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Research Article

Investigating the effect of nano-silica and micro-silica on the mechanical characteristics of high strength concrete

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Abstract

Today, the role of concrete as the most widely used building material in the development of the civil and economic infrastructure of societies is undeniable. On the other hand, the production of cement requires the consumption of natural resources and the release of a significant amount of carbon dioxide into the environment, so the need to revise and change the ingredients of concrete in such a way as to meet the needs of construction and to minimize risks and damage to the environment. It is necessary that pozzolans are .among the materials that can be used to improve this
Iran is one of the countries that can be a leader in this matter due to its diverse geographical areas and the availability of various mines. Therefore, this research presents the effect of using nano-silica (NS) and micro-silica (SF) of Hamadan city on the mechanical .(properties of ultra-high-strength concrete (UHPCs
For this purpose, two groups of concrete with and without silica fume (SF) were made. Also, nano silica (NS) was used as an additive to cement in amounts of 0%, 0.5%, 1%, 2% and 3%. In general, the results show the appropriate effect of pozzolanic materials produced in Iran in improving the properties of concrete in a way that gives that among the different contents of NS, UHPC containing 2% NS has the best results in terms of compressive strength, tensile strength, modulus of elasticity, and bending strength. Showed in 90 days. Also, UHPC samples containing dual cement materials (NS and SF) showed better results than concretes containing only NS.
Keywords:*nano-silica,concrete,micro cilica, high strength concretemechanical characteristic*

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1. Introduction

Today, concrete is the most widely used construction material in the world. The annual production and consumption of millions of tons of cement is proof of the importance of this material.

A large amount of cement is produced and consumed every year. The most polluted part of the concrete industry is the cement production process, approximately one ton of carbon dioxide enters the atmosphere for every ton of Portland cement produced. In recent years, Iran has produced more than 85 million tons of cement annually, and this huge production of cement, in addition to consuming large amounts of energy, causes the release of large amounts of carbon dioxide gas, which can harm both the environment and human health. Therefore, it is necessary to reduce the amount of cement used in concrete as much as possible, and one of the materials that researchers pay attention to in this regard is pozzolanic materials, which can be used in various geographical areas and the availability of different mines in this regard. Be a leader in the way that these materials are produced in many cities, including Isfahan, Mashhad, Hamedan, etc.

Over the past years, ultra-high performance concrete (UHPC) has become one of the most popular concretes [1-3]. UHPC has been used in many strategic and sensitive projects, such as connecting beams in tall buildings, precast members, infrastructure reconstruction, blast-resistant structures, and special facilities such as nuclear waste storage containers [4]. The main composition of UHPC includes a large amount of ordinary cement and silica fume as a binder, fine sand and quartz, etc. Very low water-to-binder ratios are also commonly used in UHPC mixtures, resulting in reduced workability that may be managed by the addition of a superplasticizer [5,6].

In order to obtain the mechanical properties of UHPC concrete, increasing the hardness and strength of the interfacial transition zone (ITZ) to a comparable and acceptable level, silica fume and (or) nanosilica materials may be used [7]. Since the past decades, silica fume has been used in the range of 10 to 25% of the weight of cement in concrete making, and therefore the pozzolanic and filler effects on concrete properties are widely known [8]. The reaction of pozzolanic silica with calcium hydroxide in the final stages forms more C-S-H gel (chemical effect) and also filling the remaining voids in the fresh and semi-hydrated cement paste with the same concrete (physical effect), causing an increase in density. becomes concrete [9].

Nano silica seems to be one of the most popular nano particles in researchers' research due to its many benefits in concrete. The important point is that it is not the case that nanosilica can only fill the empty space between cement particles and silica fume, but its high specific surface area to volume ratio creates a high rate of pozzolanic reaction, which leads to an increase in activity potential. It becomes chemical. Recent studies have shown that the addition of nano-silica has significantly improved the mechanical structure [12], durability [13], physical characteristics [14] and microstructure of concrete [15]. Researchers have proven that the smaller the silica particles, the higher the strength of UHPC. However, there are different opinions and poor views on the optimal percentage of nano-sized particles when replacing cement for concrete production. In the case of conventional concrete, Sobolev et al. [16] reported that the addition of 0.25% of SiO_2 nanoparticles increased the 28-day compressive and flexural strength by 10% and 25%, respectively.

Zaki and Ragab [17] studied the effect of nano-silica on the strength of self-compacting concretes with 0.35 and 0.39 ratios of water to binder (w/b). They used nano silica at replacement levels of 0.5%, 0.7% and 1% by weight of cementitious materials. The compressive strength measured at the ages of 7, 28, 90 and 365 days showed that the nano-silica used at the replacement level of 0.5%, regardless of the age of the test, brought the highest results. Safan et al. [18] used copper-zinc nanoferrite in the production of Portland cement pastes and mortars with a w/c ratio of 0.25 and 0.40, respectively. The optimal amount of nano materials is 1% by weight of cement, which increases the pressure.

Despite the beneficial effects of nanomaterials mentioned above, there are some studies in which the use of nanomaterials on the mechanical properties of conventional concrete has been insignificant. According to Sanaf et al. [21], the use of nano-silica in the manufacture of cement paste and mortar did not lead to a significant increase in compressive strength. Even in the study of Latifi et al. [22], lower compressive strength was reported for mortars with 3% nano-silica compared to plain samples. In addition, Hosseini et al. [23] and Abbas [24] observed the negative effects of high amounts of nano-silica on efficiency.

Compared to other types of concrete, there are few studies on the properties of ultra-high-strength concrete (UHPC) containing nanomaterials. Rong et al. [25] stated that the addition of 3% of nano-silica leads to a 100% increase in compressive strength compared to reference concretes. According to Yu et al. [26], however, the effect of nano-silica was relatively small and the compressive strength of UHPCs decreased from 200 to 150 MPa when Weil and Naman [27] replaced Portland cement with only 1% nano-silica in the mixtures.

Therefore, in this research, the mechanical characteristics (compressive strength, tensile strength and modulus of elasticity of concrete, modulus of rupture of concrete (super strong) under different amounts of nano silica (NS) and silica fume (SF) produced in Hamadan city have been investigated in order to maintain International standards, as well as attention to the availability of pozzolanic materials in the country, is a suitable model for reducing economic costs and environmental problems.

2. Laboratory studies

2.1. Materials used and mixing plan

The materials used in the production of concrete for this research included ordinary Portland cement [28], silica fume (SF) and nano silica (NS) produced in Hamadan city. Their chemical composition, physical and mechanical properties are given in Table 1. Also, aggregate with a specific gravity of 2.65 was used. Also, a new generation of superlubricant (SP) of polycarboxylate type was used to meet the performance specifications according to ASTM C 494 [29].

The mixing design studied in the experimental program is shown in Table 2. The mixing plan of groups 1 and 2 includes 0% and 10% SF, respectively, with mutual NS content of 0%, 0.5%, 1%, 2%, and it should be mentioned that 3% of super-lubricant in different amounts to set the sufficient efficiency for the mixture. were used. The mixtures in Table 2 were determined based on the substitution level of NS and SF. For example, SF0NS1 represents a mixture containing 0% silica fume and 1% nano-silica.

Table 1.Characteristics of ordinary Portland cement, silica fume and nano silica

Amounts (%)	Cement	silica fume	Nano silica

CaO	62.12	0.45	–
SiO_2	19.69	90.36	99.8
Al_2O_3	5.16	0.71	–
Fe_2O_3	2.88	1.31	–
MgO	1.17	–	–
SO_3	2.63	0.41	–
K_2O	0.88	1.52	–
Na_2O	0.17	0.45	–
Cl	0.0093	–	–
Loss on ignition	2.99	3.11	–
Insoluble residue	0.16	–	–
Free CaO	1.91	–	–
Specific surface (m^2/kg)	394[a]	21,080[b]	150,000[b]
Specific gravity	3.15	2.2	2.2

Table 2. Concrete mixing scheme under different amounts of nano silica and silica fume

Group	mixing design	Cement (kg/m^3)	Silicon soot (kg/m^3)	Nano-silica (kg/m^3)	Water (kg/m^3)	Lubricant (kg/m^3)	Seed Stone (kg/m^3)
1	SF0NS0	800	0	0	160	21.6	1471.3
	SF0NS0.5	796	0	4	160	25.2	1461.1
	SF0NS1	792	0	8	160	28.8	1450.8
	SF0NS2	784	0	16	160	36.0	1430.2
	SF0NS3	776	0	24	160	43.2	1409.7
2	SF10NS0	720	80	0	160	29.6	1422.9
	SF10NS0.5	716	80	4	160	33.6	1411.6
	SF10NS1	712	80	8	160	37.6	1400.3
	SF10NS2	704	80	16	160	44.8	1379.8
	SF10NS3	696	80	24	160	52.0	1359.2

2.2. Number and dimensions of tested samples

The compressive strength test was performed on 100 mm cubes at the ages of 1, 3, 7, 14, 28, 56 and 90 days according to ASTM C39 [30]. Tensile tests were performed on 100 mm cubes at the age of 28, 56 and 90 days according to ASTM C496 [31]. Also, the modulus of elasticity was determined on 150 mm cubes at the age of 90 days according to ASTM C469 [32]. . For this, the cube samples were loaded three times up to 40% of the final load determined from the compressive strength test and then unloaded. The first set of readings from each cube was discarded and the elastic modulus was reported as the average of the other two sets of readings.

3. Test results

3.1. pushing resistance

The effects of using nano silica (NS) on the development of compressive strength of UHPC with and without silica fume (SF) are shown in Tables 3 and 4 as well as Figures 1 and 2, respectively. According to the test results, the compressive strength of concrete regardless of the SF content increases continuously up to 2% NS content, after which the strength starts to decrease. Also, silica fume concretes aged up to 7 days, regardless to the NS content, they had lower compressive strength, in fact, among the different NS contents studied, UHPC with 2% NS had the highest compressive strength from 7 to 90 days. However, a decrease in the initial strength of concrete with NS was observed, especially at ages 1 and 3, which can be attributed to the lack of hydration process at early ages.

Similarly, the positive effect of SF was achieved after 14 days onwards. Finally, the initial strength of nano-silica concretes was higher than that of micro-silica concretes. However, due to cement hydration at older ages being controlled by the ability of ion diffusion through hydrates, a compact gel structure of nanosilica pozzolanic hydration products leads to diffusion block and thus reduces the degree of hydration [38].

Table 3. Compressive strength of samples at different ages with 0% silica fume (SF in megapascals (mpa)

Age of samples in days							**Sample specifications**
90	56	28	14	7	3	1	
125	119	115	112	107	104	93	**0% Nano_Silica**
136	121	116	113	107	100	83	**0.5% Nano_Silica**
130	124	121	114	108	99	78	**1% Nano_Silica**
134	126	124	116	109	95	76	**2% Nano_Silica**
130	123	119	111	106	94	75	**3% Nano_Silica**

Table 4. Compressive strength of samples at different ages with 10% silica fume (SF in megapascals (mpa)

Age of samples in days							**Sample specifications**
90	56	28	14	7	3	1	
130	124	121	115	104	91	82	**0% Nano_Silica**
133	128	125	118	105	88	78	**0.5%**
137	135	130	123	106	85	69	**1% Nano_Silica**
143	137	132	126	107	84	62	**2% Nano_Silica**
138	133	127	119	103	83	56	**3% Nano_Silica**

The 90-day compressive strength of the UHPC concrete control with and without microsilica (SF0NS0 and SF10NS0) were 124 and 130 MPa, which can be seen in Figure 1, respectively. Substitution of 2% NS resulted in 6% and 8% higher resistance than the reference mixtures, respectively. At 28 days, similarly, the increase in strength for concretes with and without SF was approximately 6% and 8%. The results showed that the addition of NS had a moderate effect due to the fact that most of the NS pozzolanic reaction in the cement paste was completed at early ages [39 41]. However, a strong increase in strength was observed from 1 to 3 and from 3 to 7 days such that a 45% increase in strength was observed for the SF10NS3 mixture from 1 to 7 days. In addition, according to Tables 3 and 4, at the age of 90 days, the compressive strength of the mixture containing 1% nano-silica (SF0NS1) was almost equal to 10% microsilica (SF10NS0).

For example, concrete with 10% SF had compressive strengths of 115, 121, 124, and 130 MPa at the ages of 14, 28, 56, and 90 days. The corresponding strength values for 1% NS concrete were 114, 121, 122 and 130 MPa respectively.

The slightly lower compressive strength of samples containing 3% NS may be attributed to the improper dispersion of nanoparticles in the mixture. Nanoparticles tend to agglomerate more than other pozzolans such as microsilica because of their much smaller size and high interparticle van der Waals forces [9, 42,43]. The amount of SiO2 nanoparticles in the mixture also exceeded the consumption of calcium hydroxide compounds to form C-S-H gel. Therefore, it did not help to increase the strength of the samples [44].

It is well known that the crystallinity of the hydration products has a great influence on the mechanical properties of cement-based materials, and a suitable ratio of crystals to non-crystals is desired to produce higher mechanical properties [45]. Considering this issue, an optimal amount of nanosilica can obtain a suitable ratio of crystal to non-crystal in cement added to nano-silica [38, 45].

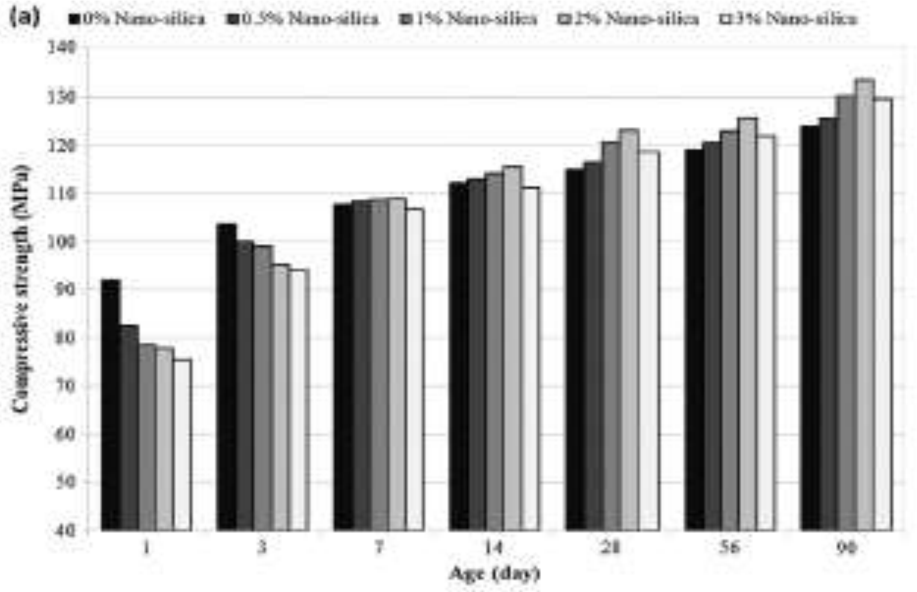

Figure 1. Water compressive strength of different ages in plain UHPC with 0% SF

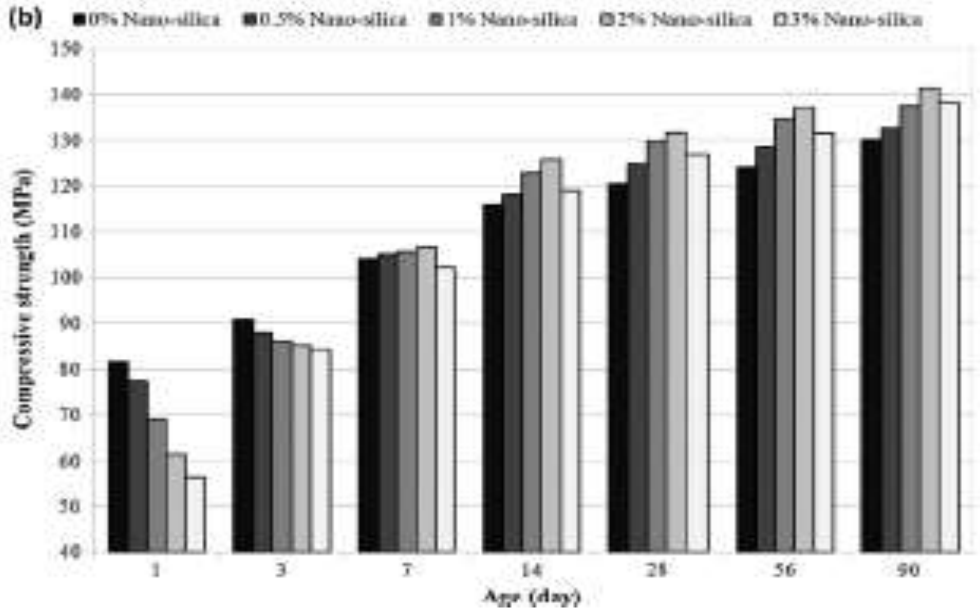

Figure 2. Water compressive strength of different ages in plain UHPC with 10% SF.

In addition, Table 2 presents the superlubricant demand of the mixtures to provide the target performance. Obviously, the mixture with NS requires a higher amount of superlubricant, which is especially evident at higher NS substitution levels. Interestingly, concretes with 1% NS or 10% SF had similar superplasticizer demand, which agreed well with the observed compressive strength behavior.

2.3. Split tensile strength

When some tensile stress is applied to concrete, first micro cracks and then macro cracks are created. Increasing load encourages critical crack development at macrocrack tips, which ultimately leads to concrete failure [46]. The easiest way to indirectly determine the tensile strength of concrete is the split tensile test. The study of tensile strength is necessary to provide information about the maximum tensile load that concrete can withstand before cracking. The test results are given in Tables 5 and 6.

Table 5. Tensile strength of samples at different ages with 0% silica fume (SF in megapascals (mpa)

Age of samples in days			
90	28	7	**Sample specifications**
7.7	7.2	7	**0% Nano_Silica**
7.9	7.5	7.2	**0.5% Nano_Silica**
8.6	7.9	7.5	**1% Nano_Silica**
8.8	8.3	7.6	**2% Nano_Silica**
8.5	8.2	7.4	**3% Nano_Silica**

Table 6. Tensile strength of samples at different ages with 0% silica fume (SF in megapascals (mpa)

Age of samples in days			
90	28	7	**Sample specifications**
8.5	7.9	7.3	**0% Nano_Silica**
9	8.4	7.6	**0.5% Nano_Silica**
9.8	9.3	7.8	**1% Nano_Silica**
10.4	9.6	8.3	**2% Nano_Silica**
9.8	9	7.7	**3% Nano_Silica**

The growth of tensile strength against different values of NS is shown in figure 3 and 4. It was found that the tensile strength increases by adding NS up to 2% for two groups of concrete.

At the age of 90 days, the addition of 0.5%, 1%, 2% and 3% of NS compared to the samples without NS, improves the tensile strength by 2%, 9%, 12% and 8% for the first group, which is The second group is 5%, 14%, 24% and 13%, respectively. Therefore, it seems that the combined use of SF and NS is more effective on tensile strength. Basically, the main components of concrete such as cement paste and aggregates have a higher tensile strength than the concrete itself when tested separately. The above phenomenon is caused by the negative effect of ITZ, which is known as the weakest part in concrete. that the combination of samples with different NS reduces the empty spaces in the ITZ region and thus helps to create a denser and stronger ITZ [47]. So that in this case the improvement of tensile strength is observed [11,48].

On the other hand, the increase in tensile strength was limited immediately after the addition of 2% NS. This may be due to the excessive amount of NS particles present during the hydration process.

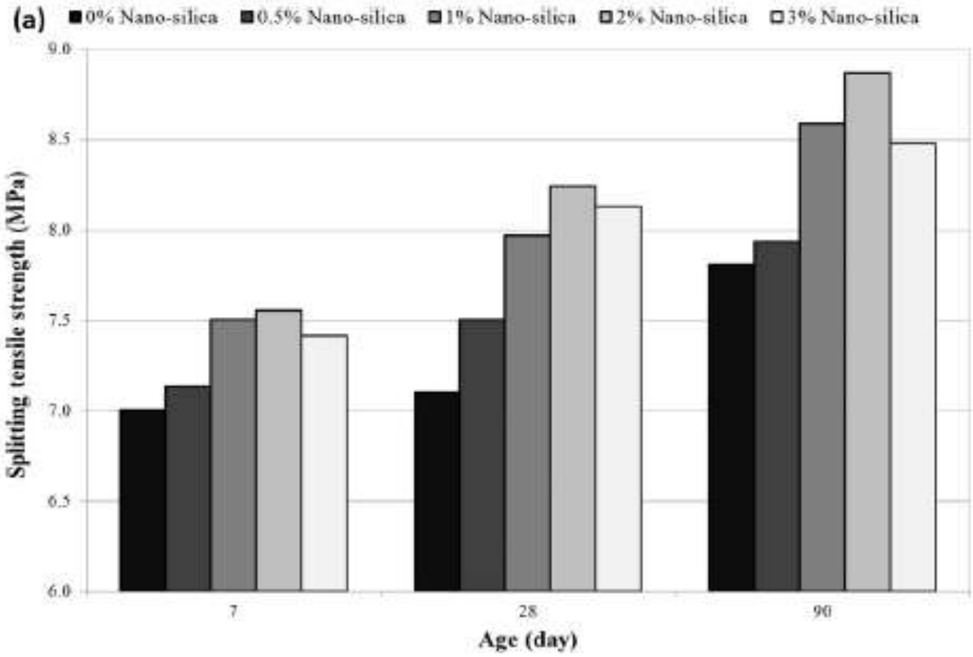

Figure 3. Tensile strength of samples at different ages with 0% silica fume (SF in megapascals (mpa)

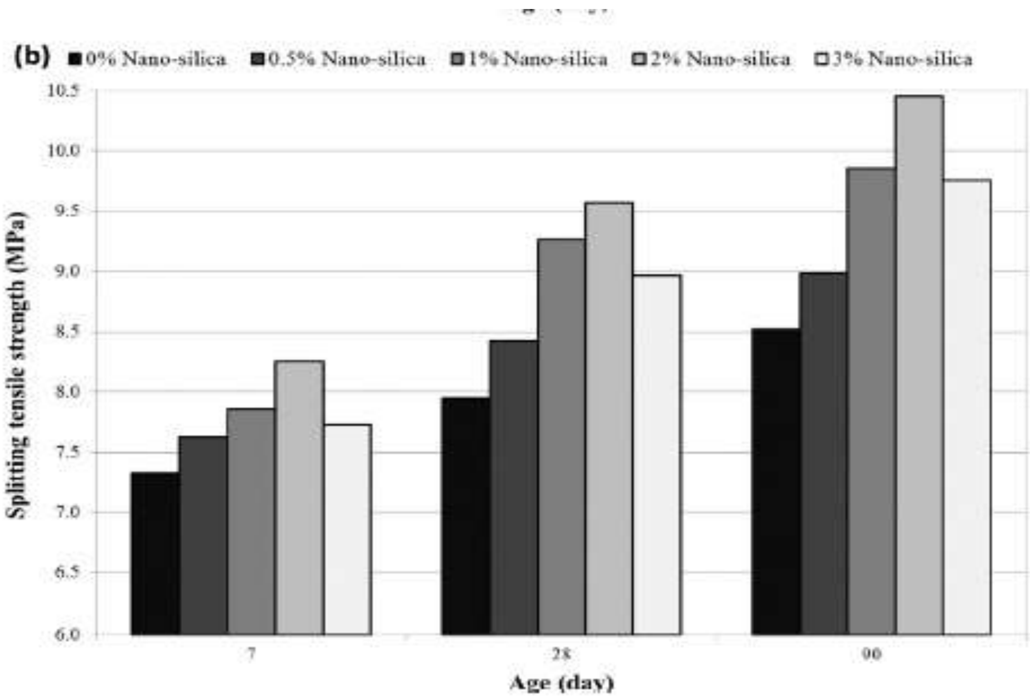

Figure 4. Tensile strength of samples at different ages with 0% silica fume (SF in megapascals (mpa)

3.3. Modulus of elasticity and modulus of rupture

Since the modulus of elasticity provides useful information about the ability of concrete to deform elastically, it is therefore one of the most important factors used in the design of concrete structures. Researchers investigated that a limited amount of silica nanoparticles gives a steeper slope in the stress-strain relationship curve and reduces the local strain [50]. This means that concrete with optimal content of nanoparticles has better hardness because the bond density of paste with aggregates is better [51]. Figure 5 shows the 90-day modulus of elasticity of the samples for different NS and SF content. The important point is that the behavior here was very similar to the compressive strength. It can be seen that the effect of using NS regardless of the presence of SF was to increase the static elastic modulus of concrete.

This increasing trend continued up to 2% NS content, after which it started to decrease. In addition, the test results showed that the effect of 1% NS (SF0NS1) on the modulus of elasticity is almost equal to 10% SF ((SF10NS0). As it was also observed from the mixtures of the second group, the effect of the combined use of nano and microsilica with Substitution of nano materials alone was more obvious.

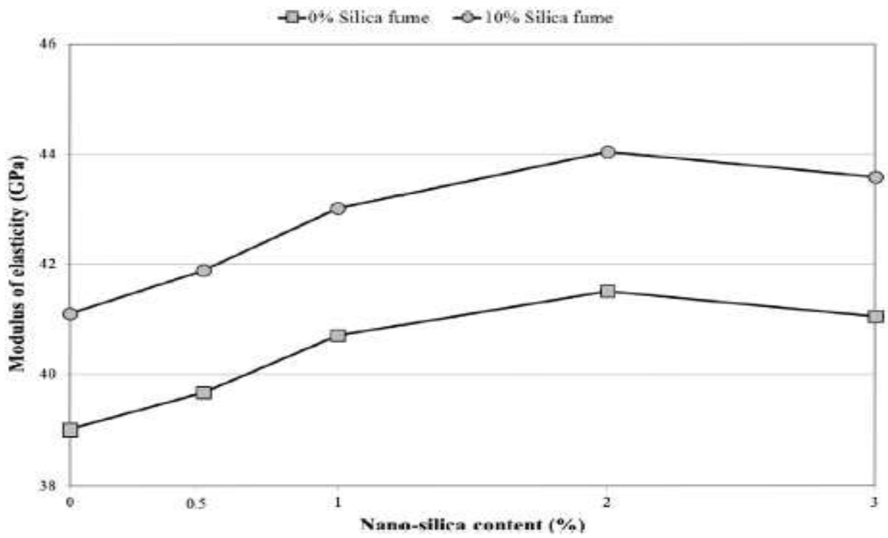

Figure 5. Elastic modulus of the samples with 0% and 10% silica fume (SF at the age of 90 days in Gigapascals (Gpa)

Figure 6 shows the change of modulus of rupture according to different percentage of NS. Flexural modulus increases with increasing NS content regardless of concrete groups. When the concrete was placed at a replacement level of 3% NS. Despite the reduction of its flexural modulus with respect to the addition of 2% NS, the results were still 5% and 6% higher in the first and second groups, respectively, than their control mixture, the same results recently reported by other researchers [52,53]. The improvement in modulus of rupture may be due to the rapid consumption of calcium hydroxide associated with NS, which helps to improve the bond between aggregate and cement mortar [47]. And as a result, more energy is needed to break the samples.

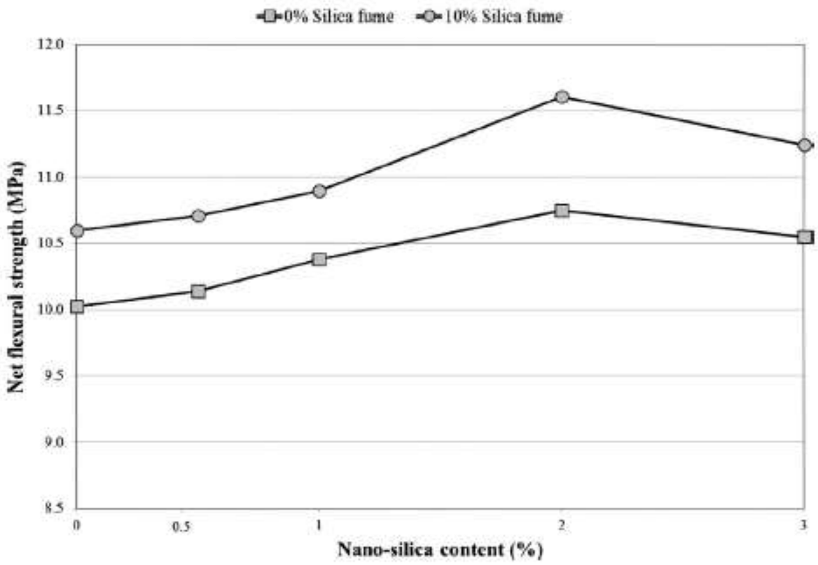

Figure 5. Modulus of rupture of samples with 0% and 10% silica fume (SF) at the age of 90 days in megapascals (Mpa)

4 - Conclusion

In this study, the mechanical characteristics of super-strength concrete were investigated using nano silica and silica fume produced in Iran and the city of Hamedan, and the most important results are given below.

1. The compressive strength of concrete samples, regardless of SF content, increases continuously up to 2% NS content, after which the strength starts to decrease, in fact, among the different NS contents studied, NS 2% is the highest and showed the most optimal compressive strength.

2. Silica fume concretes aged up to 7 days, regardless of the NS content, had lower compressive strength and the positive effect of SF was obtained after 14 days. That is, in the early years, the strength of concrete is often caused by nanosilica materials.

3. At the age of 90 days of the samples, the compressive strength of the mixture containing 1% nano-silica (SF0NS1) was almost equal to 10% micro-silica (SF10NS0), which clearly shows the good effect of nano-silica in improving concrete behavior.

4. According to the test results, the direct tensile strength of the samples is optimal and maximum regardless of SF values at 2% NS, and at lower NS values, a greater decrease in strength was shown than at higher NS (3%), which is the reason This can be attributed to the reduction of the empty spaces in the ITZ region and thus help to create a denser and stronger ITZ.

5. The highest tensile strength occurred in the sample with 10% SF and 2% NS, which indicates the suitability of SF and NS of Hamedan city in improving the tensile strength of concrete.

6. Silica showed a good effect in improving the elastic modulus, so that the elastic modulus of samples containing 10% SF is much higher than its 0%, and the effect of NS on the modulus of rupture is optimal and is at the maximum value of 2%. .

7. Flexural modulus increases with increasing NS content regardless of SF values. When the concrete was placed at a replacement level of 3% NS. Despite the reduction of its flexural modulus compared to the addition of 2% NS, the results were still 5% and 6% higher than their control mixture compared to the 1% and 0.5% NS samples, respectively.

8. The results of the experiment show the proper effect of silica fume and nano silica produced in Iran and Hamedan city in improving the mechanical characteristics of high-strength concrete according to international standards, so that it can be used optimally to reduce economic costs and environmental problems.

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