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Durability and Mechanical Properties of Self-compacting Concretes with Combined Use of Aluminium Oxide Nanoparticles and Glass Fiber

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ABSTRACT

The presence of fibers in concrete specimens has an effective role on how the specimens were failed. In this study, the effects of aluminium oxide nanoparticles on the workability, mechanical and, durability properties of SCCs containing glass fibers were investigated. Glass fibers contents of 0, 0.5, 1, and 1.5 % by volume of concrete and aluminium oxide nanoparticles contents of 0, 0.5, 1, 1.5, 2, and 3 % by weight of cement were used. The properties of fresh concrete were evaluated according to EFNARC consideartions. The mechanical properties were evaluated by compressive strength, splitting tensile strength, and ultrasonic pulse velocity tests. The durability of the specimens was also measured using water absorption tests, water penetration depth and, electrical resistivity. Combined use of 2% aluminium oxide nanoparticles and 1% glass fiber has increased the compressive and tensile strengths of SCCs by 59% and 119.2%, respectively. Aluminium nanoparticles have a very high specific surface area and their reactivity causes them to react rapidly with calcium hydroxide to produce silicate-hydrate gels. Therefore, calcium hydroxide crystals are reduced and the cavities in the cement gel are filled and the compressive strength is increased. The use of aluminium oxide nanoparticles along with glass fibers reduces the water absorption rate compared to the sample without these materials. This is one of the effective properties of aluminium oxide nanoparticles, which increases the resistance to adverse environmental factors by reducing water absorption.

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1. INTRODUCTION

Today, the use of nanotechnology in the construction of concrete has good practical potential and has different features [1-4]. Brittleness of concrete limits its use for parts that are completely or locally under tension. In practice, this fundamental defect of concrete is resolved by reinforcing it by installing steel rebars in the direction of tensile forces. In order to create isotropic conditions and reduce the brittleness of concrete, glass fibers can be used in concrete [5].

On the other hand, the use of nanoparticles in concrete has attracted the attention of many researchers in recent years. Silva et al. (2016) examined the effect of silica and aluminium oxide nanoparticle additives with steel fibers on the behaviour of RC beams. They showed that nanoparticles can improve the performance of RC beams [6]. Joshaghani et al. (2020) showed that titanium, aluminium, and iron oxide nanoparticles can improve mechanical and durability and reduce workability [7]. Mohammed et al. (2020) investigated calcium and aluminium oxide on the physical attributes of cementitious mortar. For this purpose, different percentages of calcined eggshell powder were used along with 1% of aluminium oxide nanoparticles. The experiments showed that the combined use of aluminium oxide nanoparticles and eggshell powder reduced the compressive strength and density, but increased the percentage of water absorption [8]. Ansari rad et al. (2020) studied the properties of basalt fiber reinforced concrete containing silica nanoparticles and aluminium nanoparticles. Basalt fibers reduced the flowability of

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self-compacting specimens and have little effect on improving compressive strength [9]. Zin al-Abedini et al. (2020) showed that the concrete made of nanolime showed higher resistance than nano-silica and this type of concrete can be considered in the group of high performance and high strength concrete [10].

There have also been several studies on the use of fibers in concrete. Ganesh (2016) examined self-compacting concrete containing glass fibers. The length of fibers added to the mixture was 1.2, 1.8, and 2.4 mm, respectively, and the percentage of fibers were 0%, 0.25, 0.5%, 0.75%, and 1%. The highest compressive strength was obtained in a specimen containing 1% fiber [11]. Soratur et al. (2018) stated that glass fiber and foundry sand can lead to a significant improvement in mechanical characteristics of concrete [12]. Alex and Arunachalam (2018) conducted an experimental study of steel fibers and glass fibers on the attributes of lightweight concrete. The use of glass fibers and steel fibers improved tensile and flexural strength of specimens [13]. Vasu et al. (2019) used 0.1, 0.2 and 0.3% of glass fibers. They indicated that glass fibers could improve the mechanical characteristics of concrete [14]. Hemavathi et al. (2020) examined the properties of concrete reinforced with glass fibers containing silica fume. For this purpose, different percentages of "manufactured sand" (30, 40, 70, and 100%) were replaced with natural sand. It was shown that glass fiber and silica fume in concrete containing 30% sand and 70% natural sand can be effective [15]. Kwan et al. (2018) examined the durability of high-strength self-compacting concrete specimens in corrosive environments. For this purpose, glass fibers were used at a rate of 0.6 to 2.40%. Specimens in which more glass fibers were used showed greater resistance to adverse environmental conditions [16]. Tabkhi Wayghan et al. (2019) investigated the contribution of GFRP bars on the compressive strength of concrete columns with circular cross section. It has been shown that these rebars can contribute significantly to compressive strength of concrete columns if the column confinement is provided sufficiently [17]. Ali et al. (2019) investigated the influence of glass fibers on mechanical properties of concrete with recycled coarse aggregates (RCA) and normal coarse aggregates (NCA). The results indicated that the addition of glass fibers was very useful in enhancing the split tensile and flexural strength of both RCA and NCA concrete [18]. Shadmand et al. (2020) investigated the use of steel fiber in concrete jacket with the purpose of retrofitting RC beams. They showed that steel fiber-can improve the concrete jacket performance and it is an adequate choice for reinforcing the concrete of RC jacket [19].

In general, the results of the mentioned studies show that the use of various fibers in concrete reduces cracks and improves tensile strength. But the addition of some fibers, along with their benefits, has drawbacks that can affect their performance. For example, steel fibers have a higher density than other fibers and are relatively more expensive to make. In addition, steel fibers do not function well in corrosive atmospheric conditions and can affect the durability of concrete. However, fibers such as polypropylene, carbon, basalt and glass do not have these weaknesses.

On the other hand, in the area between the cement paste and the aggregate surfaces and the boundary areas between the fibers and the aggregates, there are always cracks that in the long run can lead to porosity in concrete and reduce strength. The use of pozzolans can overcome this weakness by strengthening the mentioned boundary areas. The results of various studies show that aluminium oxide nanoparticles have an effective role in improving the mechanical properties of concrete and their use can lead to increase adhesion between concrete and rebar in concrete [2, 6]. Also, these nanoparticles have a relatively higher resistance to heat caused by fire compared to other nanoparticles [20-22].

The combined use of different fibers and nanoparticles in concrete is considered as an effective step in preventing the spread of microcracks and cracks and compensating for the weak tensile strength of concrete. From an economic point of view, the use of fibers and nanoparticles depends on the application and conditions of the project. Fiber has already found its place in construction projects and its economic evaluation is more related to the type of fiber which is used and how to use it. However, in cases where fibers are used instead of steel reinforcing mesh, not only equal price of fibers and steel mesh but also skilled manpower, tools, equipment, material storage space, etc are considered and even this issue can be looked at with foresight. Maintenance costs, weather conditions and future applications of the structure that may have in the future are all the factors that can justify the use of fibers economically or vice versa. In some cases, project scheduling may be very important and the use of fibers can speed up the process and save a lot of money and this can lead to abundant economic savings.

Therefore, in this study, the combined use of glass fibers and aluminium oxide nanoparticles on the workability, mechanical, and durability properties has been evaluated. Glass fiber volume fractions between 0% to 1.5% in combination with 0% to 3% aluminium oxide nanoparticles were used. For this purpose, the properties of fresh concrete were determined by conventional experiments which were introduced by EFNARC [23], and the mechanical properties were determined by performing compressive strength and tensile strength tests. The durability properties were performed by water absorption, electrical resistivity and water penetration tests. Also, non-destructive properties were evaluated using ultrasonic pulse velocity (UPV). The flowchart of the experimental tests is presented in Figure 1.

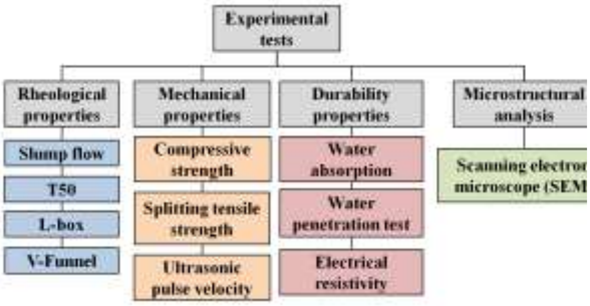


Figure 1. Flowchart of the experimental tests

2. EXPERIMENTAL STUDY

2. 1. The Used Materials

Materials include cement, sand, gravel, glass fiber, aluminium oxide nanoparticles, water, and superplasticizer. Portland cement (Type II) was used. Its chemical properties were presented in Table 1.

The gradation of sand and gravel curve is within the allowable range of ASTM C33 [24] (Figure 2). The used sand is a river type with a density of 2640 kg/m^3. The coarse aggregate is a broken type with a density of 2580 kg/m^3 and its size is between 4.75 and 19 mm.

TABLE 1. Chemical attributes of aluminium oxide nanoparticles and cement

Components	Cement type II	Components	AL_2O_3
SiO_2 %	21.27	Al_2O_3	99≥%
Al_2O_3 %	4.95	Ca	25ppm ≤
Fe_2O_3 %	4.03	Fe	80ppm ≤
CaO %	62.95	Cr	4ppm ≤
MgO%	1.55	Na	70ppm ≤
SO_3%	2.26	Mn	3ppm ≤
K_2O %	0.65	Co	2ppm ≤
Na_2O %	0.49		

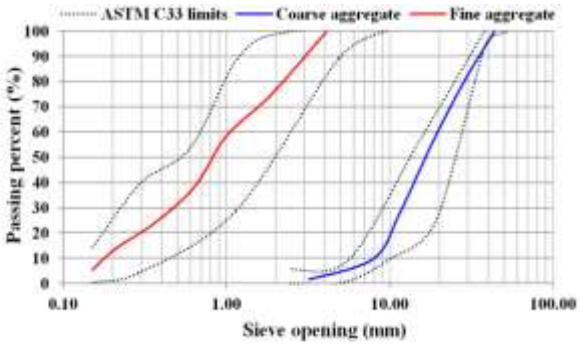


Figure 2. Aggregates grading diagram

The length and diameter of glass fibers were considered 12 and 0.02 mm, respectively. Also, tensile strength and density of glass fibers were 14000 kg/cm^2 and 2.44 kg/cm^3, respectively. Aluminium oxide nanoparticles are artificial and white matter which is composed of very tiny AL_2O_3 particles. The alumina which is used in nano- aluminium powder in this study was more than 99%. The density and specific surface area of aluminium oxide nanoparticles were 3.89 g/cm^3 and 138 g/cm^2, respectively. Also, the diameter of its solid particles was about 20 nanometers. The chemical properties of aluminium oxide nanoparticles were presented in Table 1. The water which was used for making and curing specimens was under the criterion recommended by ASTM D1129 [25]. In this study, the third generation superplasticizer based on carboxylic ether with the brand name of GLENIUM_110P was used. This material is opaque and cloudy in color and its density at a temperature of 20 degrees Celsius is 1.1 g/cm^3.

2. 2. Experiments

In order for self-compacting concrete to be used in a variety of projects, it must be evaluated in terms of the parameters such as stability and filling ability. Each of these parameters is estimated by one or more experiments [26]. In this study, according to the considered abilities, slump flow test was selected to appraise the flowability, T50, and V funnel tests were selected to assess the viscosity and L-box test was selected to evaluate the transmission capability. In the slump flow experiment, the diameter of the circle that the concrete forms after spreading will be the criterion of examining filling ability. The appropriate range for slump flow based on EFNARC [23] is considered between 650 and 850 mm. Self-compacting concrete with this range of slump flow is suitable for use in a variety of conventional applications of self-compacting concrete such as use in beams or building columns. Concrete viscosity is the strength against fresh concrete flow and is usually evaluated by T50 and V funnel tests.

Concrete viscosity should usually be considered for areas with heavy reinforcement and when concrete pouring levels are required. The time which is needed for reaching the slump flow of specimen with a diameter of 50 cm is called T50. T50 FLow time can cause separation and high T50 time can cause concrete blockage. To determine the time of V-funnel, first, the inner surface and the funnel valve were cleaned and moistened. The moment of the complete evacuation of concrete from the funnel is called V funnel time. The L-box test is applied to determine the passing properties of specimens in the presence of reinforcement without separation or blockage. In L-box, two or three rebars with a certain diameter and distance can be used, depending on the density of the reinforcement at the execution site. The values of H2 (concrete height at the end of the set-up) and

H1 (concrete height behind the gate) were calculated. The H_2/H_1 proportion indicates the blocking ratio. Figure 3 shows the images of fresh concrete experiments.

Compressive strength experiments were conducted using 300×150 mm cylindrical specimens [27]. During testing, the sample was located along the center of the top plate of set-up and loading was conducted continuously at a rate of 0.125 cm/min.

Standard cylindrical specimens of 300×150 mm were pressed along the diameter of the specimen [28]. Splitting tensile strength was determined from Equation (1):

$$f_t = \frac{2p}{\pi Ld} \quad (1)$$

The parameters of Equation (1) are presented below:

f_t: Tensile stress; P: Failure load; L: Length; D: Diameter

The non-destructive properties of concrete were evaluated by UPV test in accordance with ASTM C597 [29]. For this purpose, specimens with dimensions of 10×10×10 cm were made and tested at the age of 28 days (Figure 4).

The water absorption of concrete specimens indirectly indicates the porosity and extent of capillary cavities in it [30]. Water absorption test was performed on 10 cm cubic specimens at age of 28 days in accordance with ASTM C1585-04 [31]. Three cubic samples were made from each mixture and the final water absorption was calculated based on the average of the water absorption values obtained from the specimens.

There are no specific instructions in the various standards for determining the electrical resistivity of concrete specimens [32], and therefore special equipment has been used to perform this test. Thus, a device for determining the electrical resistivity with a frequency of 1 Hz and a final capacity of 1 MΩ with two copper plates has been used. In order to connect and establish proper flow between the main sample (cement paste or intermediate hardened concrete) and copper plates, some fresh cement paste is placed and spread evenly by the spatula. Also, to prevent short circuits and inaccurate responses, the dough protruding from the copper plates and the sample should be removed with a cloth. Finally, by connecting each of the wires of the device to one of the plates, the amount of electrical resistivity is recorded. Figure 5 shows how to measure the electrical resistivity of concrete specimens and copper plates and additional specimens (to prevent connection to the workbench and ground).

The water penetration depth is a parameter for comparing the performance of the specimens against the penetration of destructive ions. The lower permeability of one concrete specimen than another specimen may indicate that destructive ions and the extent of their damage are less likely to penetrate the concrete specimen. Water penetration test was conduted according to DIN 1048 [33] on cubic specimens with a dimension of 15 cm. These specimens were cured in saturated lime water until 28 days and then placed in a water permeation tester (Figure 6).

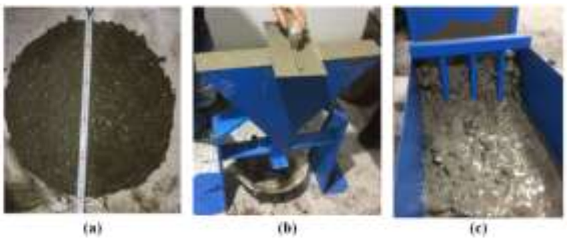


Figure 3. Fresh concrete experiments a: Slump flow b: V funnel c: L-box

Figure 4. UPV test

Figure 5. Electrical resistivity test

Figure 6. Water pentration test

In this device, water with a pressure of 5 bar acts on the specimens for three days. According to the standard, the surface of the specimen that is affected by water pressure should be slightly roughened with a wire brush. The water infiltration was determined after three days.

2. 3. Mixed Design 24 types of mixed designs were investigated. The variables included glass fibers (0, 0.5, 1 and 1.5% by concrete volume) and aluminium oxide nanoparticles (0, 0.5, 1, 1.5, 2 and 3% by weight of cement|), respectively. The mixed design was considered in accordance with ACI211-1-89 [34]. First, the aggregates were mixed and then the fibers that previously had been separated by sieve were added. At this stage, a mixture of aluminium oxide nanoparticles and cement were combined, and after mixing, water was added along with a superplasticizer. In order to prevent the fibers from sticking together and to create the balling phenomenon, as well as to prevent the formation of separate granules of aluminium oxide nanoparticles due to contact with water, the mixed design operation was carried out carefully. For each mixed design of compressive, tensile, and flexural strength tests, three cylindrical specimens were made and their mean was evaluated as the final result .The environment of concrete curing was drinking water with a temperature of about 20 degrees Celsius. Table 2 presents the values of used materials for each design separately.

TABLE 2. Mixed design (kg/m^3)

Mix code	C	W	AL	FA	CA	GF	SP
NA0-F0	450	216	0	700	955	0	7
NA0-F0.5	450	216	0	700	945	12.2	7
NA0-F1	450	216	0	700	930	24.4	7
NA0F1.5	450	216	0	700	920	36.3	7
NA0.5-F0	447.75	216	2.25	700	955	0	7
NA0.5-F0.5	447.75	216	2.25	700	945	12.2	7
N0.50-F1	447.75	216	2.25	700	930	24.4	7
NA0.5-F1.5	447.75	216	2.25	700	920	36.3	7
NA1-F0	445.5	216	4.5	700	955	0	7
NA1-F0.5	445.5	216	4.5	700	945	12.2	7
NA1-F1	445.5	216	4.5	700	930	24.4	7
NA1-F1.5	445.5	216	4.5	700	920	36.3	7
NA1.5-F0	443.25	216	6.75	700	955	0	7
NA1.5-F0.5	443.25	216	6.75	700	945	12.2	7
NA1.5-F1	443.25	216	6.75	700	930	24.4	7
NA1.5-F1.5	443.25	216	6.75	700	920	36.3	7
NA2-F0	441	216	9	700	955	0	7
NA2-F0.5	441	216	9	700	945	12.2	7
NA2-F1	441	216	9	700	930	24.4	7
NA2-F1.5	441	216	9	700	920	36.3	7
NA3-F0	436.5	216	13.5	700	955	0	7
NA3-F0.5	436.5	216	13.5	700	945	12.2	7
NA3-F1	436.5	216	13.5	700	930	24.4	7
NA3-F1.5	436.5	216	13.5	700	920	36.3	7

C: Cement, W: Water, GF: Glass fiber, FA: Fine aggregates, CA: Fine aggregates, AL: Aluminium oxide nanoparticles, SP: Superplasticizer

3. RESULTS AND DISCUSSION

3. 1. Rheological Properties The results of fresh concrete tests and the allowable range of EFNARC [23] are presented in Table 3. EFNARC has classified self-compacting concrete in terms of slump flow into three categories: SF1, SF2, and SF3. The slump flow of the specimens in this study are in the range of 657 to 749 mm. Therefore, the specimens are classified as SF2 and can be used in structural members with high-density. With increasing glass fibers and aluminium oxide nanoparticles, the slump flow in self-compacting concrete decreased. For the slump flow to be within the allowable range, more superplasticizer must be used. On the other hand, if the used superplasticizer exceeds the amount recommended by the manufacturer, it will have a negative effect on the attributes of concrete. The highest value of slump flow is related to NA0-F0 design (749 mm) and its lowest value is related to NA3-F1.5 design (657 mm). The allowable range of T50 is between 2 and 5 seconds that the specimens under study are within this range. The decrease in slump flow and the increase in T50 time due to the presence of fibers and nanoparticles have been observed in the studies of Mazaheripour et al. (2011) [35], Mohsenzadeh et al. (2019) [5], and Faez et al. (2019) [2]. Considering the changes of slump flow in the specimens, it can be stated that by increasing the accuracy in the method of adding superplasticizer, a desirable result can be achieved.

Self-compacting concrete is divided into PA1 and PA2 based on the ability to pass. Because the purpose is to consider the access to concrete with the ability to pass through compacting rebars, three rebars were used in the L-box test. The blocking ratio of the specimens are within the range of 0.8 to 0.97 and are in the PA2 category. In general, fibers and nanoparticles lead to slow concrete movement, which can be overcome by using the allowable value of a superplasticizer.

Self-compacting concrete based on its viscosity is divided into two categories, VS1/VF1 and VS2/VF2. Self-compacting concrete in the VS1/VF1 category even has a good filling ability in the presence of large rebars. The passing time from V funnel for the specimens is in the range of 7.4 to 11.1 seconds, and the T50 time is in

TABLE 3. Fresh concrete results

Mix code	Slump flow (mm)	T50 (s)	V_{funnel} (s)	L_{box} (H_2/H_1)
NA0-F0	749	2.9	7.4	0.8
NA0-F0.5	740	3.4	7.9	0.83
NA0-F1	726	3.6	8.3	0.85
NA0F1.5	716	3.7	8.9	0.87
NA0.5-F0	726	3.1	7.6	0.84
NA0.5-F0.5	708	3.5	8.2	0.85
N0.50-F1	702	3.7	8.5	0.86
NA0.5-F1.5	684	3.8	9.1	0.89
NA1-F0	714	3.2	7.8	0.89
NA1-F0.5	694	3.6	8.5	0.91
NA1-F1	683	3.9	8.8	0.91
NA1-F1.5	674	4	9.4	0.92
NA1.5-F0	699	3.3	8.1	0.9
NA1.5-F0.5	693	3.7	8.9	0.92
NA1.5-F1	687	4	9.9	0.93
NA1.5-F1.5	675	4.1	10.1	0.94
NA2-F0	689	3.4	8.5	0.91
NA2-F0.5	681	3.8	9.6	0.93
NA2-F1	671	4.1	10.4	0.95
NA2-F1.5	669	4.2	10.6	0.96
NA3-F0	671	3.7	8.9	0.94
NA3-F0.5	665	3.9	10.1	0.95
NA3-F1	660	4.4	11.2	0.96
NA3-F1.5	657	4.9	11.1	0.97
EFNARC	SF1: 550-650 SF2: 660-750 SF3: 760-850	VS1: ≤ 2 VS2: >2	VF1: < 8 VF2: 9-25	PA2 ≥ 0.8 (with three bars)

the range of 2.9 to 4.9 seconds. Therefore, in terms of viscosity, it can be stated that most of the specimens are in the VS1/VF1 category. With increasing glass fibers and nanoparticles, the viscosity of concrete specimens increased. For example, the V-funnel time of the specimen containing 3% of aluminium oxide nanoparticles and 1.5% of glass fiber increased by 50%. In general, considering the results, it can be stated that the concrete specimens made in the present study have the necessary self-compaction.

3. 2. Hardened Concrete Results

3. 2. 1. Compressive Strength

Table 4 presents the results of compressive test of cylindrical specimens at 28 days for 24 mixed designs in MPa. In this table, the percentage of compressive strength changes of the specimens containing aluminium oxide nanoparticles and glass fibers compared to the control specimen is presented. The lowest and highest compressive strengths were 41.8 MPa (NA0-0F0) and 68.2 MPa (NA2-F1), respectively, and the lowest and highest splitting tensile strength were 2.6 MPa (NA0-0F0) and 5.7 MPa (NA3-F1.5), respectively. Figure 7 shows the compressive strength of the specimens and their increased percentage. As can be seen, glass fibers have little effect on increasing compressive strength. For example, in specimens without alumina oxide nanoparticles, the compressive strength of the specimens reinforced with 1% glass fiber increased by a maximum of 1.9%. Also, in specimens containing nanoparticles, the addition of glass fiber has increased the compressive strength by a maximum of about 2.5%. However, the addition of aluminium oxide nanoparticles to concrete has

TABLE 4. Compressive and tensile strength of specimens

Mix code	Compressive strength (MPa)		Splitting tensile strength (MPa)	
	Strength (MPa)	Variations (%)	Strength (MPa)	Variations (%)
NA0-F0	41.8	0.0	2.6	0.0
NA0-F0.5	42.4	1.4	2.9	11.5
NA0-F1	42.6	1.9	3.4	30.3
NA0F1.5	42.2	1.0	3.7	41.0
NA0.5-F0	48.1	15.1	2.9	9.6
NA0.5-F0.5	48.7	16.5	3.3	14.0
N0.50-F1	49.1	17.5	3.9	48.7
NA0.5-F1.5	48.4	15.8	4.4	66.7
NA1-F0	54.3	29.9	3.1	19.2
NA1-F0.5	55	31.6	3.6	38.3
NA1-F1	55.6	33.0	4.4	69.0
NA1-F1.5	54.7	30.9	4.8	83.5
NA1.5-F0	61.1	46.2	3.5	34.5
NA1.5-F0.5	61.8	47.8	4.0	52.5
NA1.5-F1	62.8	50.2	4.6	77.0
NA1.5-F1.5	61.5	47.1	5.1	95.4
NA2-F0	66.5	59.1	3.7	41.8
NA2-F0.5	67.2	60.8	4.2	60.9
NA2-F1	68.2	63.2	5.0	90.0
NA2-F1.5	66.9	60.0	5.4	106.5
NA3-F0	64.3	53.8	3.9	47.9
NA3-F0.5	65.1	55.7	4.4	66.7
NA3-F1	65.9	57.7	5.2	97.3
NA3-F1.5	64.7	54.8	5.7	119.2

significantly increased compressive strength. In specimens without glass fiber, the use of 0.5, 1, 1.5, 2, and 3% aluminium oxide nanoparticles increased the compressive strength by 15.1, 29.9, 46.2, 59.1, and 53.8%, respectively. Therefore, according to the mentioned values, the use of only aluminium oxide nanoparticles as a replacement to a part of cement in increasing the compressive strength of the studied concrete specimens is more effective than using only glass fibers in concrete; So that the maximum increase in compressive strength of the samples in which the fibers are only used is 2.5% and the maximum compressive strength of the specimens in which the aluminium oxide nanoparticles are only used is 59.1%. The reason for this increase could be the appropriate reactivity of aluminium nanoparticles with Portland cement during the cement hydration process; Aluminium nanoparticles have a very high specific surface area and their reactivity causes them to react quickly with calcium hydroxide $Ca(OH)_2$ and produce silicate-hydrate gel (C-S-H). Thus, the $Ca(OH)_2$ crystals are decreased and the cavities in the cement gel are filled and the compressive strength is increased [2, 36-39].

SEM images of the specimens presented in Figure 8 also confirm the mentioned result. The control specimen contains numerous air cavities that the use of nanoparticles fills these cavities and increases the bond between cement and aggregates. The use of aluminium oxide nanoparticles in cement not only improves the structure due to the filling of the pores but also makes the pozzolanic reactions more active.

Figure 8 clearly shows the microstructure difference between concrete with and without aluminium oxide nanoparticles and glass fibers after 28 days. The increase of compressive strength due to the addition of aluminium oxide nanoparticles has also been reported in related studies. Arefi et al. (2011) [40] reported that the use of 3% aluminium oxide nanoparticles increases the compressive strength by 63%. The mentioned results can confirm the validity of the compressive strength test performed in the present study.

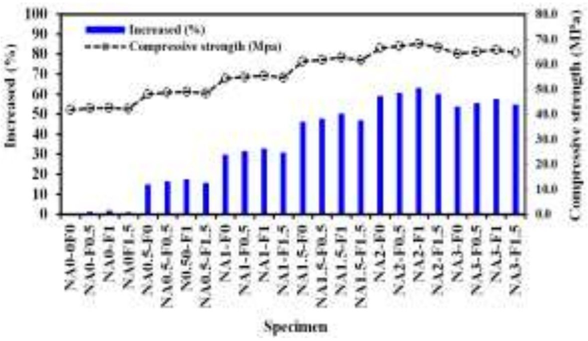
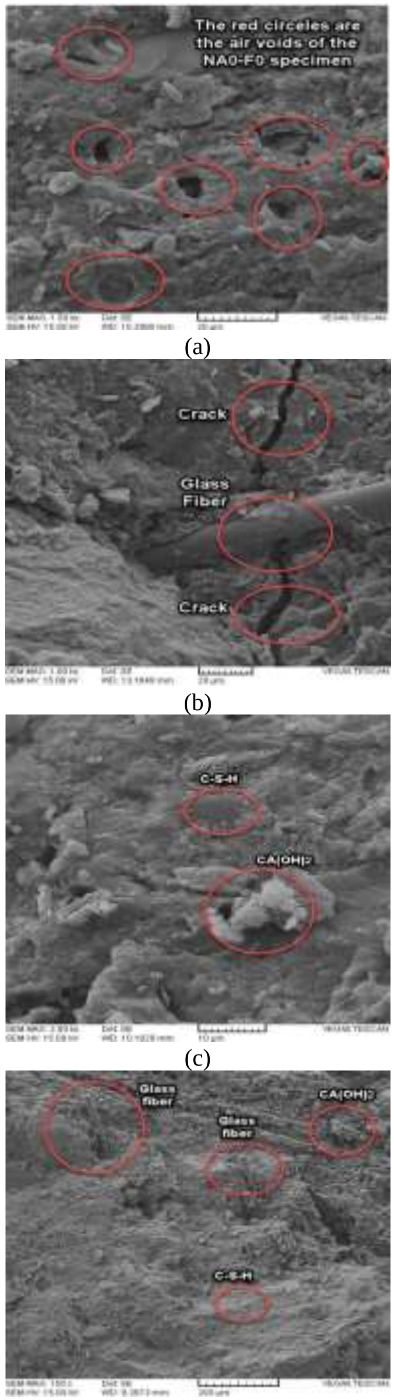


Figure 7. 28-day compressive strength of cylindrical specimens and their percentage increase compared to the control specimen



(a) (b) (c) (d)

Figure 8. Microstructural images of 4 specimens examined at 28 days a: NA0-F0 b: NA0-F1.5 c: NA3-F0 d: NA3-F1.5

3. 2. 2. Splitting Tensile Strength Table 4 and Figure 9 show the splitting tensile strength at 28 days. The combined use of nanoparticles and glass fiber has a very efficient impress in improving the splitting tensile strength; In specimens without glass fibers, the use of 0.5, 1, 1.5, 2 and 3% aluminium oxide nanoparticles increased the splitting tensile strength by 9.6, 19.2, 34.5, 41.8 and 47.9%, respectively. In specimens without nanoparticles, the use of 0.5, 1, and 1.5% glass fibers increased the splitting tensile strength by 11.5, 30.3, and 41%, respectively.

The presence of glass fibers in the brittle binder matrix reduced crack width and thus increased the splitting tensile strength. The combined use of 1.5% glass fiber and 3% aluminium nanoparticles increased the tensile strength by 119.2%. Therefore, according to the obtained values, it can be stated that the combined use of glass fibers and aluminium oxide nanoparticles has a greater efficacy on increasing splitting tensile strength compared to the use of only one of them. The presence of fibers in concrete specimens had an effect on the failure of specimens. In the specimens without glass fiber, the failure was done abruptly, and with the separation of the two pieces, and in the concrete specimens containing 1 and 1.5% of fiber, the failure was done gradually. Also, the combined use of aluminium oxide nanoparticles and glass fibers increased the interaction between cement particles and fibers. This can lead to an increase in density and splitting tensile strength.

In a study by Sivkumar et al. (2018), it was shown that the use of 0.8% glass fiber increases the tensile strength by 18% [41]. Hilles and Ziara (2018) also found that the use of 1.2% of glass fibers can increase the tensile strength by about 63% [42]. In general, it can be stated that the strengths obtained in this study and their variations are in the range of similar studies and the difference between the results is due to the quality of the materials, curing environment, accuracy of measuring set-ups and type of cement.

Changes in the cylindrical compressive strength against the splitting tensile strength of the self-compacting specimens containing glass fibers and aluminium oxide nanoparticles are presented in Figure 10.

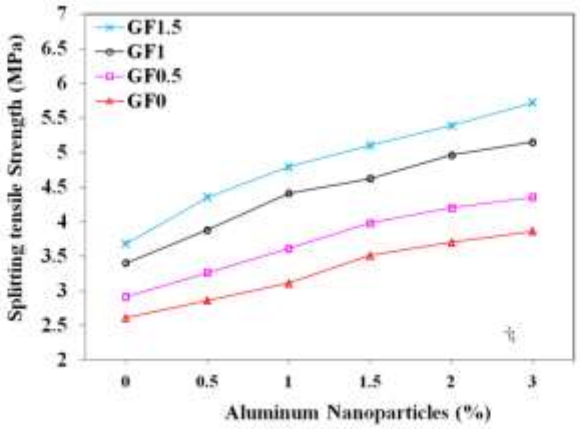


Figure 9. Comparison of splitting tensile strength of specimens at 28 days

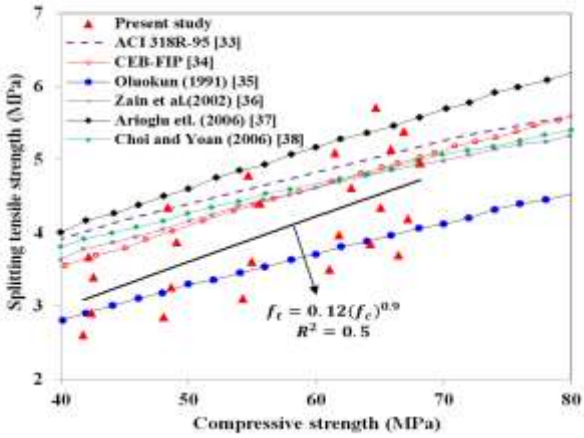


Figure 10. The correlation between splitting tensile and compressive strengths

Figure 10 also shows the proposed relationships by ACI 318-R [43] and CEB-FIP [44] and a number of studies [45-48] on high-strength concrete. As can be seen, the slope of the diagram for the results of the present study is almost the same as the slope of the various diagrams presented. The correlation analysis coefficient (R2) [49] between splitting tensile and compressive strengths of the studied specimens is presented in Equation (2).

$$f_t = 0.12(f_c)^{0.9} \quad (2)$$

3. 2. 3. UPV Figure 11 compares the UPV vs compressive strength of the specimens. In samples without nanoparticles, the addition of glass fibers had little effect on changes of the UPV. Minor changes in UPV of concrete due to the addition of glass fibers have also been observed in the studies of Rath et al. (2017) [50] and Hedjazi and Castillo (2020) [51]. The combined use of aluminium oxide nanoparticles and glass fibers has an effect on increasing the UPV. The UPV of the NA0-F0 and NA2-F1 specimens are 4.10 and 5.15 km/s, respectively. In fact, the combined use of 2% aluminium oxide nanoparticles and 1% glass fiber has increased the UPV by about 26%. Increasing the aluminium oxide nanoparticles will increase the UPV, but when the amount of aluminium oxide nanoparticles in the mixture increases too much, it will reduce the UPV.

By increasing the percentage of nanomaterials more than the optimum value, the compressive strength and UPV decrease. This may be due to the fact that increasing the amount of nanopowder to its optimum limit causes the nanoparticles to not disperse well. The accumulation of nanoparticles creates a weak zone in the form of a cavity and consequently, the microstructure of the cement hydrate cannot be formed, which in turn reduces the compressive strength.

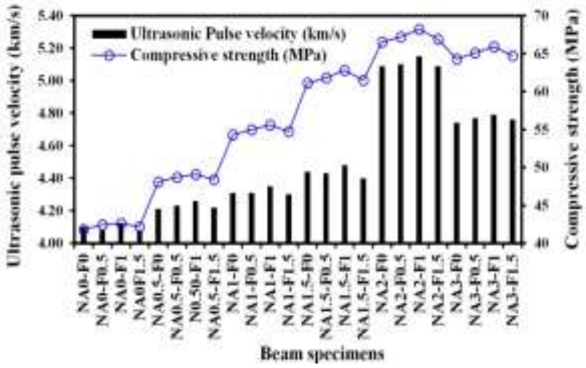


Figure 11. UPV vs compressive strength of the specimens

3. 3. Durability Properties

3. 3. 1. Water Absorption

Figure 12 compares the water absorption of the specimens. According to CEB [52], concrete specimens are divided into three groups according to water absorption percentage: good, medium and poor. Most of the studied specimens are in the medium range. Addition of aluminium oxide nanoparticles reduced the water absorption of the specimens containing glass fibers by about 10 to 46%, depending on the fibers contents compared to the control specimen. The lowest water absorption decrease is related to the specimen in which 3% aluminium oxide nanoparticles are used (N3-F0) and the highest water absorption is related to the sample in which 1.5% glass fibers are used (N0-F1.5). The use of aluminium oxide nanoparticles has reduced the voids of the specimens due to the formation of hydrated silicate gel and thus significantly reduced water absorption. Considering the changes in water absorption of self-compacting concrete specimens containing glass fibers and aluminium oxide nanoparticles, it can be concluded that the use of glass fibers along with aluminium oxide nanoparticles causes the water absorption rate to be less compared to specimens without these materials. This is one of the effective properties of aluminium oxide nanoparticles, which increases the resistance to adverse environmental factors by reducing water absorption.

3. 3. 2. Electrical Resistivity

Figure 13 compares the electrical resistivity of the specimens at the age of 28 days. Higher electrical resistivity indicates that concrete is more durable. Song and Saraswathy (2007) [53] and Elkey and Sellevold (1995) [54] divide concrete into four categories in terms of corrosion probability (Figure 13). Specimens without nanoparticles are in the high range and specimens containing nanoparticles are in the Low to moderate range. The addition of aluminium oxide nanoparticles to concrete specimens containing glass fibers was effective and increased the electrical resistivity by about 98 to 265% compared to the control specimen.

The addition of aluminium oxide nanoparticles to specimens with and without glass fibers greatly increases the electrical resistivity. The extremely fast reactivity of aluminium oxide nanoparticles causes it to react with calcium hydroxide and produce hydrated calcium silicate, which by filling small cavities and increasing the density of concrete, prevents more ions from moving in the concrete, thus increase the electrical resistivity of concrete and concrete corrosion is reduced. The electrical resistivity of all fiber specimens is lower than the control sample. The fibers in the concrete increase the air and thus reduce the electrical resistivity.

Figure 14 presents the results of water penetration depth concrete for 24 specimens at the age of 28 days. The addition of aluminium oxide nanoparticles to self-compacting concrete specimens containing glass fibers has significantly reduced the water penetration depth. The addition of 0.5, 1, 1.5, 2 and 3% aluminium oxide nanoparticles to the specimens without fiber reduced the water penetration depth by 4, 19, 23, 34 and 38%, respectively. Addition of 0.5, 1, 1.5, 2 and 3% aluminium oxide nanoparticles to specimens containing 0.5% fibers reduced the water penetration depth by 6, 20, 24, 33 and 37%, respectively. The addition of 0.5, 1, 1.5, 2 and 3% aluminium oxide nanoparticles to specimens containing 1% fiber reduced the water penetration depth by 8, 20, 24, 31 and 37%, respectively. Also, adding 0.5, 1, 1.5, 2 and 3% of aluminium oxide nanoparticles to specimens

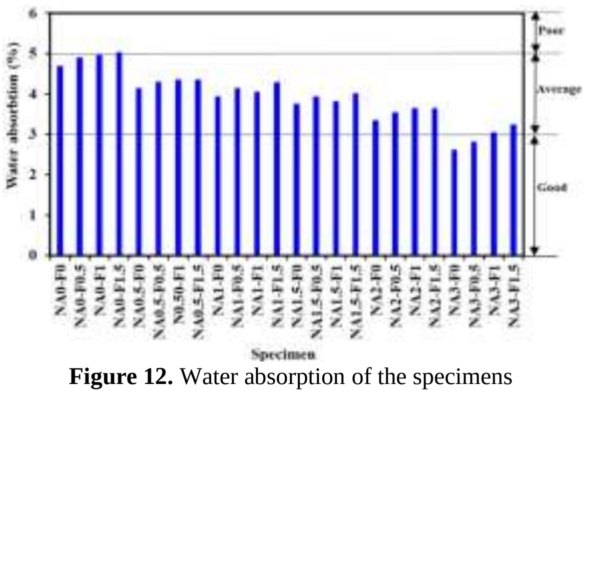


Figure 12. Water absorption of the specimens

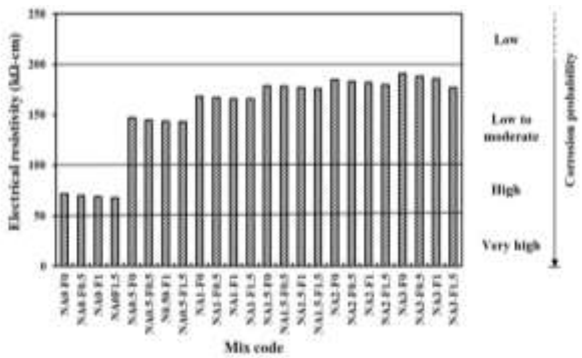


Figure 13. Electrical resistivity of samples in different specimens

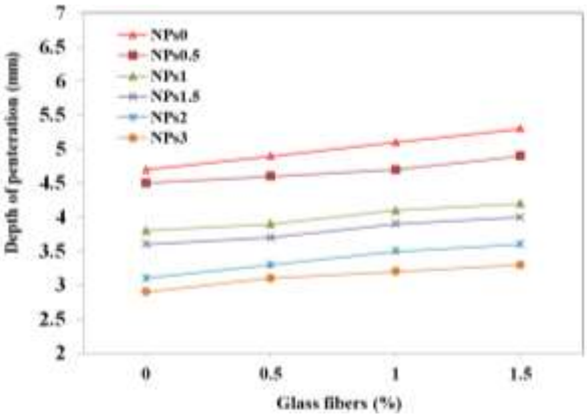


Figure 14. Depth of penetration

containing 1% fibers reduced the water penetration depth by 8, 21, 25, 32 and 38%, respectively. Powder effect and pozzolanic reaction rate of nanoparticles are among the reasons for reducing water penetration inside concrete samples. The decrease in permeability with the increase of aluminium oxide nanoparticles up to 3% by weight of cement is related to the reduction of cracks due to the flooding of concrete and the filling of pores in nano and micro dimensions in concrete.

4. CONCLUSION

In the present study, the combined use of glass fibers and aluminum oxide nanoparticles on rheological, mechanical, durability and, microstructure properties of self-compacting concrete was investigated. In previous studies, the use of only each of these materials was considered. The distinguishing feature of this study from other similar studies was the combined use of glass fibers and aluminum oxide nanoparticles. In this section, the most important results are presented:

- The maximum increase in compressive strength of the specimens in which fibers are only used is 2.5% and the maximum compressive strength of the specimens in which the aluminium oxide nanoparticles are only used is 59.1%. The reason for this increase could be the reactivity of aluminium nanoparticles to Portland cement during the cement hydration process.
- SEM images show that the control specimen contains numerous air cavities and the use of nanoparticles fills these cavities and increases the bond between cement and aggregates.
- The combined use of 1.5% glass fiber and 3% aluminium nanoparticles increased the tensile strength by 119.2%. The combined use of glass fibers and aluminium oxide nanoparticles has a greater effect on increasing tensile strength compared to use only one of them.
- The presence of fibers in concrete specimens with and without nanoparticles had an effect on the failure of specimens. In the specimens without glass fiber, the failure was done abruptly, and with the separation of the two pieces, and in the concrete specimens containing 1 and 1.5% of the fiber, the failure was done gradually.
- The combined use of aluminium oxide nanoparticles and glass fibers has caused the interaction surface between cement particles and fibers to increase.
- Adding aluminium oxide nanoparticles to the specimens also results in more C-H-S gel, which increases the strength of the matrix in the concrete. Also, part of the tensile stress is also borne by the glass fibres.
- The use of nanoparticles in self-compacting concretes containing glass fibers improves the UPV. For example, the addition of 2% of aluminium oxide nanoparticles to specimens containing 1% glass fibers increased the UPV by about 26%.
- The use of glass fibres along with aluminium oxide nanoparticles causes the water absorption rate to be less compared to specimens without these materials. This is one of the effective properties of aluminium oxide nanoparticles, which increases the resistance to adverse environmental factors by reducing water absorption.
- The utilization of glass fibers alongside aluminium oxide nanoparticles decreased water absorption and water penetration compared to specimens without these materials. This advantage makes it possible to use concretes in environments that are exposed to water flow.

In general, the results showed that the combined use of glass fibers and aluminum oxide nanoparticles has a positive effect on improving the properties of self-compacting concrete and they can be more useful in projects in which high tensile and flexural strengths are considered. The application of these materials can reduce the use of steel rebar in reinforced concrete and it may be more cost-effective.

Also, the results showed that the use of glass fibers alone does not seem very suitable in terms of permeability and water absorption. Aluminium oxide nanoparticles can compensate for this weakness and improve the durability properties of concrete. On the other hand, glass fibers increase the tensile strength of concrete by increasing the cracking resistance. Therefore, the combined use of these two materials is effective and can improve the mechanical properties and durability of concrete

The use of other fibers such as steel fibers, nylon fibers, polypropylene fibers, carbon fibers in the composition of aluminum oxide nanoparticles in different types of concretes is the topics that can be investigated in future studies.

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Persian Abstract

چکیده

نانو ذرات به عنوان افزودنی‌های جدید و تأثیرگذار در کنار الیاف، می‌توانند به نحو مطلوبی خواص بتن خودتراکم را بهبود بخشند. در مطالعه حاضر به بررسی اثرات نانو ذرات اکسید آلومینیوم بر کارایی، خصوصیات مکانیکی و دوام بتن‌های خودتراکم حاوی الیاف شیشه پرداخته شد. الیاف شیشه به مقدار ۰، ۰/۵، ۱ و ۱/۵ درصد و نانوذرات اکسید آلومینیوم به مقدار ۰، ۰/۵، ۱ و ۱/۵، ۲ و ۳ درصد وزنی سیمان استفاده شد. خواص بتن تازه، با آزمایش‌های اسلامپ، T50، قیف V و جعبه L ارزیابی شد. خصوصیات مکانیکی با انجام آزمایش‌های مقاومت فشاری و مقاومت کششی ارزیابی شد. خواص غیر مخرب بتن با استفاده از آزمایش التراسونیک بررسی شد. همچنین دوام نمونه‌ها با استفاده از آزمایش‌های جذب آب، عمق نفوذ آب و مقاومت الکتریکی سنجیده شد. نتایج نشان داد استفاده ترکیبی از نانوذرات و الیاف شیشه نقش تاثیر گذاری بر بهبود خواص مکانیکی بتن دارد؛ بطوریکه به عنوان مثال استفاده ترکیبی از ۲ درصد نانوذرات اکسید آلومینیوم و ۱ درصد الیاف شیشه مقاومت‌های فشاری و کششی بتن‌های خودتراکم را به ترتیب ۵۹ و ۱۱۹/۲ درصد افزایش داده است. نانوذرات آلومینیوم دارای سطح ویژه بسیار بالایی می‌باشند و واکنش‌پذیری آنها سبب می‌شود که با هیدروکسید کلسیم به سرعت واکنش داده و ژل سلیکات– هیدرات تولید کنند. از این رو کریستال‌های هیدروکسید کلسیم کاهش می‌یابد و حفرات موجود در ژل سیمانی پر شده و مقاومت فشاری افزایش می‌یابد. همچنین الیاف شیشه نیز با محدود کردن امتداد ترک‌ها می‌تواند گزینه مناسبی در ترکیب با نانوذرات اکسید آلومینیوم با هدف افزایش مقاومت کششی بتن‌های خودتراکم باشد. استفاده از نانوذرات اکسید آلومینیوم در کنار الیاف شیشه سبب می‌شود که میزان جذب آب در مقایسه با نمونه فاقد این مواد کمتر شود. این مسئله از خواص موثر نانوذرات اکسید آلومینیوم می باشد که سبب می‌شود با کاهش جذب آب، مقاومت در مقابل عوامل نامساعد محیطی افزایش یابد. افزودن نانوذرات اکسید آلومینیوم به نمونه‌های حاوی و فاقد الیاف شیشه باعث افزایش خیلی زیاد مقاومت الکتریکی شد. نانوذرات اکسید آلومینیوم با پر کردن حفرات ریز و افزودن بر تراکم بتن، مانع تحرک هر چه بیشتر یون‌ها در بتن گردید و بدین ترتیب خوردگی بتن کاهش یافت.