nano silica is a wonderful material with a large surface area that reacts quickly and increases the density of fresh concrete. The rate of decrease for mixtures containing nano-silica was 15.8,30.4, and 46.4% for partial replacement percentage nano silica 0.5, 0.75, and 1%, respectively.

Table 11: Segregation results.

Mix	Segregation (%)
M0	13.89
MS1	11.69
MS2	9.67
MS3	7.45

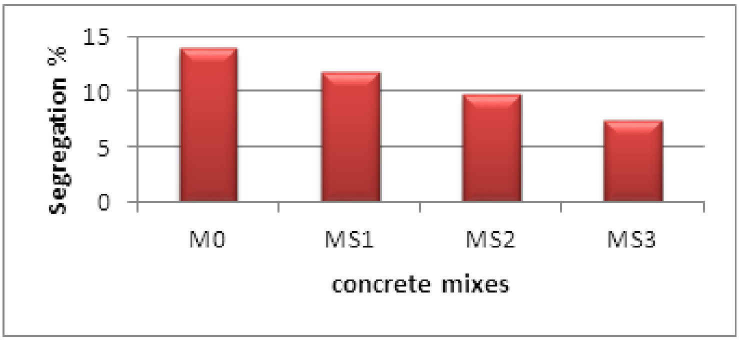

Figure 3: Results of segregation test for all concrete mixes.

3.1.3 L-Box Test

The L-box test is used to determine self-compacting concrete's capacity to flow through narrow apertures, such as gaps between reinforcing bars and other barriers, without segregation or blockage, according to BS EN 12350-9 [19]. The results of the L-box test are shown in Table 12 and Figures 4, 5. Indicate a decrease in the value of H2/H1 when adding nano-silica, which means an increase in the density of the fresh concrete mixture due to the increase in the fine, fast-reacting nano-silica.

Table 12: L-box test results.

Mix	H2/H1
M0	0.9
MS1	0.89
MS2	0.87
MS3	0.81

Figure 4: L-Box test

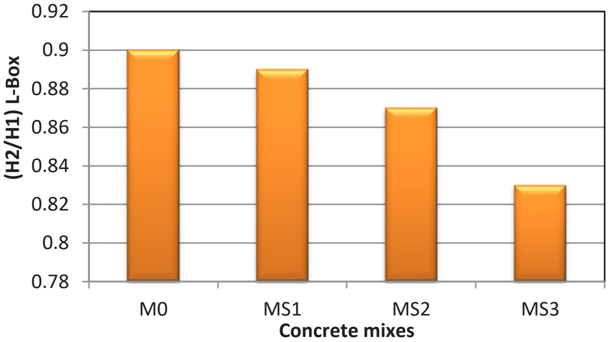

Figure 5: Results of L-box test for all concrete mixtures.

3.2 Hardened Tests

3.2.1 Compressive Strength

This test was conducted on 100 mm cubes following (BS EN 12390-3) [20]. The samples were tested at 7, 28, and 90 days old, and the testing results were dependent on the average of three specimens. The results are shown in Table 13 and Figure 6. The examination results showed that adding nano-silica improved the compressive strength, as the replacement percentage of 1% showed the best results by a 17.35% increase at 90 days. This increase can be attributed to the interaction of nanomaterial with calcium hydroxide Ca(OH)2 crystals in the inter-facial zone (ITZ) between the hardened grout and aggregate, which creates packing of C-S-H gels and nanoparticles and dense microstructures. Jalal et al. [21] prove that compressive strength and tensile strength at the break of the blend with silica fume and Nano silica are increased, possibly due to accelerated C-S-H gelation rather than Due to the increased amount of crystalline $Ca(OH)_2$ early years. The strength increase is achieved by Increase binder content.

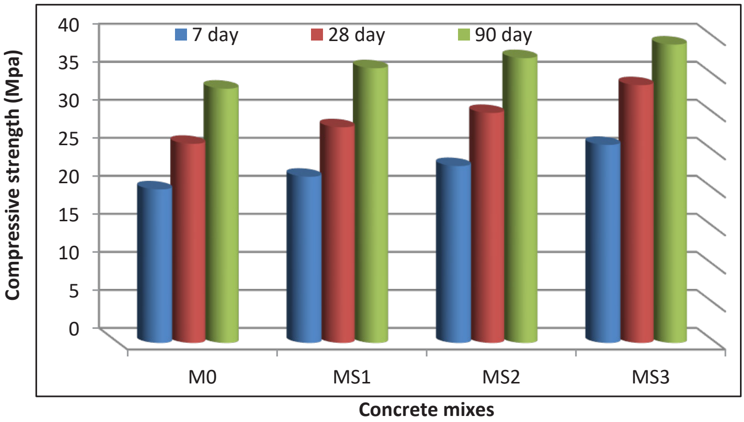

Figure 6: Compressive strength results for mixes with nano SiO_2.

Table 13: Compressive strength results.

Mix	Compressive strength at 7 days (MPa)	Compressive strength at 28 days (MPa)	Compressive strength at 90 days (MPa)
M0	20.19	26.18	33.43
MS1	21.85	28.36	36.12
MS2	23.26	30.24	37.45
MS3	26.04	33.89	39.23

3.2.2 Flexural Strength

By using the center point method, flexural strength was assessed in accordance with ASTM C 293-07 [22]. The 80x80x380 mm prism specimens were tested at 7, 28, and 90 days old. They were simply supported with a 300mm span. For each mix, an average of three prisms was taken.

The modulus of rupture was calculated with the following:

$$\mathrm{Fr} = 3\mathrm{PL}/2\mathrm{bd}^2 \qquad (1)$$

Where Fr is the flexural strength (MPa), P is the maximum applied load indicated by the test machine (N), L is the average length of the specimen (mm), b is the average width of the specimen (mm), and d the average depth of the specimen (mm). The results are shown in Table 14 and Figure 7. Silica particles increased the strength of concrete by converting calcium hydroxide to C-S-H when they were added. By incorporating Nano silica particles, the pozzolanic reactivity was improved while maintaining the strength of the concrete. The flexural strength of the concrete mix containing nano-silica with 1% partial replacement increased by 16.26 % at 90 days of curing.

Table 14: Flexural strength results.

Mix	Flexural strength (MPa) at 7 days	Flexural strength (MPa) at 28 days	Flexural strength (MPa) at 90 days
M0	4.5	4.77	4.98
MS1	4.7	4.93	5.13
MS2	4.9	5.09	5.34
MS3	5.1	5.35	5.79

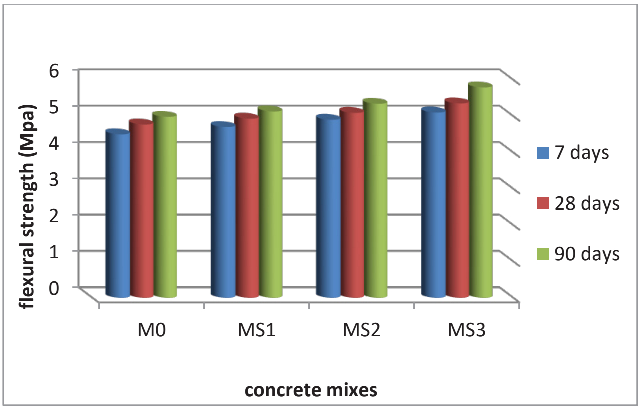

Figure 7: Flexural strength results for mixes with nano SiO_2.

3.2.3 Splitting Tensile Strength

The tensile strength test of concrete was evaluated using cylindrical specimens with dimensions of 150x300 mm are tested by compressive machine according to ASTM C 496-04 [23]. In this test method, a concrete cylindrical specimen is subjected to a diametric compressive force along its side until tensile failure occurs. The compressive machine's steel plate is used to evenly distribute the applied load along the length of the cylinder. The cylinders were tested at ages seven and twenty-eight days, with an average of three cylinders being used as the outcome. The cylinders were examined at 7, 28, and 90 days of age, and the average of three cylinders were obtained.

The results in Figure 8 and Table 15 below indicate that splitting tensile strength increased noticeably in mixtures containing nano-silica. This improvement may be attributable to accelerated C-S-H gel formation brought on by increased crystalline $Ca(OH)_2$ content at young ages. Clearly, the highest replacement percentage, 1%, was the optimal improvement in all ages of the test. The increase was about (10.45, 16.98, and 11.73%) for mixes with 1% nano-silica at 7,28, and 90 days of curing, respectively. Mohamed [24] proves that this improvement can be attributed to the reaction of nanomaterial with calcium hydroxide $Ca(OH)_2$ crystals in the interfacial zone (ITZ) between the hardened grout and aggregate and generates packing of C-S-H gels and nanoparticles, resulting in dense microstructures.

Table.15: Splitting tensile strength results.

Mix	**Splitting tensile strength (MPa) at 28 days**	**Splitting tensile strength (MPa) at 28 days**	**Splitting tensile strength (MPa) at 90 days**
M0	2.87	3.12	3.58
MS1	2.93	3.22	3.76
MS2	3.05	3.45	3.84
MS3	3.17	3.65	4

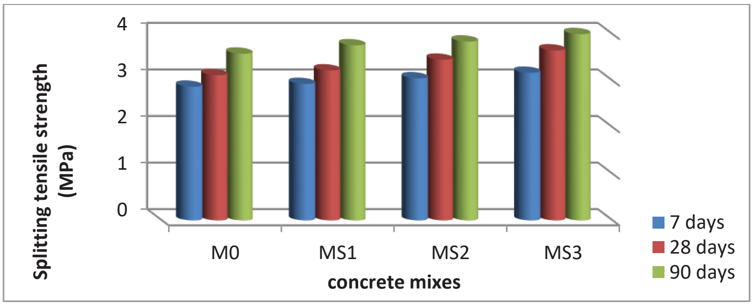

Figure 8: Splitting tensile strength results for mixes with nano SiO_2.

3.2.4 Oven Dry Density

Samples were tested according to ASTM C-567 [25]. The average results of three samples of each combination were calculated (7, 28, and 90) days after the cubes were removed from the curing water and their surfaces were cleaned with a cloth. The hardened concrete's mass (kg/m3) per unit volume is called density (ρ). Density is determined from the air-dried sample mass and sample volume (100 x 100 x 100 mm). As shown in Table 16 and Figure 9, the oven-dry density of the samples increases with age, as the density of the samples increases with the addition of nano-silica, where the nanomaterial behaves like pozzolanic material, as it fills the voids as a result of its high surface area, and thus makes the samples containing nano-silica denser.

Table 16: oven dry density results.

Mix	**Oven dry density at 7 day**	**Oven dry density at 28 day**	**Oven dry density at 90 day**
M0	1806	1811	1834
MS1	1816	1824	1839
MS2	1828	1839	1880
MS3	1845	1893	1904

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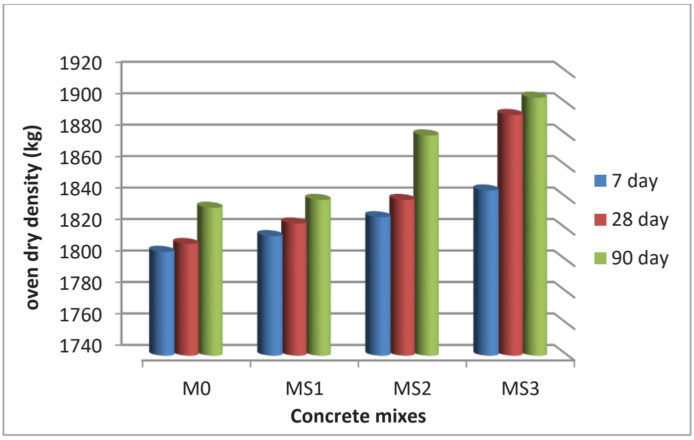
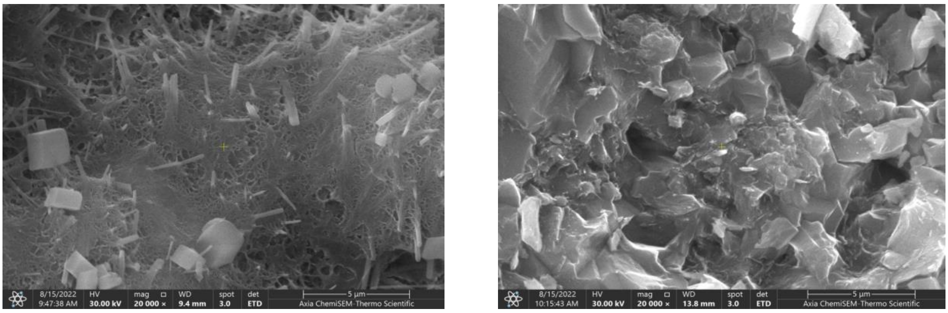


Figure 9: Oven dry density for all concrete mixes.

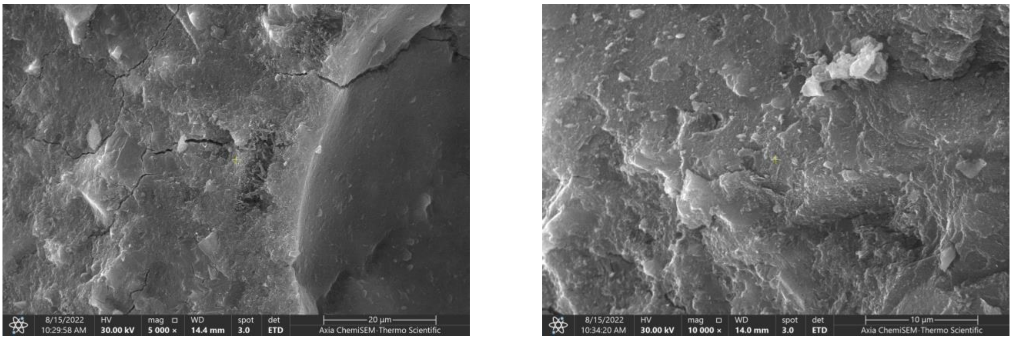
3.2.5 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) examined the concrete at the micro level. SEM enables the examination of many aspects of the device's microstructure. Using this tool, the sample was sliced into pieces about 5x5x10 mm from the middle of the crack. The SEM examination shows the internal structure of the samples. Through the images shown below, the nano-silica material improved the material's density and the sample's internal coherence. Figures 10 and 11 showed that incorporating nano silica into concrete improved the interfacial transition zone between cement and aggregate. The added nano-silica 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.



(a) (b)

Figure 10: (a) SEM image for reference mix at 60 days, (b) SEM image for concrete mix with 0.5% nano silica at 60 days.



(a) (b)

Figure 11: (a) SEM image for concrete mix with 0.75% nano silica, (b) SEM image for concrete mix with 1% nano silica at 60 days.

4. CONCLUSIONS

- The results of the slump flow test indicate a decrease in slump flow in the mixtures containing nano-silica compared with the reference mixture.
- The segregation decreases when adding nano silica compared to the reference mix because nano silica is a very fine material with a large surface area that reacts quickly and increases the density of fresh concrete.
- The results of the L-box test indicate a decrease in the value of H2/H1 when adding nano-silica, which means an increase in the density of the fresh concrete mixture.
- Adding nano-silica improves the compressive strength, as the replacement percentage of 1% showed the best results.
- The flexural strength of the mixtures containing nano silica and the improvement was clear, as when the percentage of nano silica was increased, the flexural strength increased, as the replacement rate of 1% showed the best results.
- The splitting tensile strength increases significantly when adding nano silica compared to the reference mixture without addition. Clearly, the highest replacement percentage, 1%, was the optimal improvement in all ages of the test.
- The oven-dry density of the samples increases with age, as the density of the samples increases with the addition of nano-silica, where the nanomaterial behaves like pozzolanic material, as it fills the voids as a result of its high surface area, and thus makes the samples containing nano-silica denser.

- The SEM test showed that nano-silica material improved the material's density and the sample's internal coherence.
- The fresh concrete and hardened concrete tests showed that the replacement percentage for nano-silica was 1%, which showed the best results.

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