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Research article

Effects of Micro and Nano Silica and Steel and Polypropylene (PPS) Fibers on the Characteristics of High-Strength Self-Compacting Concrete (HSC-SCC)

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Abstract

This paper presents the effects of the Nano-Silica and Steel and polypropylene (PPS) fiber on the characteristics (properties) of High-Strength Self-Compacting concrete (HSC-SCC). HSC-SCC samples were produced according to concrete mixing plans by using lubricant, Nano-Silica and steel fibers. 7, 28 and 90 days were determined as the processing time of the samples for test. Rheological properties, compressive strength, tensile strength, flexural strength, non-destructive ultrasonic velocity test, modulus of elasticity and water absorption, tests were performed. Test results indicate that Nano-silica and Steel Fiber have negative effects on the Rheological properties, however, the Sustainability and also the Compressive and tensile strength were increased. Flexural strength with the 4% Nano-silicon and 8% micro-silica is in the optimum condition. Moreover, by increasing the Nano-Silica percentage up to the optimum point (4%), the Modulus of elasticity was increased as well, which causes a decrease in the number of pores, micro currents and water absorption ratio and an increase in the velocity of waves.

Keywords: Self-compacting concrete; high strength concrete; Nano-Silica, steel fibers, rheological properties; compression testing; indirect tensile strength; bending strength; non-destructive ultrasonic velocity test; modulus of elasticity; water absorption

Introduction

Concrete is one of the most widely used materials in civil engineering, and its usage is increasing day by day. On the one hand, with the advancement of science and technology and the emergence of more complicated building systems, and on the other hand, with the growth of construction at the macro level, the need to use newer building materials with more efficiency is very tangible. Since the design of concrete structures is developing fast, the shape of designed sections and structural members has been more sophisticated, and the density of reinforcement in such sections does not seem unusual anymore. Furthermore, civil engineers have always faced a lack of skilled workers on the construction site. Self-compacting concrete (SCC) has been mentioned as a suitable solution to potential problems. Self-compacting concrete is a new technology in which the concrete can be poured into the form of various shapes with bulk reinforcement, without any need for vibration. Its most interesting property is that it can compact itself by its weight and maintain uniformity simultaneously. The deterioration of concrete is strongly dependent on the formation of cracks and micro-cracks due to loading or environmental issues. Heat and humidity fluctuations cause micro-cracks in cement paste, and these micro-cracks focus on the surface of coarse aggregates. Due to the more impact of loading and other environmental issues, micro-cracks join together, form cracks, and eventually spread in the concrete body. The use of different fibers in concrete and the manufacture of fiber-reinforced concrete is considered a practical step in preventing the propagation of microcracks and cracks and compensating for the weak tensile strength of concrete. Since vital structures with regard to their occupancy and location are exposed to erosion due to adverse internal factors of concrete or external (environmental) factors, it is required to consider suitable performance levels in the modern design of concrete structures to maintain their strength and profitability in a certain lifetime. Therefore, considering the durability in addition to strength in concrete design leads to lower maintenance costs and the preservation of national capital.

Background

Literature review

Self-compacting concrete was first proposed for achieving durable concrete in 1988, and preliminary studies on the performance of self-compacting concrete were conducted by Ozawa (1989) and Okamura (1993) at the University of Tokyo [1-3]. According to a theory, self-compacting concrete is concrete with enough fluidity that it can be compacted without the need for external energy and also remains uniform during and after pouring concrete and moves easily between dense reinforcement [4]. Faster execution of structures, labor reduction because of self-compaction characteristic, durability improvement arising from permeability decrease, and more freedom in section design are advantages of SCC usage. The first practical application of SCC was in the construction of a building in 1990 in Japan, and then in 1991, it has been used in the towers of the Shinkiba Ohashi cable suspension bridge no.1, Japan [5]. Some of the preliminary studies in Europe about SCC belong to RILEM International Conference, 1996, London. Many various papers were presented at the University of London, which their focus was more on SCC design. Also, at this conference, a model for SCC mix design was proposed by Swedish Cement and Concrete Research Institute (CBI) [6]. Sweden was the first country in Europe to research and develop self-compacting concrete. In 1993, the Swedish Concrete and Cement Research Association (CBI) organized a seminar with contractors and concrete manufacturers its main purpose was the application of SCC in the construction industry of Sweden [7]. In recent years, the use of alternative materials in concrete with lower environmental impacts has been investigated [8]. It is worth noting that cement additives extend the useful lifetime of concrete structures while also reducing early failures [9].

The usage of fibers in some countries dates back several thousand years ago. At that time, short pieces of stems of dried plants and water and soil were used as a mortar to construct walls and bricks (For example, the thatch is still used in Iran). The fibers are used to control cracks resulting from volume changes due to shrinkage, expansion, and thermal stresses, as well as to increase tensile strength, and energy absorption capacity and finally provide an integrated system. Currently, there are several types of fibers which only some of them are appropriate to use in concrete. The production of different types of synthetic fibers began with the evolution of the petrochemical industry in the early 20th century. Some of these fibers are used in various industries, such as textile weaving (including Nylon and Kevlar in bulletproof vests) and also to reinforce and strengthen some parts in the automobile and aerospace industries.

The mechanical properties of fiber-reinforced concrete are affected by type, percentage, length to diameter ratio, strength, size, shape, and production method of samples, and also the size and shape of aggregates. So, to use it in every particular case, we should provide a concrete mix design and test it. This should preferably be done on samples similar to structural parts. The fiber is used as a part of fiber-reinforced concrete mortar volume, and this part is usually a fraction of the volume of the mortar, which means coarse grains are not considered. The fiber influences the mechanical properties of concrete and mortar at all failure states, especially those that cause fatigue. Concrete reinforcing by fiber is in the form of stress transfer from the body to the fibers by surface shear, but if the surface of the fibers is ribbed, the process will be in the form of an interlock between the fibers and the body. The stress divides between the body and the fiber by cracking, and after that, the stress transfers to the fiber increasingly. Increasing the volume amount of fiber changes concrete properties. We cannot expect any fiber in any quantity in the concrete mixture to result in a homogenous mortar with acceptable properties. For instance, six millimeters-thick polypropylene fibers cannot be mixed homogeneously except in small amounts. Long fibers with relatively large diameters are needed for high volume amounts [9]. Compressive strength enhancement in concretes made of steel fibers is between 0-40% compared to those without fibers. Usually, straight fibers do not cause any increase in compressive strength, but fibers with an appropriate shape of 0.5-2.5% volume amount lead to a 10% enhancement in compressive strength. The amount of increase in tensile strength is 70% for the case where the fibers are randomly distributed and about 400% for the fibers oriented in the structural member. Although the tensile strength and energy absorption capacity of carbon fiber concrete with a random distribution of fibers are significant, concrete with oriented fibers has a much higher energy absorption capacity [10-14].

Materials

Sand & gravel

The maximum size of gravel was 12.12 mm, the bulk density was 2750 and the mass density was 1630. Rainfall sand was used with a bulk density of 2640. The softness modulus and value of sand were 2.73 and 98%, respectively.

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Sand and gravel properties, according to the ASTM standards, are presented in Tables 1 & 2 and Figures 1 & 2.

Cement

The Portland Type II cement, with a specific gravity of 3150 , was used in this study. The initial retention for this type of cement is 100 minutes and the final retention is 180 minutes, its 3, 7 and 28 days compressive strength were 17.4, 21.44, and 34.1MPa, respectively.

Table 3 [10], Shows the chemical composition of this cement.

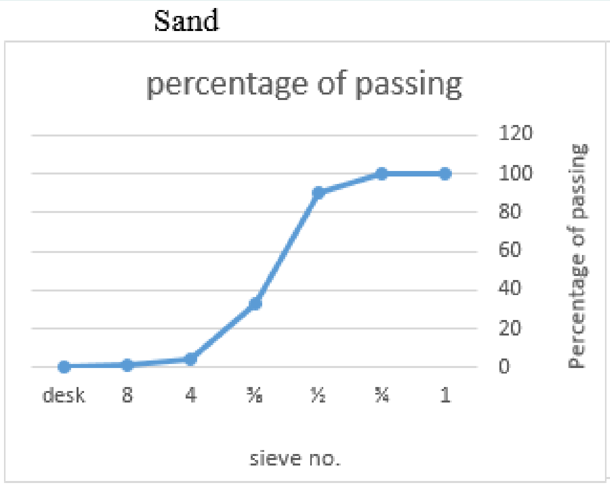

Figure 1: Sieve Analysis for Sand.

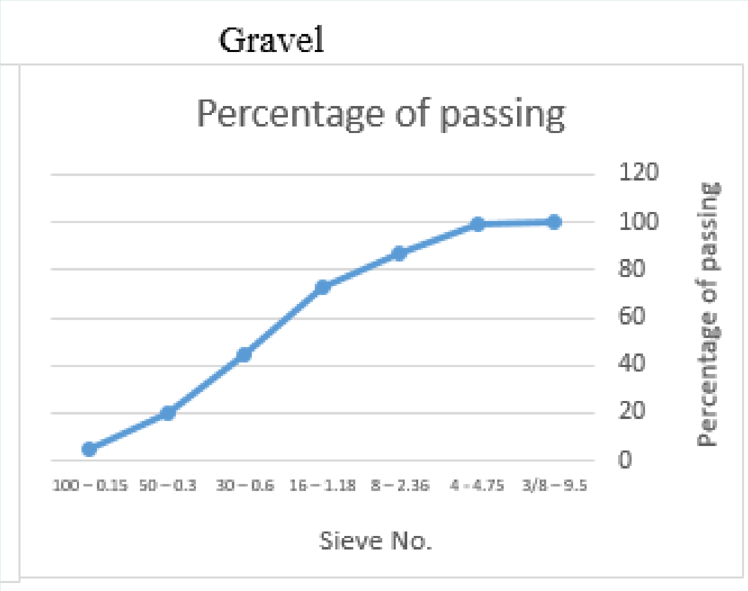

Figure 2: Sieve Analysis for Gravel

Table1: Sand Properties

Sieve No.	Percentage of passing
1	100
¾	100
½	90.38
⅜	33.31

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4	4.41
8	1.13
Desk	0

Table 2: Gravel Properties

Sieve No.	Percentage of passing
3/8 – 9.5	100
4 - 4.75	99.55
8 – 2.36	86.68
16 – 1.18	72.5
30 – 0.6	44.1
50 – 0.3	19.81
100 – 0.15	4.5

Table 3: Chemical Composition of Cement

Chemical Components	CAO	SiO_2	AL_2O_3	FE_2O_3	MgO	NaO_2	K_2O	SO_2
Quantity in simple (Gram)	64	21.5	8	3.5	1.2	0.4	0.6	2.5

Micro-Silica

Table 4: Chemical Analysis of Micro-Silica are presented

Components	%SiO_2	%Al_2O_3	%Fe_2O_3	%CaO	%MgO	%SO_3	Na_2O%	K_2O%	L.O.I%
Percent	93.16	1.13	0.72	0	1.6	0.05	0	0	1.58

The Micro-Silica used in this study was produced by the Forro-silicon Azna Company, with a specific density of 2. Chemical Analysis of Micro-Silica is presented in Table 4.

Nano-Silica

The Nano-Silica used in this study was Amorphous Colloidal soluble in water with density of 50% and it has more than 99% of amorphous silica.

Nano-silica was applied with 2, 4, 6% cement weight in different series.

The physical properties of Nano-Silica are presented in Table 5.

Table 5: Physical properties of Nano-Silica

Viscosity (GPA.S)	Special Weight (gr/cm^3)	Boiling and melting point	PH	Color	Condition
<50	1.05 – 1.400	100 – 0	11 – 9	Milky white	Liquid

Super Lubricant

In this study, third generation of super-lubricant (SP), based on carboxylic ether, with a specific weight of 1.1 g / cm^3 has been used.

Steel and Pps Fibers

Corrugated metal fibers with a diameter of 0.7 mm, a length of 36 mm and a specific gravity of 7.8 g / cm3 was used. The details are provided in Table 6. Fibers of Polypropylene sulfide (PPS). More details on the mechanical and physical properties of PPS fibers are given in Table 6.

Concrete Mixing Plan

The mixing design used in this study was according to the AC-237 R-07 code. Seven mix series (A, B, C, D, E, F, and G) are considered, which are presented in Table 7. According to the figures form of 5 to 7, by increasing the percentage of fiber content the efficiency is decreasing. In all of the fresh concrete experiments, in all of mixing plans, no bleeding and instability has been observed. Specially, in mixing plans containing fibers, the fiber has improved the stability of HSC-SCC compared to the Instance samples.

Table 6: Details on the mechanical and physical properties of PPS fibers

Fiber type	Shape	Special Weight (gr/cm^3)	Young's modulus	Tensile strength	Length (mm)	Diameter (mm)	Aspect ratio
steel	Two side hooked	7.8	16	21000	36	0.7	50
PPS	straight	0.9	3.5	27500	50-54	-	-

Table 7: Seven mix series.

Mixture number	Mixture series	Nano-silica	Micro –silica (%)	Fiber volume (%)		Gravel (kg)	Sand (kg)	Micro-silica (kg)	Cement (kg)	Nano-silica (kg)	Water (kg)	Super lubricant
		(%)										
1	E	0	4	-		794.8	898.2	22	528	0	176	1.5
2				St	0.2	794.8	898.2	22	528	0	176	1.5
3					0.3	794.8	898.2	22	528	0	176	1.5
4					0.5	794.8	898.2	22	528	0	176	1.5
5				P . P	0.1	794.8	898.2	22	528	0	176	1.5
6					0.15	794.8	898.2	22	528	0	176	1.5
7					0.2	794.8	898.2	22	528	0	176	1.5
1	F	0	8	-		789.9	892.5	44	506	0	176	2
2				St	0.2	789.9	892.5	44	506	0	176	2
3					0.3	789.9	892.5	44	506	0	176	2
4					0.5	789.9	892.5	44	506	0	176	2
5				P. P	0.1	789.9	892.5	44	506	0	176	2
6					0.15	789.9	892.5	44	506	0	176	2
7					0.2	789.9	892.5	44	506	0	176	2
1	G	0	12	-		784.9	887	66	484	0	176	2.4
2				St	0.2	784.9	887	66	484	0	176	2.4
3					0.3	784.9	887	66	484	0	176	2.4
4					0.5	784.9	887	66	484	0	176	2.4
5				P. P	0.1	784.9	887	66	484	0	176	2.4
6					0.15	784.9	887	66	484	0	176	2.4
7					0.2	784.9	887	66	484	0	176	2.4

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Compressive Strength

According to Figures 3 & 4 in the non-fibrous mixing plan, by increasing the Nano-Silica (cement weight) from 2% to 4%, the compressive strength increases 14%, compared to the Instance sample. However, when Nano-silica is increased up to 6%, the compressive strength decreased. In the case of mixtures containing Micro-silica, by increasing its replacement to 8% (weight of cement), compressive strength is improved. However, more than 8% of increase in the replacement, not only has no improving effect on compressive strength but also reduces the compressive strength (Figures 5-8). In the non-fiber and Micro-silicon mixing plans (A1, B1, C1, and D1) which contain, respectively, 0%, 2%, 4%, and 6% of Nano-silica, by increasing the percentage of Nano silica up to 4%, the compressive strength grows to 12.1%, compared to the Instance sample concrete. Using more than 4% of Nano silicon in the mixture, the compressive strength is reduced, hence, a 4% of Nano silica is considered optimal. According to Figures 8 & 9, the rate of obtaining compressive strength for 7 days old samples with Nano-silica is at its maximum in the beginning and as the age of samples increases the rate decreases. Samples with 4% of Nano-silica reach 78.86% of their final residual strength within 7 days. According to the results of Figures 5-12, in the non-fiber and Nano-silicon mixing plans (A1, E1, F1, and G1) which contain, respectively, 0%, 4%, 8%, and 12% of Micro-silica, by increasing the micro-silica up to 8%, the compressive strength grows to 7% of the Instance sample concrete and by using more than 8% of Micro silicon, the compressive strength reduces. The results from Figures 12 & 14 indicate that the compressive strength is decreased by increasing the percentage of metal fibers up to 0.3% (vol.), and after that it decreases (in 0.5% vol.). In Figures 6-8 the downward trend of the compressive strength is obvious as the percentage of PPS fibers increases. Demonstrated in Figures 9 & 10, by increasing the fiber percentage up to 0.15% (vol.), the compressive strength increases, and afterwards the compressive strength decreases. In all fiber-based designs, the compressive strength increases with increasing the percentage of Nano-silica and Micro-silica up to the optimal percentages (4 and 8%). The reasons for this increase in the compressive strength are probably the proper placement of fibers and their uniform distribution in the concrete. According to the results of this experimental study, for a suitable fiber distribution at the concrete, the optimal amount of fiber is 0.3% (vol.).

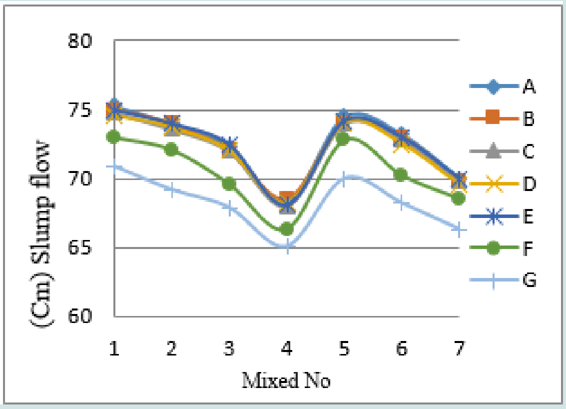

Figure 3: Modulus of elasticity of concrete containing nano-SiO2 and Metal fibers

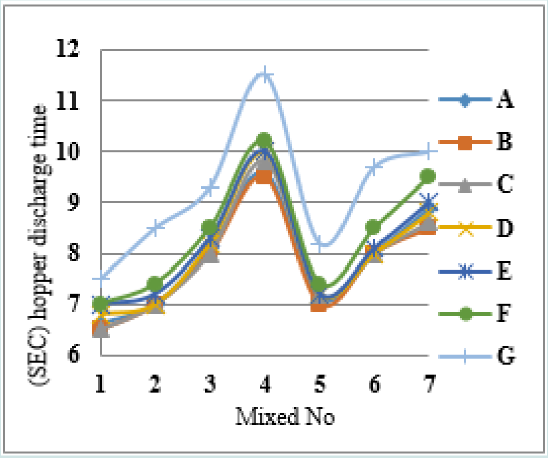

Figure 4: Modulus of elasticity of concrete containing nano-SiO2 and Metal fibers

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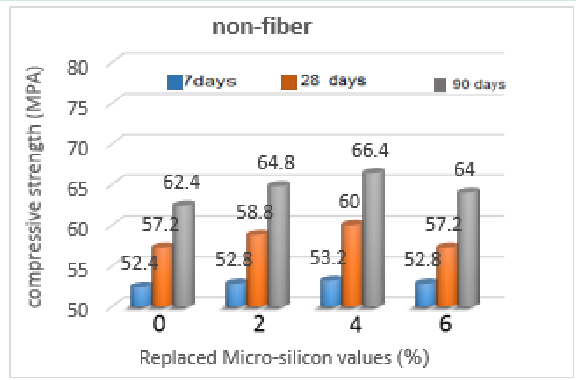


Figure 5: Modulus of elasticity of concrete containing Micro-silica and metal fibers.

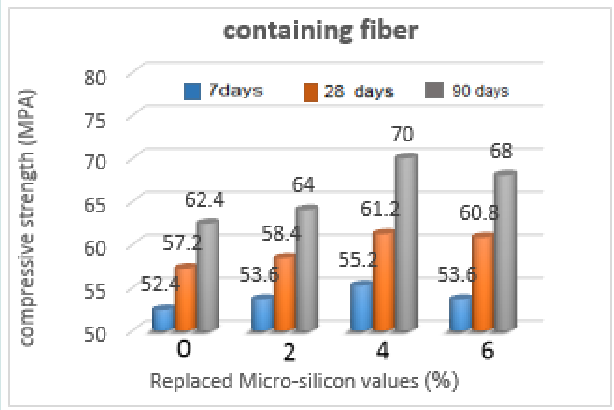
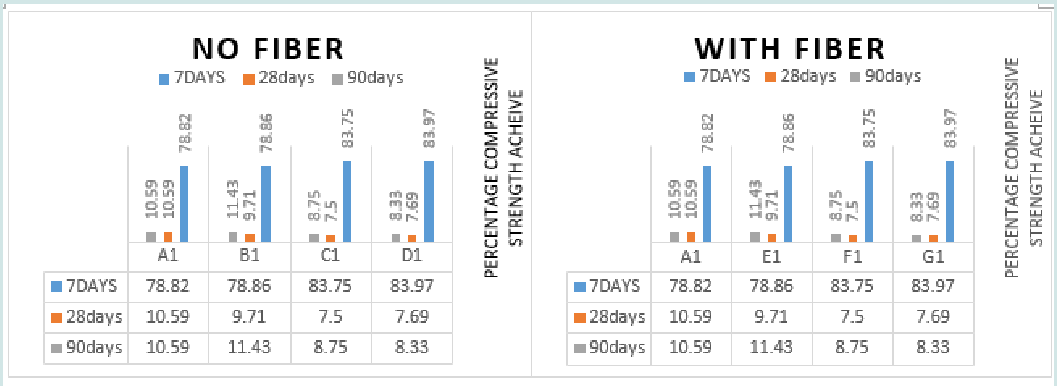


Figure 6: Compressive Strength Specification of Containing Nano-silica without Fiber



	A1	B1	C1	D1
7DAYS	78.82	78.86	83.75	83.97
28days	10.59	9.71	7.5	7.69
90days	10.59	11.43	8.75	8.33

	A1	E1	F1	G1
7DAYS	78.82	78.86	83.75	83.97
28days	10.59	9.71	7.5	7.69
90days	10.59	11.43	8.75	8.33

Figure 7: Compressive strength diagram of concrete containing Micro-silica without fiber.

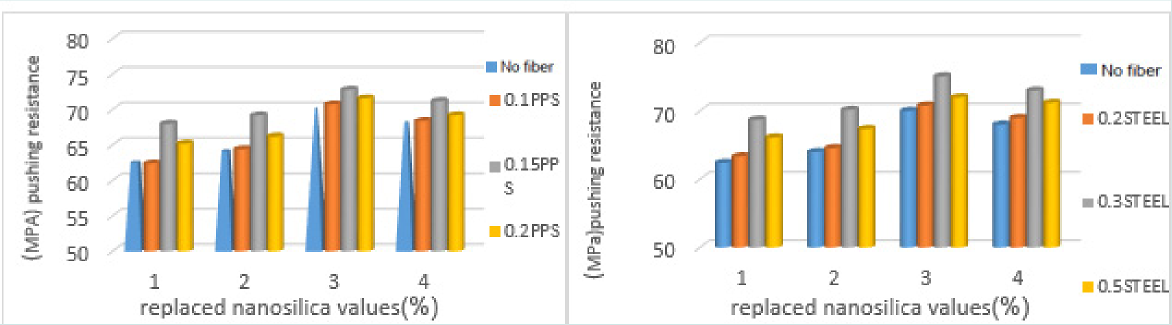


Figure 8: Compressive Strength Specification of Containing Nano-silica without Fiber.

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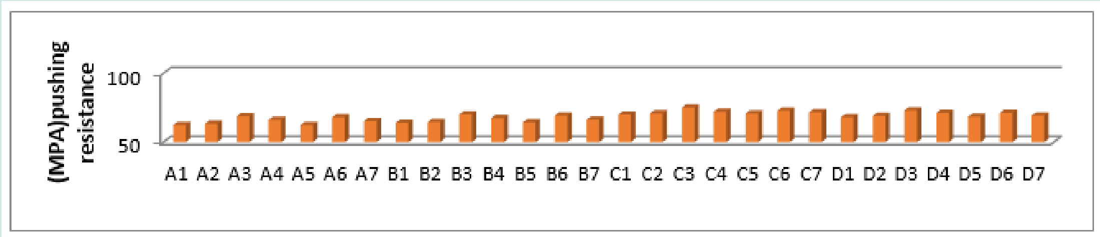

Figure 9: Compressive strength diagram of concrete containing Nano-silica and metal fibers and PPS.

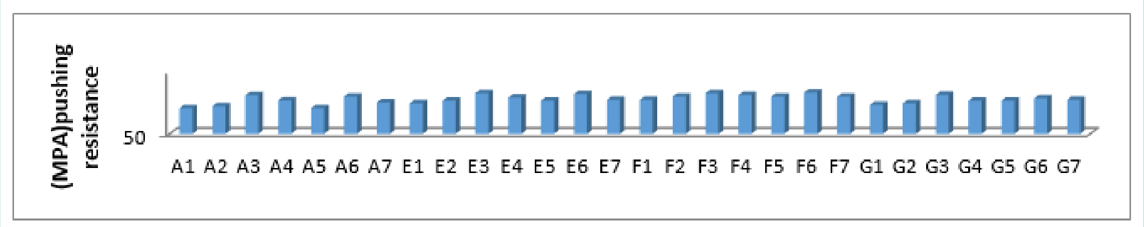

Figure 10: Compressive strength diagram of concrete containing Micro-silica and metal fibers and PPS

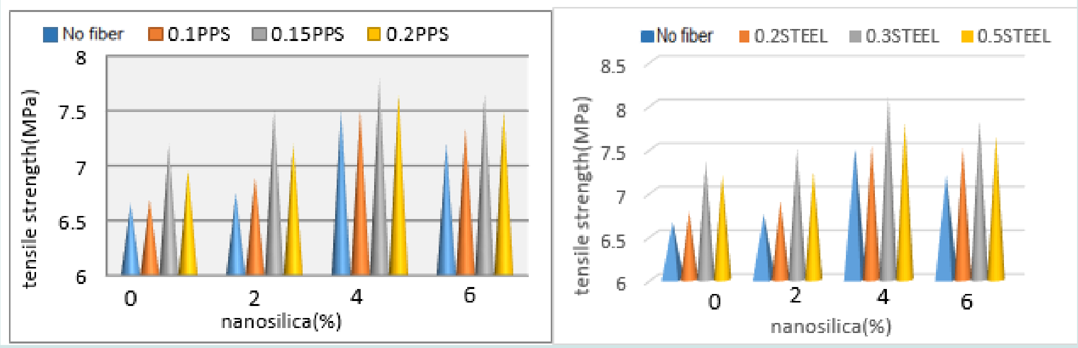

Figure 11: Tensile strength diagram of concrete containing nano-SiO2 and metal fibers.

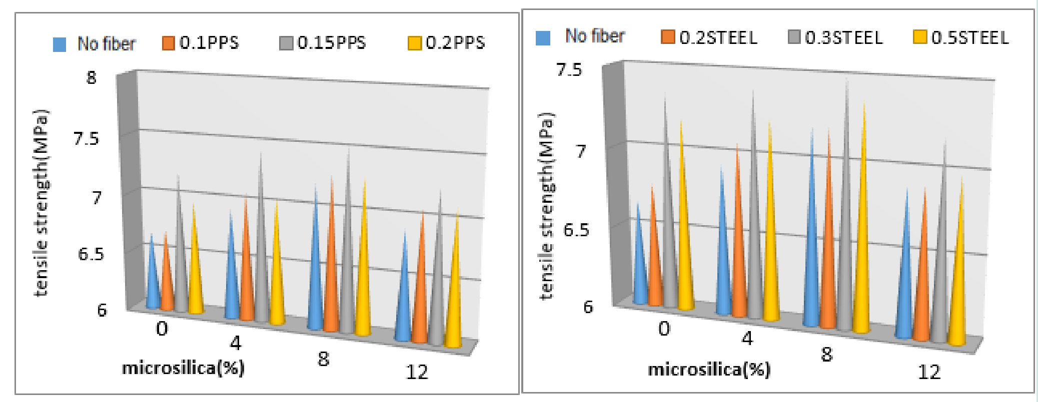

Figure 12: Tensile strength diagram of concrete containing Micro-silica and metal fibers.

The reason for the reduction in the compressive strength of concrete, with the Fiber content more than optimal amount, is the fibrous bullet phenomenon (the fiber's desire to concentrate at one point), which results in the non-uniform distribution of fibers and inappropriate engagement with the cement matrix.

Results of Indirect Tensile Strength

The results shown on Figures 11 & 12 indicate the positive effect of increasing the fiber percentage on the tensile strength. As shown in Fig. 14, in the fiber contained samples by increasing the percentage of metal fibers from 0 to 0.5%, the tensile strength is

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increased compared to non-fiber samples. For example, in the samples with 0.3% of metal fibers, the tensile strength is increased up to 10.3% compared to the instance samples. This increasing rate of tensile strength grows by increasing the percentage of Nano-silica. Samples with 4% of Nano-silica (optimal amount) had the maximum increase in the tensile strength. For example, in a sample with 0.3% of metal fiber and 0.4% of Nano silicon, the amount of tensile strength is 21.6% higher than the instance samples.

Figures 13 & 14 show the increase in the tensile strength due to PPS fiber content. By increasing the percentage of PPS fibers up to 0.2%, the tensile strength grows up to 8.1% compared to the control (controlled) samples. The growth rate of the tensile strength is enhanced by increasing the percentage of Micro and Nano silica. Overall, using the optimum amount of Micro and Nano Silica (8% and 4%, respectively), the samples had the maximum increase in the tensile strength (for Micro-silica and 17.1 % for Nano silica) compared to control (controlled) samples.

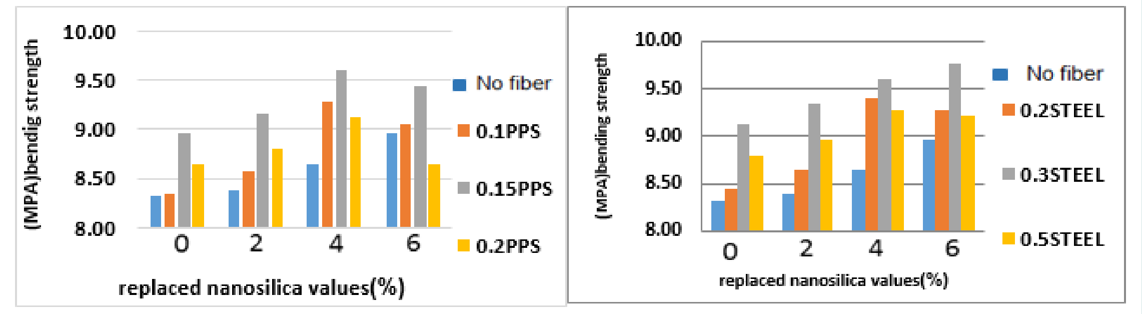

Figure 13: Tensile strength diagram of concrete containing Micro-silica and metal fibers.

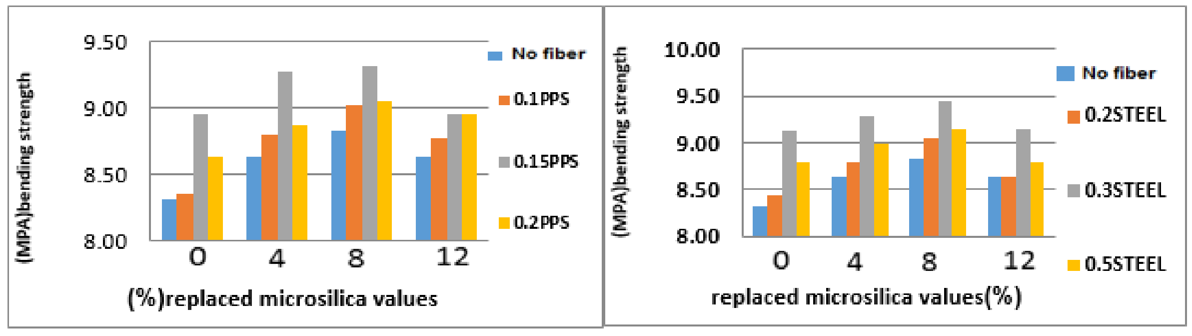

Figure 14: Tensile strength diagram of concrete containing Micro-silica and metal fibers.

Results of Flexural Strength

The results of the Flexural strength test are presented in Figures 15 & 16. Increasing the percentages of two types of metal (fibers and PPS), affects the rate of change (variation rate, slope) in the flexural strength, which is ascending at the beginning and descending towards the end. The maximum amount of this increase for metal fibers (in 0.3% vol.) is 76.9MPa, and for PPS fibers (in 0.15% vol.) is 6.9MPa. Also, the maximum increase of flexural strength for these two types of fibers (metal and PPS) are 32% and 21%, respectively, in comparison with samples without fiber (A1).

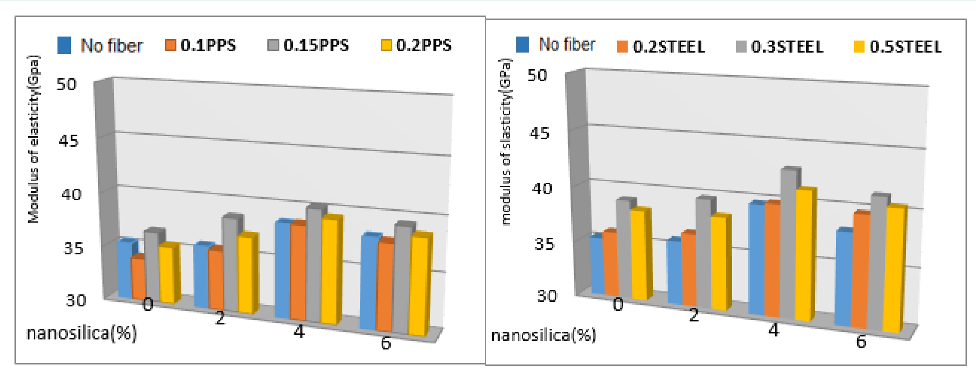

Figure 15: Flexural strength curve of concrete containing nano-SiO2 and fibers PPS.

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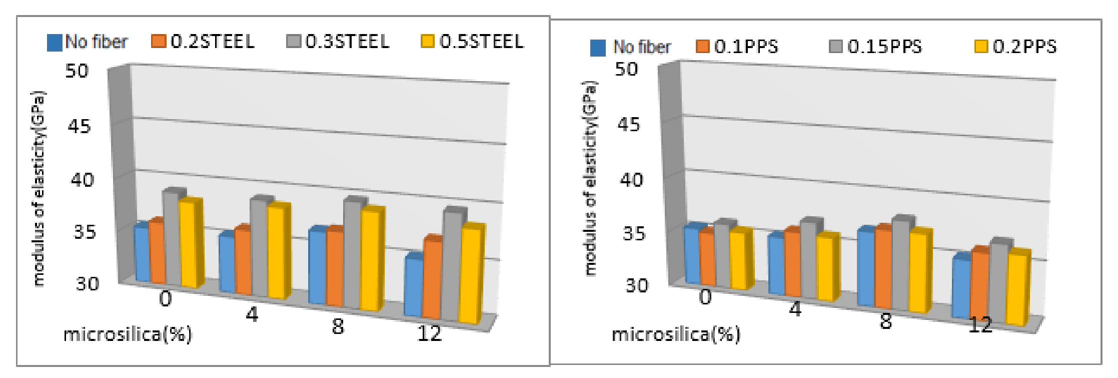

Figure 16: The flexural strength curve of concrete containing Micro-silica and PPS.

Moreover, in Figures 17 & 18, by increasing the percentage of Nano-silica from 2% to 6%; and Micro-silica from 4% to 12%, the flexural strength of sample without fiber, have increased up to 4% for Nano-silica and 8% for Micro-silica. However, afterwards it almost remains constant. This process indicates that 4% of Nano-Silica and 8% of Micro-Silica are also the optimum amount for reaching the maximum flexural strength. By studying these curves, it becomes obvious that by increasing the percentage of Micro and Nano silica (fiber content), the increasing trend of the flexural strength is enhanced, for example in the samples with metal fibers and PPS, by increasing Nano Silicon to 4%, the flexural strength increases 17% and 15%, respectively in comparison with the instance samples. The results of flexural strength test indicate an increased adhesion in the contact areas of concrete, due to the filler and posology properties of Nano-Silica.

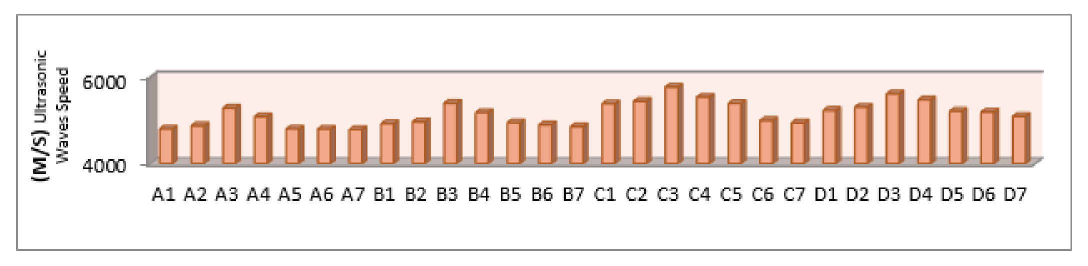

Figure 17: The flexural strength curve of concrete containing Micro-silica and PPS.

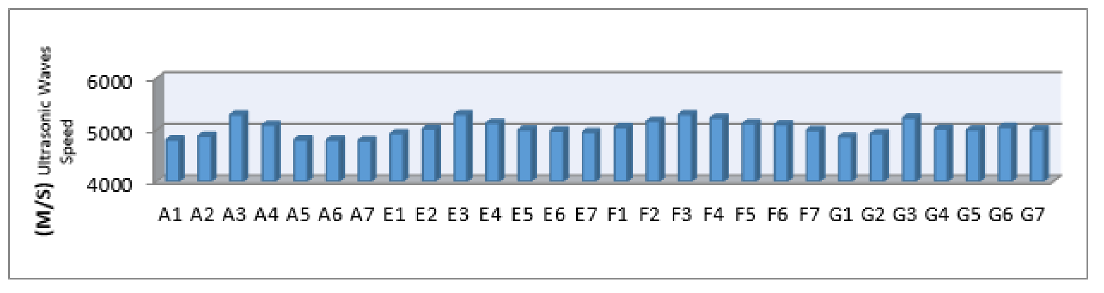

Figure 18: Results of ultrasonic wave velocity testing of mixtures containing Micro-silica.

Results of the Modulus of Elasticity Test

According to the results of Figures 19, it is clear that PPS fibers have very slight effect on the Modulus of Elasticity of HSC-SCC. Whereas, steel fibers are more effective on the Modulus of Elasticity of HSC-SCC, compared to PPS fibers. As seen in the curves, the Modulus of Elasticity is more sensitive to the changes in the percentage of Nano Silica rather than the percentage of fibers. For instance, by increasing the percentage of Nano-Silica up to the optimal percentage (4%), modulus of elasticity was increased in all of the samples.

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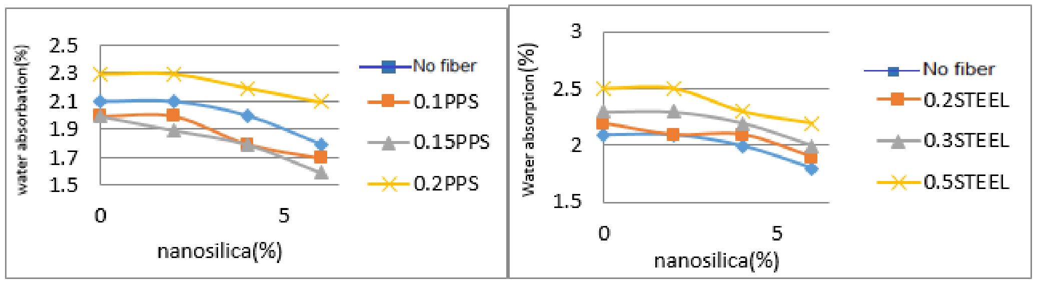

Figure 19: Water absorption diagram of concrete containing Nano-SiO2 and metal fibers.

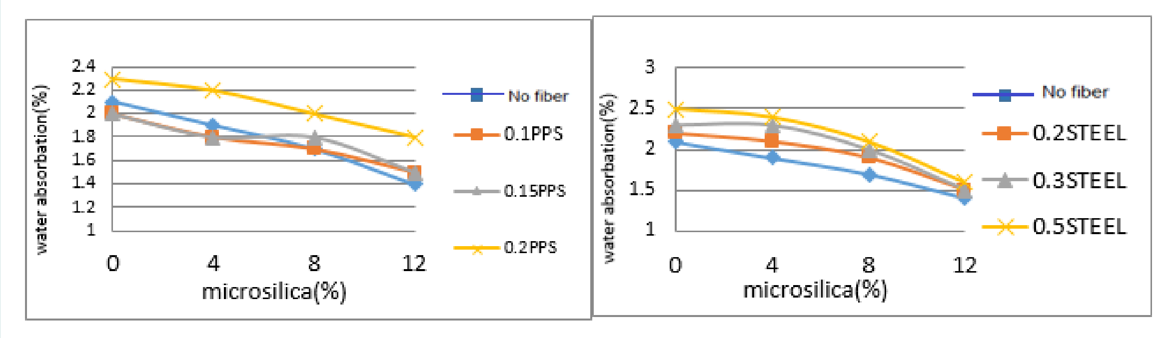

Figure 20: Water absorption diagram of concrete containing Micro-silica and metal fibers.

Results of Ultrasonic Wave Speed Test

The results of the pulse velocity test are presented in Figures 20. The speed of ultrasonic waves is increased by increasing the steel fibers ratio in samples with certain percentages of Micro and Nano Silica. However, by increasing PPS fibers the speed of ultrasonic waves is decreased. Moreover, increasing the Micro and Nano Silica ratio also increased the velocity of ultrasonic waves in the concrete. It seems that increasing this ratio in concrete leads to an increase in the density of the cement past. Cement paste has a lower ability to transmit waves than concrete aggregates. Therefore, the reduction of pores and microcracks in this section of the concrete increases the velocity of the waves. Comparison of the results between samples containing Micro and Nano-Silica shows that ultrasonic transfer velocity in the samples containing Nano-Silica is more than samples with Micro-silica. The reason for this difference is the reduction of micro cavities due to usage of Nano-Silica. Generally, the velocity of the waves in the ultrasonic velocity test is increased by increasing the density of environment.

Results of Water Absorption Test

In the A series mixing plants (without fibers and polystyrene), the absorption of water is 2.9%Vol. The effect of fibers on water absorption is less than Micro and Nano Silica. By increasing the amount of Micro and Nano Silica, the absorption of water decreases rapidly. It is clear that water absorption has a direct relationship with the cavities, in which the water absorption decreases by decreasing the cavities due to usage of Micro and Nano Silica. The results of permeability and porosity are shown in Figure 19.

Conclusions

Micro and Nano silica has chemical reaction with calcium hydroxide through the hydration process. The chemical reaction with calcium hydroxide reduces its amount and leads to the production of a C-S-H gel, which causes the compressive strength and water absorption to improve (increase) by increasing Micro and Nano silica. The study of the behavior of high-strength self-compacting concrete in two fresh and hardened states with different fibers and the improvement of the cement matrix of the mentioned mixture using micro-silica and nano-silica is the most important aspect of this research.

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