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Experimental Study of the Combined Use of Fiber and Nano Silica Particles on the Properties of Lightweight Self Compacting Concrete

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ABSTRACT

In fiber concretes, microcracks in the boundary area between the cement paste and the surface of aggregates or fibers are higher. Natural and artificial pozzolans can be used for reinforcing this area. In this research, the combination of glass fiber, zeolite, and nano silica particles were used in lightweight self-compacting concrete containing scoria. Fiber volume fractions between 0% to 1.5% in combination with 0% to 6% nano silica particles were examined. The scoria aggregates and zeolite were considered constant in all mixes. The fresh and hardened properties of specimens were evaluated using T50, slump flow, V-funnel, L-box, compressive strength, splitting tensile strength, flexural strength, ultrasonic, electrical resistivity, and water absorption tests. Also, the microstructure of concrete was investigated using scanning electron micrograph images. The combined use of nano silica particles and glass fiber increased the splitting tensile strength by about 3 to 56%. Also, the use of nano silica particles increased electrical resistivity by 136 to 194%. Nano silica particles, due to their high specific surface and high reactivity, result in consuming calcium hydroxide that is quickly organized within the hydration, filling pores of the calcium silicate gel structure and eventually producing more and more compacting hydrated products.

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1. INTRODUCTION

Despite the major benefits of concrete, there are two major disadvantages inherent in it, one is low tensile strength and the other is relatively high density [1]. There are generally two different methods to resolve the relatively high weight of concrete buildings. The first method is based on increasing concrete strength to reduce dimensions of elements and thereby to decrease volume of concrete and weight of rebar. The second method is based on the density reduction of concrete and the use of lightweight concrete. However, tensile weakness of concrete, which results in low ductility and high brittle, is considered as a weak point. To solve this problem, fibers that are uniformly dispersed in the concrete volume are used. Destruction and deterioration of concrete are highly dependent on the formation of cracks and micro cracks due to loading or environmental impacts. Heat and moisture transfers in the cement paste result in the formation of microcracks, and such microcracks are concentrated on the surface of coarse grains [2–6].

Ehsani Yeganeh et al. [4] evaluated the attributes of self compacting concrete containing fiber. Three types of high density polyethylene fibers, crumb rubber and polyvinyl alcohol were used. The results showed that adding fibers improves compressive, tensile and flexural strengths and increases the cracks [4]. Badogiannis et al. [7] evaluated the behavior of steel and polypropylene lightweight concrete. For this purpose, pumice was used as a lightweight aggregate. Based on this study, fiber can improve the cracking strength of concrete [7]. Wu et al. [8] evaluated the microstructural characteristics of steel and carbon fibers lightweight concretes. Five different lightweight aggregates were used and volume percentage of fibers was considered 0.3, 0.6 and 0.9. The results showed that the use of fibers in lightweight concrete has

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little effect on compressive strength but increases tensile strength. The water-cement ratio and the properties of aggregates can also influence the results [8].

In the studies mentioned above, it was observed that making fiber concrete is an effective step in preventing the propagation of microcracks and cracks and compensating for the tensile strength weakness of concrete. The energy-absorption property of concrete can greatly reduce the risk of failure of concrete structures, especially in areas which are under repeated seismic loads. However, addition of some types of fibers such as steel fibers to structural lightweight concrete, especially with a volume greater than 1%, increases the density of lightweight concrete they have low strength against corrosion. To solve this problem, other fibers such as carbon, aramid, polypropylene (PP), polyethylene (PE) and polyvinyl alcohol, polyester, and glass fiber (GF) can be used, either in single or in combination with lightweight concrete to improve the strengths and ductility.

To reinforce the boundary area between the cement paste and the surface of aggregates or fibers, nano silica particles (nSPs) can be used as a highly active artificial pozzolan which is from nanotechnology products. The presence of nSPs can increase the bonding strength of aggregate with paste as well as fibers with cement paste. Senff et al. [9] indicated that setting time of cement was decreased by adding nSPs to the cement. Naniz and Mazloom [10] investigated the characteristics of self compacting lightweight concrete containing nSPs and silica fume. The evaluations indicated that the combined use of silica fume and nSPs significantly improve the concrete characteristics [10]. Mohammad et al. [11] evaluated the effects of nSPs on the characteristics of concrete containing fly ash as a replacement for a part of cement. NSPs decreased the porosity of cement to 13.4% [11]. Abd Elrahman et al. [12] evaluated lightweight concrete containing of nSPs. The results indicated that nSPs modify the structure of the fine pores and thereby improve the concrete transport attributes [12].

On the other hand, a lot of research has been done on the use of different fillers such as fly ash, zeolite, metakaolin, etc [13–19]. It is more important to use filler that has both filler and pozzolanic properties and to participate in the hydration reaction. Zeolite is one of the fillers that has been considered as a pozzolanic filler in concrete in various studies and has had many positive effects. Nanoparticles with different fillers can exhibit different behaviors and optimum percentages. Therefore, the investigation of nanoparticles together with various fillers is important.

This study investigated the impact of GF, nSPs and zeolite on the characteristics of self compacting lightweight concrete which were made with scoria aggregates. The fresh concrete attributes were evaluated using slump flow, T50, V-funnel, L-Box and the properties of hardened concrete were investigated using compressive, tensile, flexural and ultrasonic tests. The durability of concrete specimens was also determined by electrical resistivity and concrete water absorption tests.

2. SCHEME OF EXPERIMENTAL INVESTIGATIONS

2. 1. Materials The materials include Portland cement (Type II), sand, scoria mineral shell, drinking water, superplasticizer, GF, zeolite, and nSPs. The coarse aggregates were the scoria lightweight aggregates which were obtained from Qorveh (Iran). In general, scoria is created by entering volcanic melting materials into aquatic environments such as seas and lakes and rapid cooling. Its color is black, light gray and dark brown. It also has irregular open and closed pores and has an uneven, angular surface. The largest scoria aggregate size used in this study is 12.5 mm. Its density is 0.68 g/cm^3.

The characteristics of the scoria are introduced in Table 1. The bulk density of sand is 1800 kg/m^3 and the water absorption rate is 3.2%. ASTM C136 [20] was used for gradation of aggregates. The sand gradation and scoria characteristics are introduced in Table 2. This table shows the allowable range of ASTM C330. The range of gradation is between the upper and lower boundaries of the ASTM C330 [21].

Potable water was used with a pH of about 7.5. The cement is Portland cement type II, a product of Hegmatan plant with a density of 3.15 g/cm^3. The physical and chemical properties of this cement are presented in Table 1. The nSPs are in powder form with a size of 15 to 20 nm. The physical properties and chemical analysis of

TABLE 1. Properties of Portland cement, Scoria, Zeolite and nSPs

Item	Scoria	Portland cement	Zeolite	nSPs
SiO_2 (%)	58.8	21.54	67.79	99.98 ≥
Al_2O_3 (%)	32.16	4.95	13.66	-
Fe_2O_3 (%)	3.98	3.82	1.44	-
CaO (%)	3.28	63.24	1.68	-
MgO (%)	1.5	1.55	1.20	-
SO_3 (%)		2.43	0.5	-
K_2O (%)	-	0.54	1.42	-
Na_2O (%)	-	0.26	2.04	-
Loss on ignition (%)	3.02	-	10.23	1.00 ≤
Specific gravity (g/cm^3)	0.68	0.75	1.1	0.5
Specific surface area (m^2/g)	-	326	1.1	200

TABLE 2. Gradation properties of aggregates and their comparison with ASTM-C33

Sieve size (mm)	ASTM-C33 limits for coarse aggregates	Percentage passing (Scoria)	ASTM-C33 limits for fine aggregates	Percentage passing (Sand)
12.5	90-100	91	-	-
9.5	40-80	63	-	-
4.75	0-20	10	-	-
2.36	0-10	6	95-100	95
1.18	-	-	40-80	60
0.3	-	-	10-35	25
0.15	-	-	5-25	17

these nSPs are introduced in Table 1. The chemical analysis of zeolite-based on ASTM C311 [22] is presented in Table 1. The fibers used in this study are A/type. The characteristics of GF are presented in Table 3. The superplasticizer function is the separation and dispersion of cement by repulsive forces caused by static electric load. This product works well when silica additives are used in the mixed design for preventing slump drop. It is chlorine free and is in adjustment with ASTM-C494 [23]. Its color is light brown and it has a pH of 6 to 7 and a density of 1.2 g/cm^3.

2. 2. Mixed Design

The properties of mixed design and the amounts of each consuming materials are presented in Table 4. The mixed design was obtained by the use of previous experimental studies and trial and

TABLE 3. Properties of GF

Length (mm)	Diameter	Tensile strength (MPa)	Module of elasticity (GPa)
12	0.02	1400	77

TABLE 4. Mixed design

Mix ID	Water-binder ratio	Cement	Nanosilica		Zeolite		Glass fiber (%)	Water (kg)	Sand (kg)	Scoria (kg)	Superplasticizers	
			Percent	Content (kg)	Percent	Content (kg)					Percent	Content (kg)
NS0F0	0.4	405	0	0	10	45	0	180	950	393	1.62	7.45
NS0F0.25	0.4	405	0	0	10	45	0.25	180	950	393	1.62	7.45
NS0F0.50	0.4	405	0	0	10	45	0.5	180	950	393	1.62	7.45
NS0F0.75	0.4	405	0	0	10	45	0.75	180	950	393	1.62	7.45
NS0F1	0.4	405	0	0	10	45	1	180	950	393	1.62	7.45
NS0F1.5	0.4	405	0	0	10	45	1.5	180	950	393	1.62	7.45
NS2F0	0.4	396.9	2	9	10	44.1	0	180	950	393	1.62	7.45
NS2F0.25	0.4	396.9	2	9	10	44.1	0.25	180	950	393	1.62	7.45
NS2F0.50	0.4	396.9	2	9	10	44.1	0.5	180	950	393	1.62	7.45
NS2F0.75	0.4	396.9	2	9	10	44.1	0.75	180	950	393	1.62	7.45
NS2F1	0.4	396.9	2	9	10	44.1	1	180	950	393	1.62	7.45
NS2F1.5	0.4	396.9	2	9	10	44.1	1.5	180	950	393	1.62	7.45
NS4F0	0.4	388.8	4	18	10	43.2	0	180	950	393	1.62	7.45
NS4F0.25	0.4	388.8	4	18	10	43.2	0.25	180	950	393	1.62	7.45
NS4F0.50	0.4	388.8	4	18	10	43.2	0.5	180	950	393	1.62	7.45
NS4F0.75	0.4	388.8	4	18	10	43.2	0.75	180	950	393	1.62	7.45
NS4F1	0.4	388.8	4	18	10	43.2	1	180	950	393	1.62	7.45
NS4F1.5	0.4	388.8	4	18	10	43.2	1.5	180	950	393	1.62	7.45
NS6F0	0.4	380.7	6	27	10	42.3	0	180	950	393	1.62	7.45
NS6F0.25	0.4	380.7	6	27	10	42.3	0.25	180	950	393	1.62	7.45
NS6F0.50	0.4	380.7	6	27	10	42.3	0.5	180	950	393	1.62	7.45
NS6F0.75	0.4	380.7	6	27	10	42.3	0.75	180	950	393	1.62	7.45
NS6F1	0.4	380.7	6	27	10	42.3	1	180	950	393	1.62	7.45
NS6F1.5	0.4	380.7	6	27	10	42.3	1.5	180	950	393	1.62	7.45

error in accordance with ACI-211 [24]. The studied variables were nSPs (0, 2, 4 and 6 % by weight of cement) and GF (0, 0.25, 0.50, 0.75 and 1 and 1.5 % by weight of cement), respectively. After making and molding, the specimens were kept in the mold for 24 hours. Then they were removed from the mold and moisture curing was performed until the age of the tests.

2. 3. Procedure The fresh concrete tests include slump flow, T50, V-funnel, L-box, respectively and the hardened concrete tests are compressive, splitting tensile, flexural, ultrasonic, electrical resistivity, water absorption and scanning electron micrograph (SEM), respectively. Tests related to evaluation of self-compacting concrete were performed according to the European guildlines for self-compacting concrete (EFNARC) [25]. Compressive, tensile and flexural behavior of concrete specimens were performed in accordance with ASTM C39 [26], ASTM C496 [27] and ASTM-C293 [28], respectively (Figure 1). For compressive strength, cubic molds with dimensions of 150×150×150 mm were used. In the splitting tensile strength test, a standard cylindrical mold with dimensions of 300×150 mm was used. The load was increased uniformly at a rate of 0.8 to 1.2 MPa/min until the specimen was failed. The maximum load was recorded and the splitting tensile strength was obtained from Equation (1)

$$T = \frac{2p}{\pi L d} \tag{1}$$

T and P represent tensile stress and failure load, respectively. Also, L and d represent the length and diameter of specimen.

Prismatic specimens with dimensions of 100×100×400 mm were prepared for flexural strength test. The flexural strength was calculated by Equation (2).

$$S_f = \frac{3pl}{2bh^2} \tag{2}$$

where S_f is the flexural strength, p is the applying force in the middle of the span, b is the section width, h is the section height in mm, and l is the distance between the two supports.

a b c

Figure 1. Experimental set up; a: Compressive strength, b: Splitting tensile strength, c: Flexural strength

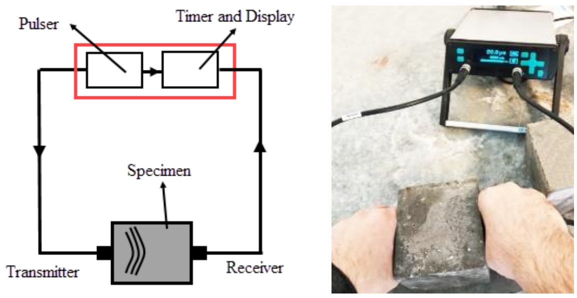
Ultrasonic pulse velocity (UPV) test was performed by ultrasonic device on concrete specimens in accordance with ASTM C597 [29] (Figure 2). Ultrasonic test is a common method used to analyze the structure of concrete and to reveal its internal weaknesses (such as hole, cracking, lamination, etc) [30, 31].

The water absorption test conducted in accordance with ASTM C642 at 28 days of age. For this purpose, cubic specimens (100×100×100 mm) were heated at 50 degrees Celsius for 14 days. The specimens were immersed in a tank filled with water after the temperature of the specimens had been remained constant with the laboratory temperature and their initial weight had been read. After 1 and 24 hours of immersion, the specimens were weighed. The water absorption percentage of the specimens was obtained using Equation (3).

$$\omega = \frac{m - m_0}{m_0} \times 100 \tag{3}$$

where m and m_0 are the weight of wet and dry specimens, respectively.

Electrical resistivity is an indicator of the relationship between holes. This indicator determines concrete strength against penetration of liquid or gas through concrete surface that is in contact with the outside environment. Electrical resistivity is one of the intrinsic properties of materials, that is dependent on the nature and topography of the structure of the holes, moisture conditions, temperature and density of soluble ions in the environment. A device for measuring the electrical resistivity with a variable frequency of 10 to 10,000 Hz was used. Copper plates were used to attach the two heads of specimen to the device. In order to prevent the copper plates from attaching to the floor and the worktable, 150×150 mm plastic molds were used, and the copper plates were positioned 100 mm apart. Because a conductive material is essential to entirely bond the copper plates to the specimen surface, a cement paste was used. The cement paste, on the one hand, has a large number of free ions which is an electrical conductor with a low strength and on the other hand, it makes a perfect connection between the concrete surface and the copper plates. The method of measuring the electrical resistivity



a b

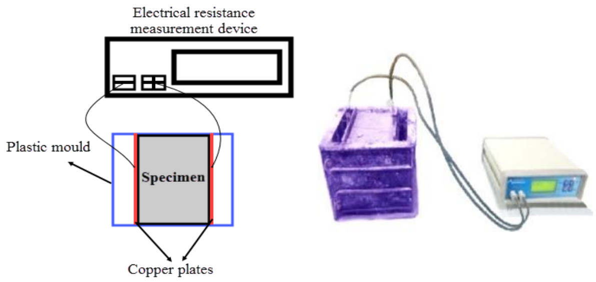
Figure 2. Ultrasonic test; a: Schematic image, b: Real image

is that some cement paste was first placed on one of the copper plates and spread by a spatula. The specimen, which was in saturated surface dry conditions, was placed on the cement paste. Then, the top level of the specimen was covered with cement paste and the top copper plate was placed on the specimen with weight. Each of the wires of the device was connected to one of the copper plates, the frequency of the device was set at 10 Hz, and the electrical resistivity number was recorded [32–35]. Figure 3 shows the specimen and copper plates and the process of measuring electrical resistivity of hardened concrete. The electrical resistivity was calculated using Equation (4).

$$\rho = \frac{R.L}{A} \tag{4}$$

where, ρ is the specific electrical resistivity of concrete in ohms-meters; R is the electrical resistivity that has been read from the device in ohms-meters, A represents the surface area of concrete (m^2) and L represents the distance between positive and negative poles in meters. Estimation of corrosion probability of buried rebars in concrete based on electrical resistivity is presented in Table 5.

The compressive strength test was performed at 7, 28 and 90 days. Also, splitting tensile, flexural, electrical strength, ultrasonic, and water absorption tests were performed 28 days after curing of specimens. Three specimens were constructed for each experiment and the average was presented as the ultimate number. According to the variables and the tests, a total of 576 specimens were made and various tests were performed on them.



a b

Figure 3. Electrical resistivity device; a: Schematic image, b: Real image

TABLE 5. Estimation of corrosion probability of buried rebars in concrete based on electrical resistivity [34, 35]

Electrical resistivity (kΩ-cm)	Estimation of corrosion probability
Less than 50	Very high
Between 50 and 100	High
Between 100 and 200	Low
More than 200	Very low

3. RESULTS

3. 1. Fresh Concrete Test

It was first tried to evaluate the concrete performance to ensure the minimum quality required for having self-compacting capabilities. Because the major physical and mechanical difference between self compacting concrete and usual concrete is the difference in efficiency and ease of transport and molding, it is necessary to control its performance. Control of fresh self compacting concrete properties is presented according to EFNARC [25] in Table 6. As it can be seen, the results of the tests on fresh concrete show that all the lightweight concrete specimens have self-compacting concrete conditions and are within

TABLE 6. Fresh concrete results

Mix ID	Slump flow		V-funnel time (sec)	L-box (H_2/H_1)
	D (mm)	T_{50} (s)		
NS0F0	747	3	8.1	0.93
NS0F0.25	733	3.2	8.7	0.92
NS0F0.50	721	3.3	8.9	0.89
NS0F0.75	716	3.3	9.3	0.88
NS0F1	691	3.5	9.5	0.86
NS0F1.5	683	3.5	9.9	0.84
NS2F0	717	3.1	9.1	0.9
NS2F0.25	713	3.3	9.6	0.89
NS2F0.50	677	3.4	9.6	0.88
NS2F0.75	656	3.4	9.9	0.87
NS2F1	645	3.6	10.1	0.85
NS2F1.5	635	3.7	10.6	0.84
NS4F0	692	3.3	9.9	0.88
NS4F0.25	684	3.5	10.2	0.87
NS4F0.50	665	3.8	10.6	0.86
NS4F0.75	642	3.9	10.6	0.85
NS4F1	614	4	10.9	0.83
NS4F1.5	609	4.2	11.3	0.82
NS6F0	677	3.7	10.6	0.81
NS6F0.25	667	3.9	10.9	0.79
NS6F0.50	642	4	11.2	0.77
NS6F0.75	619	4.3	11.5	0.76
NS6F1	608	4.6	11.7	0.74
NS6F1.5	601	4.8	11.9	0.72
EFNARC recommendatis [29]				
Min.	550	2	6	0.8
Max.	850	5	12	1

the EFNARC standard range. According to the EFNARC [25], the slump flow range should be between 550 and 850 mm and all the investigated specimens are in this range. According to EFNARC [25], the allowable range of the H_2/H_1 relation is between 0.80 and 1 and the allowable range of V-funnel is between 6 to 12 seconds and the investigated specimens are in this range. Therefore, according to the mentioned values, the investigated concrete specimens are considered self-compacting.

As shown in Table 6, it is observed that as the percentage of GF and nSPs decreases, the slump flow decreases, so that the lowest slump value occurred in the NS6F1.5 mixed design and the slump value corresponding to the control specimen became approximately 1.24 times more than the slump value corresponding to NS6F1. As it is expected, the addition of fibers reduces the slump flow, that is, it increases the locking probability. This is due to the higher value of fibers and their internal strength against flow, as well as increasing friction and internal collisions between aggregates and fibers [36]. On the other hand, the results of T50 test show that T50 increases with increasing the percentage of GF and nSPs. In the NS2F0, NS4F0 and NS6F0 modes, the T50 increased by 3.3, 10 and 23.3%, respectively; while, in the NS0F0.25, NS0F0.50, NS0F0.75, NS0F1 and NS0F1.5 modes, T50 increased by 7.5, 10, 30, 60 and 77.5%, respectively.

The effect of GF and nSPs on flow time of V-funnel and blockage ratio are presented in Table 6. The results show that the presence of fibers in self-compacting lightweight concrete containing scoria increases the viscosity of concrete and the funnel discharge time increases with increasing fiber percentage. Also, all the times obtained from the V funnel test conform to the allowable range set by EFNARC [25] (6 to 12 seconds). The use of nSPs significantly increases the V-funnel time, so that the discharge time of concrete from V funnel for each specimen containing 0.25, 0.5, 0.75, 1 and 1.5% GF in which 6% of the nSPs were used became 31, 25.3, 25.8, 23.7, 23.2 and 20.2% higher than those corresponding to the specimens without nSPs. High specific surface area and high water absorption of nanoparticles are the most important reasons that have reduced the concrete flowability. The results of the L-box test show that all designs have a good filling ability. However, observations indicate that increasing the fiber percentage led to a decrease in the H_2/H_1 ratio. In other words, the presence of fibers reduces concrete passing ability through rebars and decreases with increasing percentage of concrete passing ability of fibers. According to the results obtained by Mohsenzadeh et al. [6], adding fibers reduces the flowability and this reduction is exacerbated by increasing fiber value. This issue is also considered in this study. In a study by Sivakumar et al. [37], it was shown that adding GF to self-compacting concrete reduces the concrete fluidity and for compensating this fluidity decline, it was attempted to have a high fluidity in the initial mixture. Taheri Fard et al. [38] also stated that the use of fibers has negative effects on the rheological attributes of self-compacting concrete.

3. 2. The Results of Hardened Concretes

3. 2. 1. Density The compositions in self compacting concrete are such that they have a higher density than the conventional concrete and they have a less empty space. In a study about comparing the characteristics of self compacting concrete and conventional concrete, Persson [39] stated that, the density of self compacting concrete is higher than the conventional concrete. Weight loss of a building or structure that is related to the density of self compacting concrete has the greatest effect on reducing the risk of earthquake acceleration. The density of lightweight self compacting concrete specimens after molding is presented in Table 7. Each recorded number has a density mean of 3 cubic specimens of 150×150×150 mm. According to ACI 213R-03 [40], the density of lightweight concrete should be between 1120 and 1920 kg/m^3. According to the obtained values, all investigated concrete specimens are in the range of lightweight concrete because the obtained density is in the range of 1885 to 1897 kg/m^3. The addition of nSPs and GF increased the density of the specimens by a very small percentage (about 0.6%). Although the addition of fibers has created cavities in concrete, the use of silica nanoparticles has had a positive effect on the microstructure of concrete and increased its density, which has led to a slight increase in the density of concrete.

3. 2. 2. Compressive Strength Compressive strength of specimens at agaes of 7, 28 and 90 days is presented in Figure 4. Also, the changes of compressive strength compared to the control specimens are shown in Figure 5. The use of GF in self compacting lightweight concrete specimens was not effective and in some cases,

TABLE 7. The density of specimens (kg/m^3)

Glass fiber	Nano Silica Particles			
	NS0	NS2	NS4	NS6
F0	1886	1888	1890	1893
F0.25	1885	1890	1890	1893
F0.5	1887	1890	1892	1894
F0.75	1888	1891	1891	1895
F1	1888	1892	1893	1896
F1.5	1890	1891	1894	1897

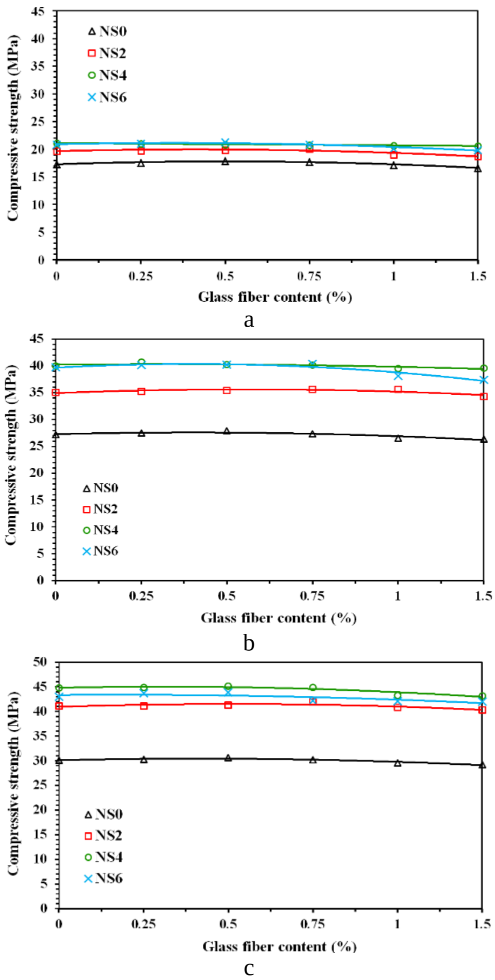


Figure 4. The results of compressive strength test; a: After 7 days, b: After 28 days, c: After 90 days

it even reduced the compressive strength at ages of 7, 28 and 90 days. The highest compressive strength obtained from adding GF is related to the specimens in which 0.5% GF were used, so that the 7, 28 and-day compressive strength of concrete specimens containing 0.5% GF (without nSPs) increased by 3.6, 2.6 and 1.75%, respectively, compared to the control specimen.

By increasing GF in self compacting lightweight concrete, their compressive strength decreased, so that the 7, 28, and 90-day strengths of specimens containing 1.5% of GF (without nSPs) decreased by 3.3, 2.9 and 3%, respectively. The decreasing process of compressive strength in lightweight concrete due to increasing fiber percentage can be ascribed to the balling phenomenon. If the percentage of fiber growth exceeds the optimum value, there is an uneven distribution of fibers followed by inappropriate fiber collision with the cement matrix and this reduces the effectiveness possibility of fibers to improve concrete structure [41]. This can be seen using the SEM images shown in Figure 6. By Examination of compressive strength of self compacting lightweight concrete specimens, it was revealed that the highest strength after 7, 28 and 90 days was related to concrete specimens containing 4% nSPs and 0.5% GF. The results showed that the use of nSPs can compensate for (or slightly increase) the compressive strength caused by adding GF. So that the 7, 28 and 90-day compressive strength of NS4F0.5 specimens grew by 21, 47.8 and 49.8%, respectively. NSPs, due to their high specific surface and high reactivity, result in consuming calcium hydroxide that is quickly organized within the hydration, filling pores of the calcium silicate gel structure and eventually producing more and more compacting hydrated products. The mentioned subject presented in the SEM images (Figure 6).

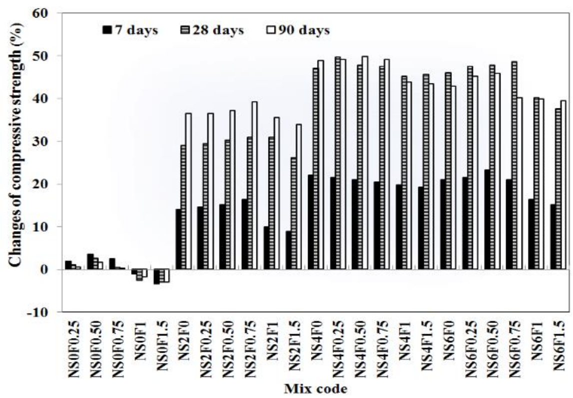


Figure 5. Changes of compressive strength

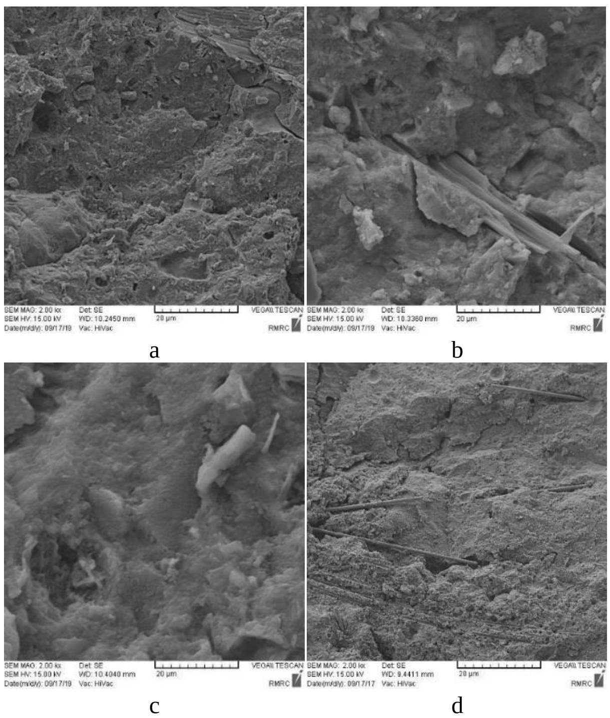


Figure 6. SEM pictures of some of the examined concrete specimens a: NS0F0 b: NS0F1.5 c: NS4F0 d: NS4F1.5

When the nano silica particles are distributed in the concrete, each particle is placed in a cubic pattern and acts as a nucleus. When hydration is started, nanoparticles, due to their high activity, accelerate to hydration and surround the hydrated products of nanoparticles as a nucleus. If the amount and distance of the nanoparticles are appropriate, the calcium hydroxide crystal growth will be restricted and the cement matrix will be more homogeneous. The smaller calcium silicate gel which usually has higher hardness is formed. By too much increasing of nanoparticles, the distance between them decreases, and the calcium hydroxide crystal cannot grow sufficiently. The use of 6% nSPs seems to be high in combination with the "free lime produced in the hydration process" and this caused the strength to decrease. A part of cement is replaced with a material that does not help the strength increase and leads to defects in strength. Another reason is that nanoparticles tend to become bulky because of their high surface energy, the content of nanoparticles which are more than the required amount results in uneven distribution, and nanoparticles appear as weak mass regions [42–44]. 4% nSPs showed the highest compressive strength among three different percentages of used nanosilica. Therefore, the optimum amount of using nSPs in concrete was obtained to increase the compressive strength of 4% by weight of cement. One possible cause of decrease in strength of the specimen containing 6% nSPs compared to the specimen containing 4% is the agglomeration of nSPs at high percentages of consumption.

3. 2. 3. Tensile Strength The tensile strengths of 24 lightweight concrete specimens were compared in Figure 7. The tensile strength in the specimens varied from 2.19 to 3.41 MPa. The combined use of nSPs and GF also had a significant effect on self compacting lightweight concrete containing zeolite and scoria aggregates. Splitting tensile strength at 28 days increased from 3 to 56% depending on the content of GF and nSPs (Figure 8). Using 0.25, 0.5, 0.75, 1 and 1.5% GF in lightweight concrete specimens containing zeolite and scoria aggregates increased the tensile strength by 2.7, 4.1, 8.7, 11.9 and 13.7%, respectively. The reason for increasing strength of GF can be due to increase in tensile strain tolerance through transfer of stresses from matrix to the fibers. Also, the use of 2, 4 and 6% nSPs in lightweight concrete specimens containing zeolite and scoria aggregates increased the tensile strength by 13.2, 47.5 and 34.7%, respectively.

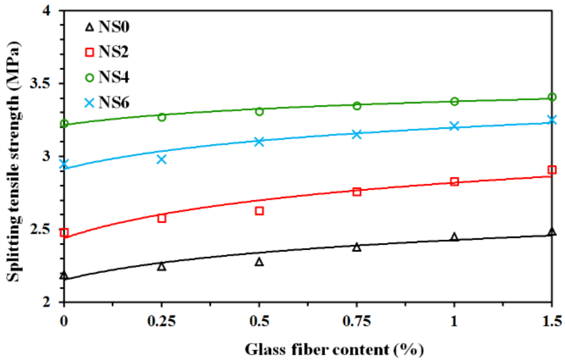


Figure 7. Splitting tensile strength

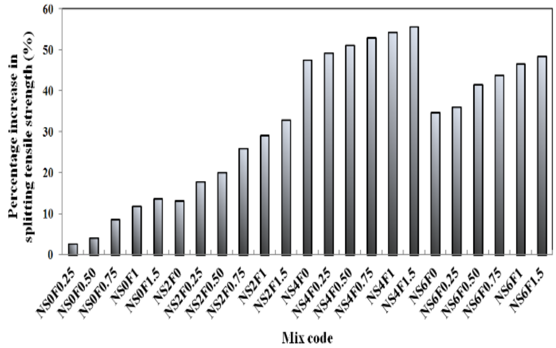


Figure 8. Percentage increase in splitting tensile strength

The highest improvement of tensile strength was due to the combined use of GF and nSPs in a specimen containing 4% nSPs and 1.5% GF and its tensile strength increased by approximately 56%. The positive effect of nSPs on increasing tensile strength also mentioned in previous studies [45]. The pozzolanic activity of nSPs with products formed in Portland cement hydration and their penetration into the pores of scoria aggregates and the creation of better aggregate interlockes with cement paste leads to the compatibility of strength between light weight aggregates and cement paste and this reason is the main reason for the increase in tensile strength of lightweight concrete. This is because as the hardness of the Scoria aggregates increases in the rupture path, the tensile strength of the lightweight concrete also increases. In lightweight concrete, cracking is usually started and passed through the lightweight aggregates. Therefore, with the presence of nanosilica and the penetration of cement paste into the aggregates, their hardness increases and eventually the cracking strength of concrete increases. The results also show that the effect of nSPs on increasing tensile strength is much greater than the effect of GF on increasing tensile strength. The reason for this is that nanosilica, by reducing cavities and increasing the density of the mixture, creates more contact surface between the cement and the aggregates compared to the fibers, and causes the tensile strength to grow more.

ACI318-95 [46] and EN1992-1 [47] codes introduce a range for tensile strength based on cylindrical compressive strength. The mention relationships were for cylindrical specimen and the investigated specimens are cubic. Therefore, the cubic compressive strengths were converted to cylindrical compressive strength by applying coefficients. Figure 9 illustrates the correlation between tensile and compressive strengths of this study

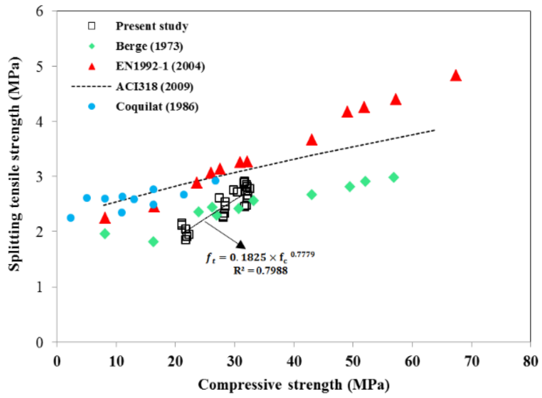


Figure 9. Correlation between tensile strength and compressive strength of lightweight concrete containing nSPs, zeolite and GF

and the mentioned codes as well as the studies of Berge [48, 49]. The strengths values of this study are very close to the experimental curves introduced by ACI 363-92 [50] and ACI318-99 [51]. Equation (5) is presented based on Figure 9.

$$f_t = 0.1825 f_c^{0.7779} \quad (5)$$

f_t and f_c are splitting tensile strength and compressive strength, respecetively.

3. 2. 3. Flexural Strength The flexural strength and its percentage increase are shown in Figures 10 and 11, respectively. The combined use of nSPs and GF in all mixed designs increased the 28-day flexural strength. As the load increases, the fibers collide with the cracks, and the fibers with their tensile strength modify the crack propagation and concrete release to achieve the tensile strength. This creates a mechanism for extra energy absorption and results in reducing stresses in the area of microcracks near the apex of the cracks, and as the crack depth decreases, the modulus of rupture increases. The highest increase in flexural strength was 35% and was obtained in a specimen in which 4% nSPs and 1.5% GF were used. Nano silica particles, with their filler and

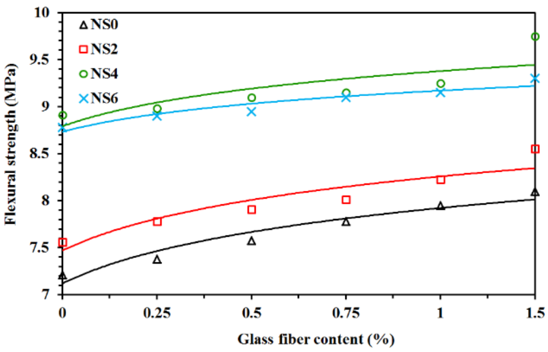


Figure 10. Flexural strength

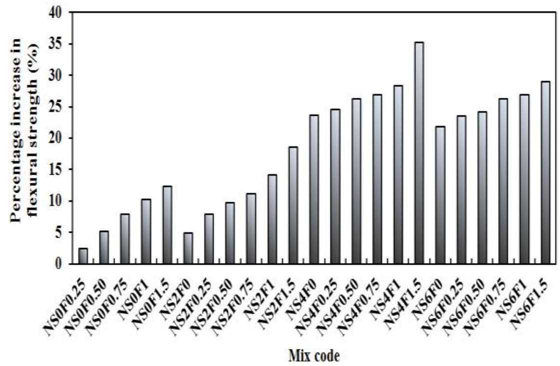


Figure 11. Percentage increase in flexural strength

pozzolanic effect, improve the properties of the cement paste contact area with fibers and aggregates and increase the adhesion of the contact areas.

3. 2. 4. Ultrasonic Pulse Velocity (UPV) The UPV test is an important non-destructive procedure. This method does not afford any damage even on the concrete surface and it can be done with low cost and fast velocity. These factors confirm the suitability of the above method for evaluation. In this study, the process of ultrasonic wave velocity changes in different designs at age of 28 days was investigated for 100×100×100 mm specimens. Table 8 and Figure 12 show the results of velocity of ultrasonic waves against compressive strength. Whitehurst [52] divided the velocity of ultrasonic waves of concrete in terms of quality into five categories: excellent (greater than 4500 m/s), good (3500 to 4500 m/s), suspicious (3000 to 3500 m/s), weak (2000 to 300 m/s) and very weak (smaller than 2000 m/s). Therefore, all mixes fall within the good range. Higher porosity results in lower velocity of waves. According to Figure 12, it can be stated that the combined use of nSPs and zeolites have an effect on filling the voids and reducing the porosity of the concrete. This can be attributed to the growing process of cement paste hydration and the filling of holes and capillary pores with cementitious reaction products and thereby compaction of cement. However, the growth of wave velocity was less than the compressive strength.

3. 3. Results of Concrete Durability Tests

3. 3. 1. Electrical Resistivity Determination of electrical resistivity is one of the tests related to durability and reliability of concrete for achieving corrosion probability of buried rebars. Electrical resistivity is defined by the movement of ions such as Na^+, k^+, OH^-, SO_4^{2-} and Ca^{2+} in the pores in the concrete mass under the influence of the electric field or the difference in ion concentration [33]. Therefore, the amount of electrical resistivity is affected by the concentration of ions in the concrete pores. For example,

TABLE 8. Ultrasonic wave velocity and cubic compressive strength (28 days)

Mix ID	UPV (m/s)	Compressive strength (MPa)
NS0F0	3891	27.2
NS0F0.25	3887	27.1
NS0F0.50	3881	26.9
NS0F0.75	3878	26.5
NS0F1	3868	26.4
NS0F1.5	3858	26.3
NS2F0	3923	35.1
NS2F0.25	3921	35.1
NS2F0.50	3920	34.9
NS2F0.75	3911	34.6
NS2F1	3895	34.5
NS2F1.5	3893	34.3
NS4F0	4001	40
NS4F0.25	3995	39.9
NS4F0.50	3991	39.8
NS4F0.75	3990	39.7
NS4F1	3990	39.5
NS4F1.5	3989	39.6
NS6F0	3999	39.7
NS6F0.25	3992	39.1
NS6F0.50	3991	38.9
NS6F0.75	3990	38.8
NS6F1	3990	38.7
NS6F1.5	3988	38.4

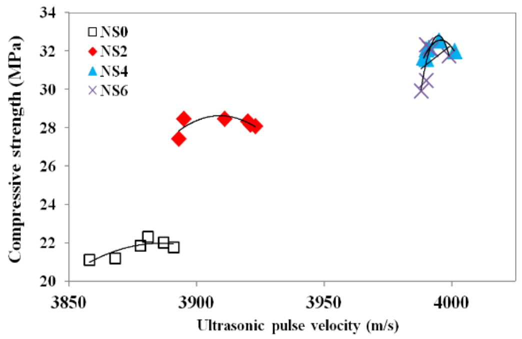


Figure 12. Correlation between cylindrical compressive strength and UPV at age of 28 days

the electrical resistivity can depend on the concentration of the Cl ion, which is one of the factors affecting the corrosion of the rebar. It is on this basis that electrical resistivity can be used as an auxiliary tool to investigate the corrosion probability of buried rebars in concrete. The electrical resistivity of concrete specimens was measured (Figure 13). The process of interpreting the results of the electrical resistivity is described in Section 2.3.

According to Figure 13, electrical resistivity of lightweight concrete specimens containing nSPs, zeolites and GF are in the range of 55 to 162 kHz/m. Hence, according to the classification provided by Song and Saraswathy [34] and Elkey and Sellevold [35], all specimens have very low corrosion probability. The results also show that the presence of GF has little effect on the electrical resistivity of the test specimens and electrical resistivity is reduced by increasing fibers. On the other hand, the use of 2, 4, 6% nSPs in specimens without GF increased the electrical resistivity of concrete by 136, 174 and 194%, respectively. The pozzolanic behavior of silica and zeolite nanoparticles increases the hydration process of concrete and fills cavities and spaces as fillers. As a result, they improve electrical resistivity.

3. 3. 2. Water Absorption Percentage Water absorption is defined as the movement of liquids in pores of solid masses due to surface tension in capillary pores. The water absorption of self compacting lightweight concrete containing zeolite, nSPs, GF and scoria aggregates were calculated and the results are presented in Figure 14. The CEB [53] divides the concrete into three categories of poor quality (above 5%), average (between 3% and 5%) and good (less than 3%). According to the CEB classification, all specimens in which nSPs were not used are in average and near-poor category. According to the durability aspect, water absorption above the scoria lightweight aggregates is an important disadvantage because most corrosive substances penetrate the concrete through water. The use of nSPs largely reduces this problem. The initial water absorption percentage of self-compacting lightweight concrete containing nSPs is in the range of 1.73 to 1.91%;

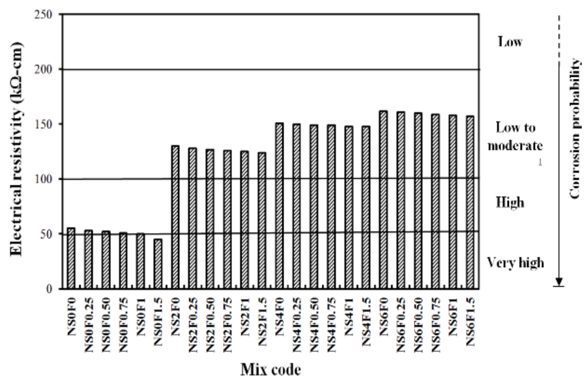


Figure 13. Electrical resistivity of self-compacting lightweight concrete containing zeolite, nSPs, GF and scoria aggregates

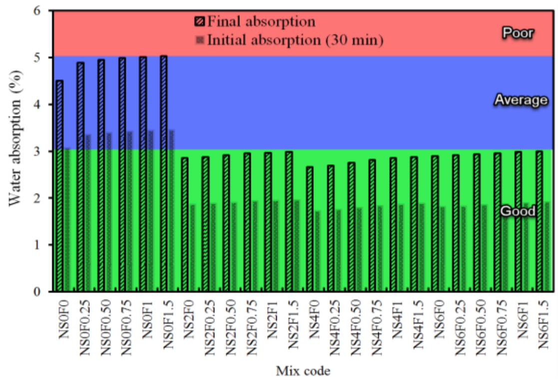


Figure 14. Water absorption percentage of the specimens containing zeolite, nanosilica, GF and scoria aggregates

According to the aforementioned classification, it can be stated that all of the lightweight concrete specimens in which zeolite and nSPs are used are in good quality range. In fact, the use of nSPs in all mixed designs reduced the water absorption percentage of concrete. For example, the use of 4% nSPs reduced the initial and final water absorption of lightweight concrete by 43 and 41%, respectively. The high pozzolanic activity of nSPs and the C-S-H gel production, the filling property of concrete porosity and the removal of fine holes in the silicate gel structure are the main reasons of this improvement.

There was no significant difference between the water absorption percentage of the specimens containing 2, 4 and 6 percent nanoparticles. The combined use of nanoparticles and zeolite has reduced the water absorption percentage to a certain extent, and then due to the presence of more than the required amount of nanoparticles to combine with the free lime produced during the hydration process, it washes more than the silica limit is reduced [44, 54]. For example, the water absorption percentage of specimens containing 6% of silica nanoparticles is much higher than the corresponding values of specimens containing 4%. In fact, part of the cement has been replaced with a material that does not help reduce water absorption further.

4. CONCLUSIONS

In this research, the effect of nSPs and zeolite on the mechanical, rheological properties and durability of self compacting lightweight concrete containg GF and scoria aggregates were investigated. The variables were nSPs (0, 2, 4 and 6 wt % by weight of cement) and GF (0, 0.25, 0.5, 0.75, 1 and 1.5% by volume of concrete). The scoria aggregates and zeolite were considered constant in all mixes. The fresh and hardened properties of specimens were evaluated using T50, slump flow, V-funnel and L-box, compressive strength, splitting tensile strength, flexural strength, ultrasonic, electrical resistivity, and water absorption tests. In this section, the most important results are presented.

- The decreasing process of compressive strength in lightweight concrete due to increasing fiber percentage can be attributed to the balling phenomenon. If the percentage of fiber growth exceeds the optimum value, there is an uneven distribution of fibers followed by inappropriate fiber collision with the cement matrix and this reduces the effectiveness possibility of fibers to improve concrete structure. The use of nSPs can compensate for (or slightly increase) the compressive strength caused by the addition of GF. So that the 7, 28, and 90-day compressive strength of NS4F0.5 specimens increased by 21, 47.8 and 49.8%, respectively.
- The combined use of nSPs and GF has a significant effect on self-compacting lightweight concrete containing zeolite and Scoria aggregates; Depending on the amount of GF and nSPs, the splitting tensile strength increased by about 3 to 56% at age of 28 days.
- The use of GF in lightweight concrete specimens containing zeolite and scoria aggregates increased the tensile strength by about 3 to 14% depending on the fiber content. The reason for increasing strength of GF can be due to increasing tensile strain tolerance through the transfer of stresses from the matrix to the fibers. The use of nSPs in lightweight concrete specimens containing zeolite and Scoria aggregates also increased the tensile strength by about 13 to 35% depending on the amount of nano.
- NSPs, due to their high specific surface and high reactivity, result in consuming calcium hydroxide that is quickly organized within the hydration, filling pores of the calcium silicate gel structure and eventually producing more and more compacting hydrated products.
- The highest increase in tensile strength was due to the combined use of GF and nSPs in a specimen in which 4% nSPs and 1.5% GF were used and its tensile strength increased by approximately 56%.
- The presence of GF has little effect on the electrical resistivity of the testing specimens and decreases with increasing fiber strength. On the other hand, the use of nSPs in specimens that do not have GF increased the electrical resistivity of the concrete from 136 to 194% depending on the number of nSPs.
- From the sustainability aspect, water absorption above the scoria lightweight aggregates is an important disadvantage because most harmless and corrosive substances penetrate the concrete through water. The use of nSPs largely reduces this problem. In fact, the use of nSPs in all mixed designs decreased the water absorption rate of concrete. This improvement can be attributed to the high pozzolanic activity of the nSPs, the gel production, the C-S-H porosity and the filling of the concrete pores, and the removal of fine holes in the silicate gel structure.

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Persian Abstract

چکیده

میزان ریز ترک‌ها در بتن‌های الیافی در ناحیه مرزی بین خمیر سیمان و سطح سنگدانه یا الیاف بیشتر می‌باشد که برای تقویت این ناحیه می‌توان از پوزولان‌های طبیعی و مصنوعی استفاده کرد. در مطالعه حاضر، اثر استفاده ترکیبی از نانو ذرات سیلیس و زئولیت بر خصوصیات مکانیکی، رئولوژیکی و دوام بتن‌های سبک خود متراکم ساخته شده با سنگدانه‌های اسکوریا که با الیاف شیشه مسلح شده است، مورد بررسی قرار گرفت. الیاف شیشه به مقدار ۰ تا ۱.۵ درصد در ترکیب با ۰ تا ٦ درصد نانوذرات سیلیس ارزیابی شد. خصوصیات بتن تازه و بتن سخت شده با انجام آزمایش‌های جریان اسلامپ، T50، قیف V، جعبه L، مقاومت فشاری، مقاومت کششی دو نیم شدن، مقاومت خمشی، التراسونیک، مقاومت الکتریکی و جذب آب انجام شد. همچنین ریز ساختار نمونه‌های بتنی با استفاده از عکسبرداری میکروسکوپ الکترونی SEM مورد بررسی قرار گرفت. استفاده ترکیبی از نانوذرات سیلیس و الیاف شیشه در بتن‌های سبک خودتراکم حاوی زئولیت و سنگدانه‌های اسکوریا اثر قابل توجهی دارد؛ بطوریکه بسته به مقدار الیاف شیشه و نانوذرات سیلیس، مقاومت کششی دو نیم شدن حدوداً از ۳ تا ٥٦ درصد افزایش یافته است. استفاده از نانوذرات سیلیس مقاومت الکتریکی بتن را بسته به مقدار نانوذرات از ١٣٦ تا ١٩٤ درصد افزایش داده است. نانو ذرات سیلیس به دلیل سطح مخصوص بالا و واکنش پذیری بالا منجر می گردد کلسیم هیدروکسید که در طول هیدراسیون به خصوص در سنین اولیه، به سرعت تشکیل می‌شود، مصرف گردد و منافذ ساختار ژل کلسیم سیلیکات پر شود و سرانجام محصولات هیدراته بیشتر و متراکم‌تر تولید می‌گردد.