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Experimental Study of Effects of Fly Ash On the Mechanical Properties of Hybrid Fiber Reinforced Cementitious Composite

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ABSTRACT: Fibers are increasingly used for enhancement of the tensile strength of conventional concrete. Using fiber cementitious composite as well as microfiber and PVA fibers can be considered to improve the mechanical property of self-compacting concretes. This study considers the mechanical properties of high-performance Hybrid fiber reinforced cementitious composite specimens, which are reinforced by micro steel fibers, PVA, and a combination of them. In order to achieve the study goals, 10 mixture ratios were considered. All mixtures underwent compressive, tensile, and flexural strength tests as well as ultrasonic pulse velocity tests. The compressive strength, tensile, and flexural strength tests were performed on cubes (100x100x100mm), cylindrical (100x200mm) and prismatic beams (320x80x60mm), respectively. Also, ultrasonic pulse velocity testing was carried out on cubic (100x100x100mm) specimens. Results of these tests exhibit high variability and vary considerably for mixtures containing different fiber contents. Micro-steel fibers have a great effect on the mechanical strength of the specimens compared to PVA fibers. The specimens with a high percentage of micro-steel fibers showed higher resistance to the first flexural crack, failure, and final energy absorption compared to those with a high percentage of PVA.. In addition, by adding a pozzolanic material like fly ash, the 28-day resistance of all the mechanical properties of the specimens were reduced.

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1. INTRODUCTION

Today, concrete is one of the most widely applied construction materials in the world. Its versatility, the availability of its constituent materials, atmospheric agents, and fire resistance, shape-able mixtures, high compressive strength, and relative economy in meeting a wide range of needs has made it a very competitive building material with high public acceptance [1-5]. High-strength concrete (high-performance) is typically recognized as concrete having with a 28-day cylinder compressive strength greater than 6000 psi or 42 MPa [6]. The self-compacting concrete was first developed in Japan in 1988 to achieve durable concrete structures by improving quality in the construction process and early studies about the self – compacting concrete were conducted by Ozawa in 1989 and Okamura in 1993 at the University of Tokyo [7-8]. Self-compacting concrete is a special type of concrete which can be placed and consolidated under its own weight without any vibration effort due to its excellent deformability, and which at the same time is cohesive enough to be handled without segregation or bleeding. On the other hand, the use of different fibers can increase the resistance of concrete to dynamic loading such as the impact loading caused by impact effects [7]. Engineered cementitious composite (ECC) is a kind of high-performance fiber-reinforced composite (HPFRC), which is known for its superior flexural behavior , durability and tight crack width due to the fibers bridging effect [8]. Typically, ECC shows relatively high strain capacity between 3-7% compared to 0.01% in conventional concrete. Therefore, ECC could be applied as ductile material and tailored in many fields [9-13]. Using a small volume fraction of fibers (~ 2%), ECC has a variety of unique properties, including tensile properties superior to other fiber-reinforced composites, ease of processing on par with conventional cement, tight crack width, and a lack of anisotropically weak planes [14]. These properties are largely due to the interaction between the fibers and cementing matrix, which can be custom-tailored through micromechanics design. Essentially, the fibers create many microcracks with a very specific range , rather than a few very large cracks. This allows ECC to deform without catastrophic failure [15]. There are a number of different varieties of ECC. Lightweight ECC have been developed through the addition of air voids, glass bubbles, polymer spheres, and/or lightweight aggregate. Compared to other lightweight concretes, lightweight ECC has superior ductility. Applications include floating homes, barges, and canoes[16]. Playable ECC, which can be pneumatically sprayed from a hose, have been developed by using various superplasticizing agents and viscosity-reducing admixtures. Compared to other sprayable

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Table 1. Chemical composition and physical properties of Portland cement and Fly ash

Composition	Cement (%)	Fly Ash (%)
SiO_2	21.1	56.95
Al_2O_3	4.37	25.76
Fe_2O_3	3.88	6.5
MgO	1.56	2.5
K_2O	0.52	0.14
Na_2O	0.39	0.14
CaO	63.33	10 to 4
C_3S	51	--
C_2S	22.7	--
C3A	5.1	--
C_4AF	11.9	--
Physical properties		
Specific gravity	3.1	2.43
Specific surface ($\frac{Cm^2}{gr}$)	3000	--

Table 2. Mechanical properties of fibers

Type	Length (mm)	Diameter (mm)	L/D	Yielding stress (MPa)	Density (Kg/m^3)
Micro steel	12-30	0.2	150-60	240	7850
PVA	6-12	0.04	-	160-800	1300

fiber-reinforced composites, sprayable ECC has enhanced pumpability in addition to its unique mechanical properties. Sprayable ECC has been used for retrofitting/repair work and tunnel/sewer linings [17]. An extrudable ECC for use in the extrusion of pipes was first developed in 1998. Extruded ECC pipes have both higher load capacity and higher deformability than any other extruded fiber-reinforced composite pipes [18]. In this research considers the mechanical and durability properties of high-performance Hybrid fiber reinforced cementitious composite specimens, which are reinforced by micro steel fibers, PVA, and a combination of them. In order to achieve the study goals, 10 mixture ratios were considered. Also on this 10mix design, compressive strength test (30 cubic 100x100x100mm specimens), flexural strength test (30 prismatic specimens), splitting tensile strength (30 cylindrical 100x200 specimens), ultrasonic pulse velocity test (30 cubic 100x100x100mm specimens), Water absorption test (30 specimens) and capillary test (30 cubic 100x100x100mm specimens) were carried out on 180 concrete specimens. The mix design was chosen in a way that effects of steel fibers and PVA fibers on the mechanical and durability of specimen are simultaneously considered. Results of these tests exhibit high variability and vary considerably for mixtures containing different fiber contents. Micro-steel fibers have a great effect on the mechanical strength of the specimens compared to PVA fibers. The specimens with a high percentage of micro-steel fibers showed higher resistance to the first flexural crack, failure, and final energy absorption compared to those with a high percentage of PVA.. In addition, by adding a pozzolanic material like fly ash, the 28-day resistance of all the mechanical properties of the specimens were reduced.

2. MATERIALS

The aggregates used in the manufacture of cementitious composite specimens of this study were natural grains passing through a sieve of 8 (cavities of 2.36 mm diameter). The cement used in this research was type 2 cement produced in Shahrood Cement Factory (see Table 1) and water used for the mixture was refined drinkable water. Also, a low percentage of cement was replaced by low-calcium fly ash of South Africa (type F -see Table 1). Sika Plastiment® PR-400 concrete super plasticizer was used to create cementitious composite properties and to optimize the performance of cementitious composite. Also, two types of micro steel fibers with a diameter of 0.2 mm and polyvinyl alcohol (PVA) fibers with a diameter of 0.04 mm were used for making specimens. The characteristics and the image of these fibers are shown in Table 2 and Fig. 1, respectively.

3. CONCRETE MIX DESIGNS AND MAKING SPECIMENS

The cement composite used in this study is fiber cementitious composite. In Fig. 2, the steps of making this composite is shown. To make different compressive, tensile and flexural strengths in composite specimens, ten mix designs containing 0, 0.5, 1, 1.5 percent micro steel fibers, PVA and a combination of them were used. Three concrete cubic specimens were made with dimensions of 100x100x100 mm for testing compressive strength, three cylinders were made with a dimension of 200x100 mm for testing tensile strength, and three specimens of the prismatic beam were made with dimensions of 60 × 80 × 320 mm for testing flexural strengths. The characteristics of the mix designs are presented in Table

a) b)

Fig 1. Used Fibers a) PVA Fiber; b) micro Steel Fiber

Fig 2. Production steps and molding of specimens

Table 3. Mixture proportions of cementitious composite (kg/m³)

Specimen designation	W/C	Water $(\frac{Kg}{m^3})$	Cement $(\frac{Kg}{m^3})$	$(\frac{Kg}{m^3})$ Aggregates	Fiber(%)		Fly Ash(%)	SP
					Micro Steel	PVA		
Specimen 1(FA0MS0PVA0)	0.35	402.5	1150	1150	0	0	0	3.68
Specimen 2(FA0MS0PVA1.5)	0.35	402.5	1150	1150	0	1.5	0	3.68
Specimen 3(FA0MS0.5PVA1)	0.35	402.5	1150	1150	0.5	1	0	3.68
Specimen 4(FA0MS1PVA0.5)	0.35	402.5	1150	1150	1	0.5	0	3.68
Specimen 5(FA0MS1.5PVA0)	0.35	402.5	1150	1150	1.5	0	0	3.68
Specimen 6(FA5MS0PVA0)	0.35	402.5	1150	1150	0	0	5	3.68
Specimen 7(FA5MS0PVA1.5)	0.35	402.5	1150	1150	0	1.5	5	3.68
Specimen 8(FA5MS0.5PVA1)	0.35	402.5	1150	1150	0.5	1	5	3.68
Specimen9(FA5MS1PVA0.5)	0.35	402.5	1150	1150	1	0.5	5	3.68
Specimen 10(FA5MS1.5PVA0)	0.35	402.5	1150	1150	1.5	0	5	3.68

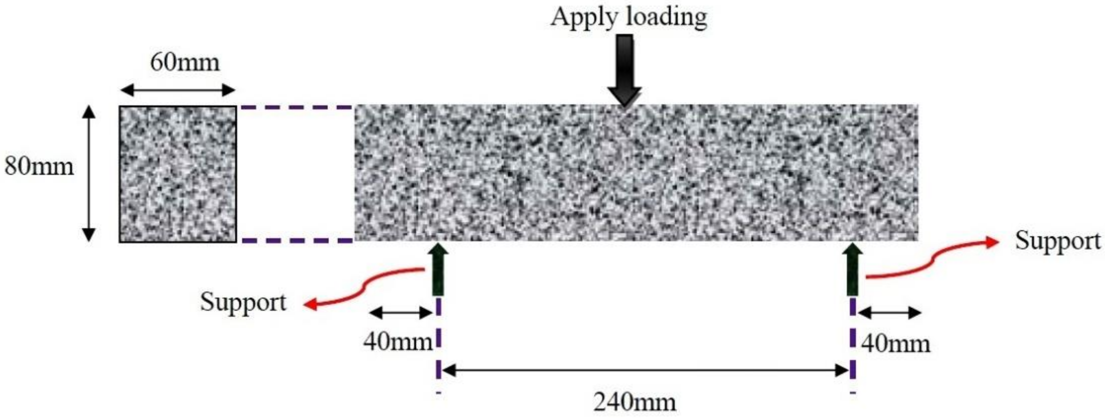


Fig 3. Method of the three-point flexural strength test

3. In the production process of the specimens first, the sand, cement and fly ash (if included) are combined and then 90% of the water was added to the mixer. The super-plasticizer was combined with remaining 10% of the water and added to the mixer. To avoid the problem of fiber balling, they were added to the cementitious composite mixture at the last moments.

4. Test Method

4-1- Compressive and Tensile Strength Test

Compressive strength test of cementitious composites was carried out using a 200 ton pressure jack and according to the ASTM C39 [19] for the cubic specimens with dimensions of 100x100x100 mm, also tensile test was conducted as an indirect tensile test (Brazilian) according to the ASTM C496 [20] in the cylindrical specimens with dimensions of 100x200.

4-2- Flexural Strength Test

The specimens were subjected to three-point bend loading (ASTM C293-79) [21]. For this purpose and according to the mentioned standard, a three-point bending test was performed on flexural specimens. The dimension of the flexural test specimen was 320 × 80 × 60 mm (length, thickness, width).

Table 4. Compressive strength test result

Specimen	Compressive Strength(MPa)				Standard deviation (MPa)	Coefficient of variation (%)
	Specimen1	Specimen2	Specimen3	Average		
Specimen 1(FA0MS0PVA0)	43.00	42.50	42.10	42.53	0.5	1.1
Specimen 2(FA0MS0PVA1.5)	38.00	38.10	39.80	38.60	1.0	2.5
Specimen 3(FA0MS0.5PVA1)	44.40	45.00	43.90	44.40	0.9	1.9
Specimen 4(FA0MS1PVA0.5)	47.50	48.60	49.00	48.37	0.8	1.6
Specimen 5(FA0MS1.5PVA0)	51.10	49.40	48.10	49.47	0.7	1.3
Specimen 6(FA5MS0PVA0)	40.30	42.10	42.10	41.50	1.0	2.5
Specimen 7(FA5MS0PVA1.5)	37.00	36.40	35.00	36.23	0.8	2.1
Specimen 8(FA5MS0.5PVA1)	44.70	44.00	42.10	43.83	0.9	2.0
Specimen9(FA5MS1PVA0.5)	46.50	47.00	48.00	47.17	0.8	1.6
Specimen 10(FA5MS1.5PVA0)	48.30	47.50	47.10	47.63	0.6	1.3


MS0-PVA0 MS0-PVA1.5 MS0.5-PVA1 MS1-PVA0.5 MS1.5-PVA0

Fig 4. Failure mode of compressive specimen

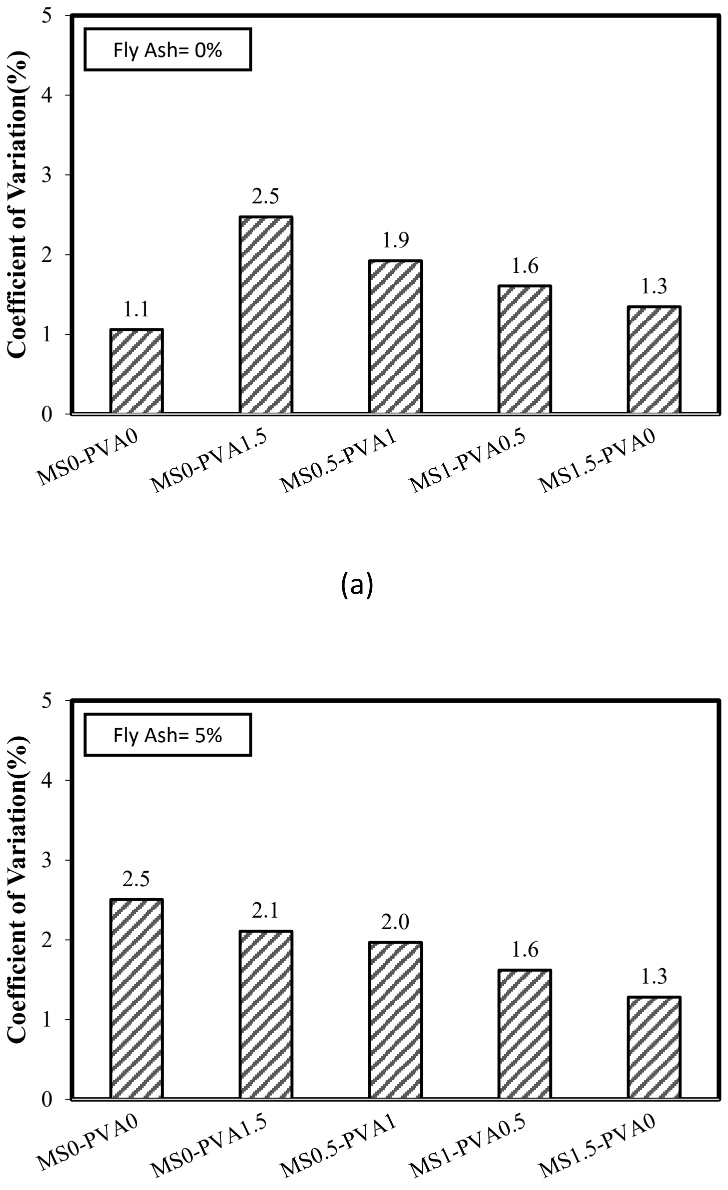
Fig. 3 illustrates the test method.

5. RESULTS AND DISCUSSION

5-1- Results of Compressive Strength Test

The results of the compressive strength test of cube specimens according to ASTM C39 [19] are shown in Table 4. The results of the experiments show that adding 1.5% PVA fiber (MS0-PVA1.5) reduces compressive strength by 10%, indicating a negative effect of the high percentage of this fiber on the compressive strength. Adding 1.5% of the micro-steel fiber (MS1.5-PVA0) increased the resistance by 16% compared to the non-fibrous specimen. Using fibers, as a mixture of 0.5% micro-fiber and 1% PVA fibers (MS0.5-PVA1) resulted in a 4% increase in compressive strength compared to the reference specimen. Also according to the results, using 1% micro-steel fiber and 0.5% PVA fiber (MS1-PVA0.5), the compressive strength increased by 14% compared to the non-fibrous specimen. On the other hand, the addition of micro-steel and PVA fibers increased the coherence of these specimens compared to non-fibrous specimens. The fibrous cube specimens retained their integrity after failure. According to Fig. 4, adding fibers to concrete specimens changes the failure mechanism and prevents the brittle failure of specimens. By adding fly ash to the specimens, the compressive strength decreases. In the group FA0-MS0-PVA0, which has no fly ash, the compressive strength of 43 MPa was measured. The compressive strength of the FA0-MS0-PVA0 group is doubled compared to the group with 5% more fly ash. In all groups, the use of fly ash decreased the compressive strength of the specimens.

As shown in Table 4, the dispersion of compression strength data is increased by adding fibers to the specimens. By adding fly ash to the compressive specimens, the coefficient of variation indicating the dispersion between the data did not change remarkably . In other words, adding fibers increases the dispersion of compressive strength data. On the other hand, by increasing the volume of PVA fibers, the dispersion of data is significantly increased. In Fig. 5, a comparison is made between the dispersion of compressive strength data for



(a)

(b)

Fig. 5. Coefficient of variation for compressive strength

different groups.

5-2- Results of Tensile Strength Test

The results of the indirect tensile test on composite specimens according to the ASTM C496 [20] are shown in Table 5. The average tensile strength of a non-fibrous and non-fly ash specimen is 2.95 Mpa. In the FA0 category, adding 1.5% of these fibers (FA0-MS1.5-PVA0) increased the tensile strength by 108%. Also, adding 1.5% PVA (FA0-MS0-PVA1.5) increased the tensile strength of the specimens by 38%. According to the results of the indirect tensile test on cylindrical specimens, the effect of steel fibers is far greater than that of PVA. FA0-MS0.5-PVA1 and FA0-MS1-PVA0.5 groups, which also had a 55 and 69 percent increase in tensile strength compared to non-fibrous specimens. In the groups with 5% fly ash, FA5-MS0-PVA1.5, FA5-MS0.5-PVA1, FA5-MS1-PVA0.5 and FA5-MS1.5-PVA0, an increase of tensile strength of 35, 60, 70 and 113 percent was observed for non-fibrous specimens, respectively. It is observed that by adding 5% fly ash to FA0-MS0-PVA0 group, the tensile strength decreases by 5% compared to FA50-MS0-PVA0 group. Also, in groups with 1.5% PVA fibers, a 5% increase in fly ash led to a 6% decrease in tensile strength. In other groups, tensile strength is observed to decrease as the percentage of fly ash increases. In other words, fly ash decreases the tensile strength of the specimens. In Fig. 6, the tensile strength curves of the composite specimens are plotted versus compressive strength considering the percentage of fly ash for the two groups. As shown in the figure, the curves of the two groups coincide

Table 5. Splitting tensile strength test results

Specimen	Splitting tensile strength (MPa)				Standard deviation (MPa)	Coefficient of variation (%)
	Specimen1	Specimen1	Specimen1	Average		
Specimen 1(FA0-MS0-PVA0)	2.99	2.95	2.91	2.95	0.04	1.36
Specimen 2(FA0-MS0-PVA1.5)	3.98	4.07	4.13	4.06	0.08	1.88
Specimen 3 (FA0MS0.5PVA1)	4.46	4.55	4.68	4.56	0.11	2.45
Specimen 4 (FA0MS1PVA0.5)	4.89	4.91	5.15	4.98	0.14	2.91
Specimen 5 (FA0MS1.5PVA0)	5.92	6.30	6.21	6.14	0.20	3.24
Specimen 6 (FA5MS0PVA0)	2.89	2.78	2.81	2.82	0.06	2.01
Specimen 7 (FA5MS0PVA1.5)	3.79	3.92	3.77	3.82	0.08	2.13
Specimen 8 (FA5MS0.5PVA1)	4.41	4.61	4.49	4.50	0.10	2.24
Specimen 9 (FA5MS1PVA0.5)	4.66	4.81	4.91	4.79	0.13	2.62
Specimen 10 (FA5MS1.5PVA0)	6.31	5.92	5.81	6.01	0.26	4.37

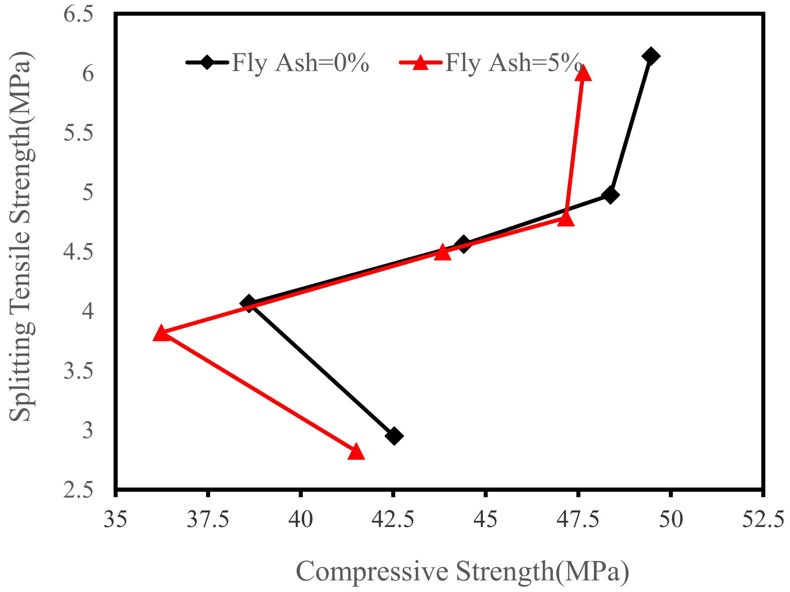


Fig 6. The relation between compressive strength and tensile strength

almost with each other. The group with 5% of fly ash has less compressive and tensile strengths than a group without fly ash.

As shown in Fig. 5, by increasing the percentage of steel fibers and reducing the percentage of PVA fibers, the dispersion of compression strength data increases. In other words, PVA fibers have less effect on the dispersion of tensile strength data. As shown in Fig. 7, the coefficient of variation of tensile strength increases with increasing the percentage of steel fibers in the composition and assuming that the amount of fly ash is constant. The maximum coefficient of variation in the group without fly ash is 3.24%. The coefficient of variation of tensile strength in the specimen FA0-MS1.5-PVA0 was 11, 32, 72 and 138 percent higher than the groups FA0-MS1-PVA0.5, FA0-MS0.5-PVA1, FA0-MS0-PVA1.5 and FA0-MS0-PVA0. The maximum coefficient of variation in the group with 5% fly ash is 4.37, which is 67, 95, 105 and 117% higher than the groups of FA5-MS1-PVA0.5, FA5-MS0.5-PVA1, FA5-MS0-PVA1.5 and FA5-MS0-PVA0.

5-2-1- Comparison of tensile strength results with other Codes and research studies

Table 6 presents a comparison between the results of the tensile test on 10 mixtures with the values obtained from other researchers' relationships. As shown in Table 6, the tensile strengths of the Brazilian tensile test in the non-fibrous groups (as compared to the fiber groups) are more consistent with the regulations of the Codes and the relationships obtained by other researchers. By increasing the fiber percentage, the difference between the experimental and

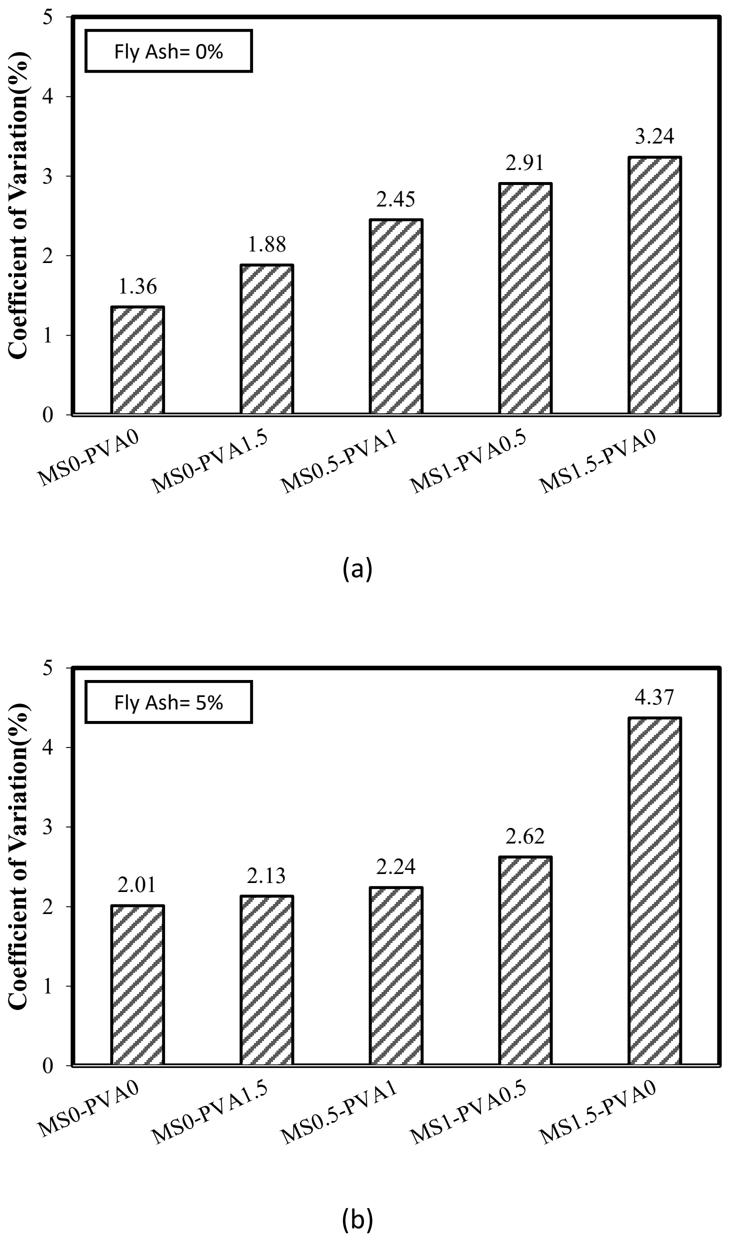


Fig 7. The tensile strength variation coefficient of cylindrical specimens

Table 6. Splitting tensile strength of cylindrical specimens

Specimen No.	Compressive strength (MPa)	Splitting strength(MPa)							
		Experimental	ACI Committee 318 (2014)	CEB-FIB (1991)	Carino and Lew (1982)	Oluokum et al (1991)	Artoglu et al (2006)	Lavanya and jegan (2015)	Gardner (1990)
			$0.56f_c'^{0.5}$	$0.3f_c'^{0.66}$	$0.272f_c'^{0.71}$	$0.294f_c'^{0.69}$	$0.387f_c'^{0.63}$	$0.249f_c'^{0.772}$	$\mathbf{0.33f_c'^{0.66}}$
1	35.51	2.95	3.57	3.92	3.67	3.45	3.43	3.16	3.34
2	31.76	4.06	3.31	3.59	3.42	3.20	3.17	2.94	3.16
3	37.32	4.56	3.69	4.07	3.78	3.57	3.55	3.27	3.42
4	41.06	4.98	3.93	4.38	4.02	3.82	3.80	3.48	3.59
5	42.17	6.14	4.00	4.47	4.09	3.89	3.88	3.55	3.64
6	34.52	2.82	3.50	3.83	3.60	3.39	3.36	3.11	3.29
7	29.41	3.82	3.15	3.39	3.26	3.03	3.00	2.79	3.04
8	36.52	4.50	3.64	4.00	3.73	3.52	3.50	3.22	3.38
9	39.92	4.79	3.86	4.29	3.95	3.74	3.73	3.42	3.54
10	40.37	6.01	3.89	4.33	3.98	3.77	3.76	3.44	3.56

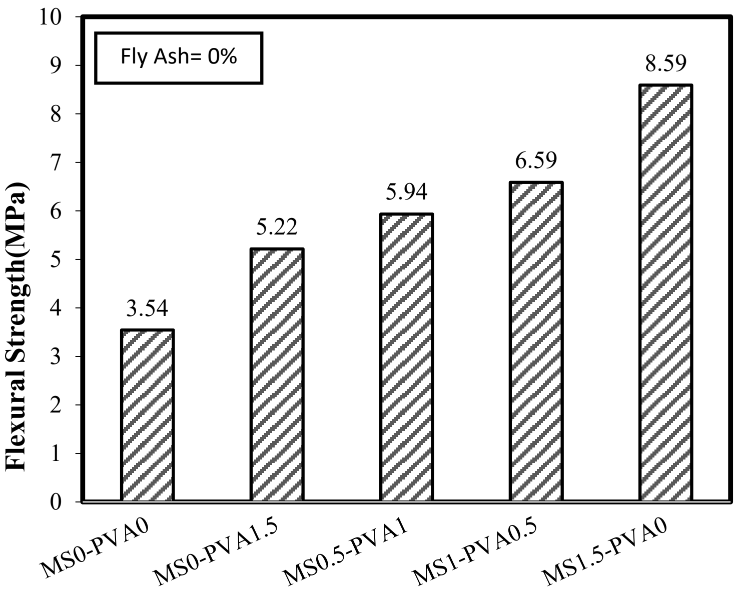


Fig 8. Results of flexural strength test on specimens

computational relationships increases. The difference between the Code results and the obtained relationships increases with increasing the percentage of steel fibers. In other words, by increasing the percentage of micro-steel fibers and reducing the percentage of PVA fibers, the difference between theoretical and laboratory relations increases.

5-3- Flexural strength test results

In this research, the flexural strength of composite specimens was calculated according to ASTM C293 standard test method. A flexural strength test was carried out on 10 different mix designs for beams containing microfiber, PVA and a combination of them with different percentages of fly ash. Also, in the column diagram of Fig. 8, the flexural strength values obtained from the laboratory results are shown. As shown in Fig. 8, the obtained maximum flexural strength is related to the group of FA0-MS1.5-PVA0. The flexural strength of the FA0-MS1.5-PVA0 group was 8.59 MPa, which is respectively, 143, 65, 45 and 30 percent more than groups of FA0-MS0-PVA0, FA0-MS0-PVA1.5, FA0-MS0.5-PVA1 and FA0-MS1-PVA0.5. This trend continues in the next group with 5% fly ash. On the other hand, due to the effect of the fiber on the flexural strength, with increasing the fiber percentage, the flexural strength of the specimens increases. According to the trend in compressive and tensile specimens, adding fly ash to the composition reduced the flexural strength of the specimens.

5-3-1- Flexural Load-displacement behavior

In Fig. 9, the load-displacement curve for the mid-span of the flexural specimens is presented. As shown in Fig. 9, the behavior of the curve changes with increasing of fiber percentages. According to the figure, the presence of steel fibers in the composition, as compared to PVA fibers, has increased the capacity of changing the displacement capacity of specimens. The initial gradient of the specimens is approximately similar.

Before 2006, researchers calculated the flexural toughness according to the ASTM C1018 [22] standard. According to this standard, displacement corresponding to the formation of the first cracks should be determined. Because of the difficulties in exact determining of the parameter, this standard became obsolete after 2006. In recent years, ASTM C1609 [23] standard is used instead of the standard ASTM C1018 to determine the flexural toughness. In this research, both ASTM C1018 and ASTM C1609 standards have been used to determine the flexural toughness. Results are analyzed using both methods. In order to determine the flexural toughness according to the ASTM C1018 standard, toughness indices including I_5, I_{10}, I_{15}, I_{20} are determined based on the characteristic points specified on the load-displacement curve shown in Fig. 10 and according to the equation (1).

$$I_5 = S_{OACD} / S_{OAB} \tag{1}$$

$$I_{10} = S_{OAEF} / S_{OAB}$$

$$I_{10} = S_{OAGH} / S_{OAB}$$

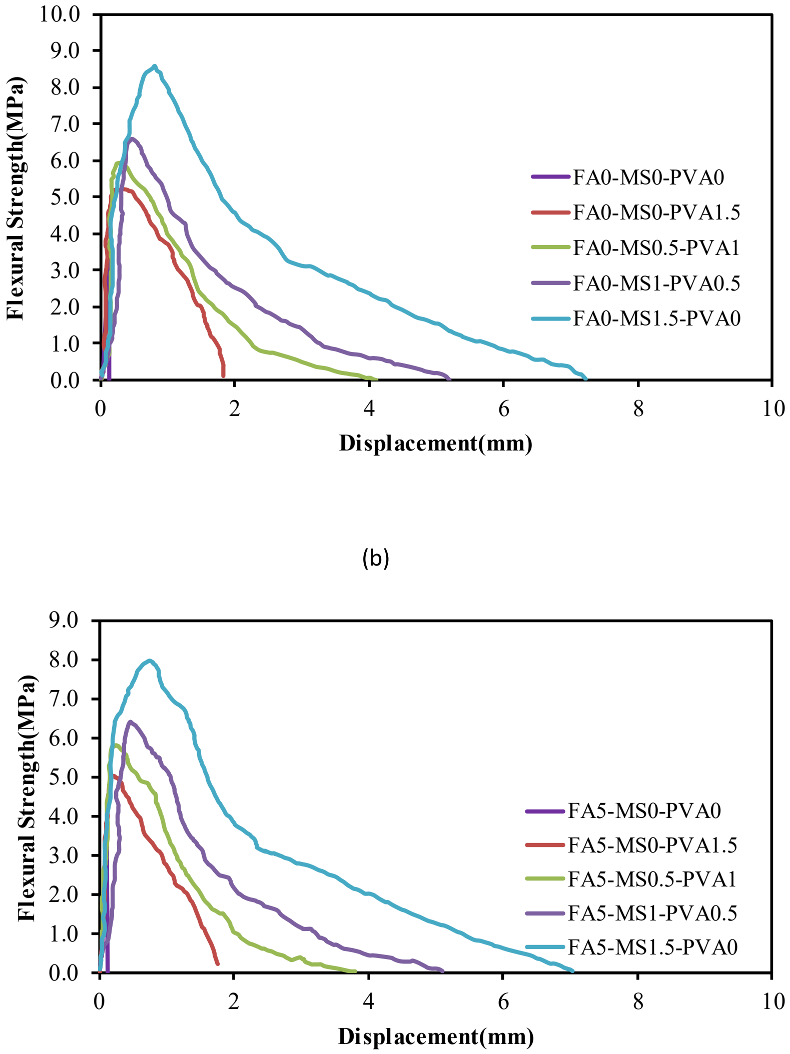
$$I_{15} = S_{OAMN} / S_{OAB}$$

In equation (1):

S_{OAB} → the area under a load-displacement curve in displacement corresponding to the first crack

S_{OACD} → the area under a load-displacement curve in displacement which is 3 times more than displacement corresponding to the first crack

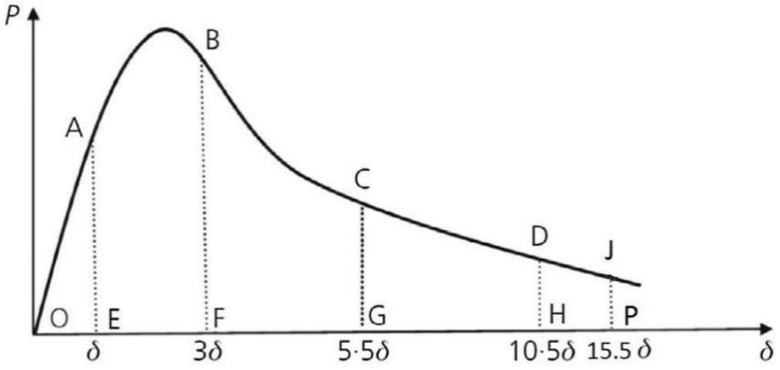
S_{OAEF} → the area under a load-displacement curve in



(b)

(a)

Fig 9. Load-displacement curve of flexural specimens



$$I_5 = \frac{Area(OABF)}{Area(OAE)} \quad , I_{10} = \frac{Area(OACG)}{Area(OAE)}$$

$$I_{15} = \frac{Area(OADH)}{Area(OAE)} \quad , I_{20} = \frac{Area(OAJP)}{Area(OAE)}$$

Fig 10. Definition of flexural toughness indices based on ACTM C1018

Table 7. Calculation of flexural durability parameters according to ASTM C1609[23] and ASTM C1018[22] standards

Specimen No	Specimen	According ASTM C1609			According ASTM C1018		
		Modulus of Rupture(MPa)	T^D_{150}(Kj)	$R^D_{T,150}$	I_5	I_{10}	I_{15}
1	FA0-MS0-PVA0	3.54	0.18	0.02	--	--	--
2	FA0-MS0-PVA1.5	5.22	6.27	0.47	1.64	6.62	8.71
3	FA0-MS0.5-PVA1	5.94	6.78	0.45	1.61	7.55	9.46
4	FA0-MS1-PVA0.5	6.59	7.26	0.43	1.47	6.28	7.47
5	FA0-MS1.5-PVA0	8.59	10.92	0.50	1.42	4.41	5.07
6	FA5-MS0-PVA0	3.26	0.14	0.02	--	--	--
7	FA5-MS0-PVA1.5	5.02	5.19	0.40	1.66	7.07	8.84
8	FA5-MS0.5-PVA1	5.81	6.55	0.44	1.70	7.30	9.74
9	FA5-MS1-PVA0.5	6.41	7.29	0.44	1.44	6.46	7.72
10	FA5-MS1.5-PVA0	7.97	10.94	0.54	1.41	4.29	5.16

Table 8. Comparison of the experimental results and the relations in the code of practice for flexural strength

Specimen No	Specimen	Flexural Strength (MPa)					
		Experimental	ACI Committee 318, 2002	ACI Committee 318, 2005	ACI Committee 363	European code (CEN, 2002)	Indian code (IS, 2000)
		fr_{exp}	$0.62\sqrt{f_c'}$	$0.517\sqrt{f_c'}$	$0.94\sqrt{f_c'}$	$0.342(f_c')^{\frac{2}{3}}$	$0.626\sqrt{f_c'}$
1	FA0-MS0-PVA0	3.54	4.04	3.37	6.13	4.17	4.08
2	FA0-MS0-PVA1.5	5.22	3.85	3.21	5.84	3.91	3.89
3	FA0-MS0.5-PVA1	5.94	4.13	3.45	6.27	4.29	4.17
4	FA0-MS1-PVA0.5	6.59	4.31	3.60	6.54	4.54	4.35
5	FA0-MS1.5-PVA0	8.59	4.36	3.64	6.62	4.61	4.41
6	FA5-MS0-PVA0	3.26	3.99	3.33	6.06	4.10	4.03
7	FA5-MS0-PVA1.5	5.02	3.73	3.11	5.65	3.74	3.76
8	FA5-MS0.5-PVA1	5.81	4.09	3.41	6.21	4.24	4.13
9	FA5-MS1-PVA0.5	6.41	4.26	3.55	6.46	4.46	4.30
10	FA5-MS1.5-PVA0	7.97	4.28	3.57	6.49	4.49	4.32

displacement which is 5.5 times more than displacement corresponding to the first crack

S_{OAGH} → the area under a load-displacement curve in displacement which is 10.5 times more than displacement corresponding to the first crack

S_{OAMN} → the area under a load-displacement curve in displacement which is 15.5 times more than displacement corresponding to the first crack

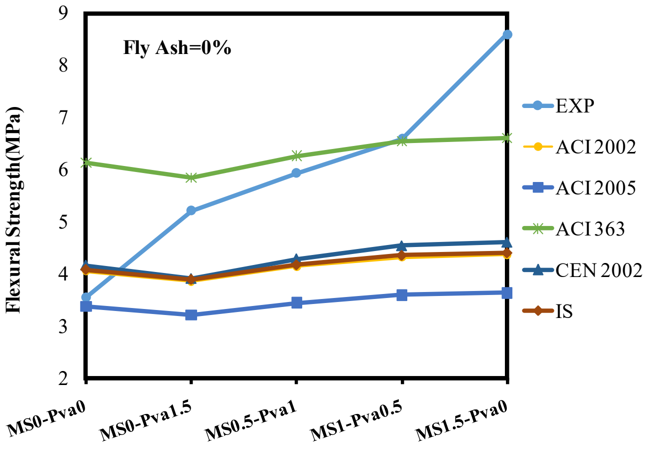
In order to compare the flexural strength of the specimens according to the ASTM C1609[23] standard, the flexural toughness is calculated as the surface below the load-displacement curve to the displacement of L/150, where L is the span length of loading in the slab and the flexural strength coefficient is calculated according to (2).

$$R^D_{T,150} = \frac{150T^D_{150}}{f_1\, b\, d^2} \qquad (2)$$

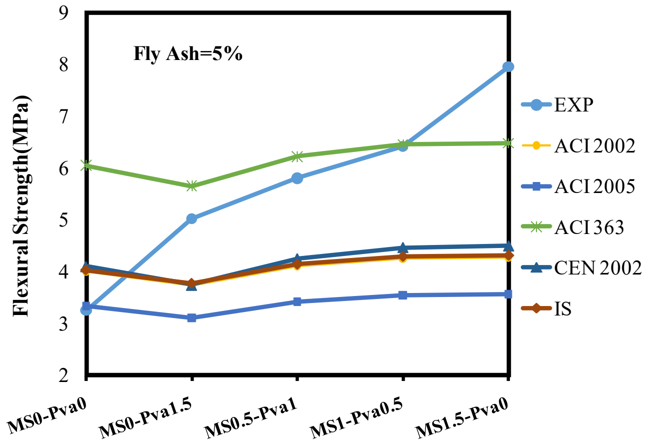
In the equation (2), $R^D_{T,150}$, the coefficient of flexural strength, T^D_{150}, the degree of flexural toughness up to the corresponding point L/150 in terms of Joule (J), f_1 is rupture modulus (stress corresponding to the first crack) in terms of MPa, and b and d are the width and height of the specimen in terms of mm, respectively. In the Table (7), the rupture module, flexural toughness of the specimens for the equivalent displacement (L/150) and the flexural strength coefficient are calculated and shown according to the ASTM C1609[23]. It can be seen that steel fibers can increase the rupture modulus of flexural specimens significantly. By increasing the fibers, the flexural strength of the specimen would increase because these fibers have high tensile strength and bridge on the cracks in the tensile region. However, the fly ash could not increase rupture module significantly. Table 7 shows the indices of toughness according to ASTM C1018[22] standard. The results also indicate that steel fibers can increase the toughness indices in this standard, which is considerably higher than specimens with fly ash .

5-3-2- Comparison of Experimental results with Codes

Table 8 illustrates a comparison between the data obtained from the test of flexural strength and the relationships in the Code of practice. As shown in Table 8, the flexural strength



a) Without Fly ash



b) Containing 5% Fly Ash

Fig 11. Comparison of the flexural strength obtained from experimental results and the code relations for specimens without fly ash

values obtained from the test for a reference specimen without fiber are not significantly different from the code values. On the other hand, with the increase of the steel fibers, the difference between laboratory values and code relationships increases dramatically. In the FA0-MS1.5-PVA0 group, the flexural strength is 8.59 mega-Pascal, which is 97, 136, 30, 86 and 95 percent higher than the values calculated by the code of practices ACI 318-2002, ACI 318-2005, ACI 363, CEN and IS. In fact, the use of fibers and the effect of fibers on flexural strength in the code of practice has not been taken into account. In Fig. 11, the results of Table 8 are presented as diagrams.

6. ULTRASONIC TEST RESULTS

Table 9 represents the results obtained by conducting the ultrasonic test. Also, Fig 12 shows how the test is conducted according to ASTM C597 [24]. According to the obtained results, the wave velocity has increased upon adding fiber to the specimens. The highest wave velocity is related to the FA5-MS1.5-PVA0 group. Wave velocities in specimens with 5% fly ash are higher than those without fly ash. The average wave velocity in specimens with 5% fly ash is 4288 m /s, which is about 2% higher than the average wave velocity in a group without fly ash. Also, adding steel fibers to the specimens was more effective in increasing the wave velocity. As shown in Fig 13, as the percentage of steel fibers increases, the wave velocity increases in ascending order. According to Fig. 13, by increasing the percentage of PVA fibers from 0 to 1.5%, the shear wave velocity would decrease.

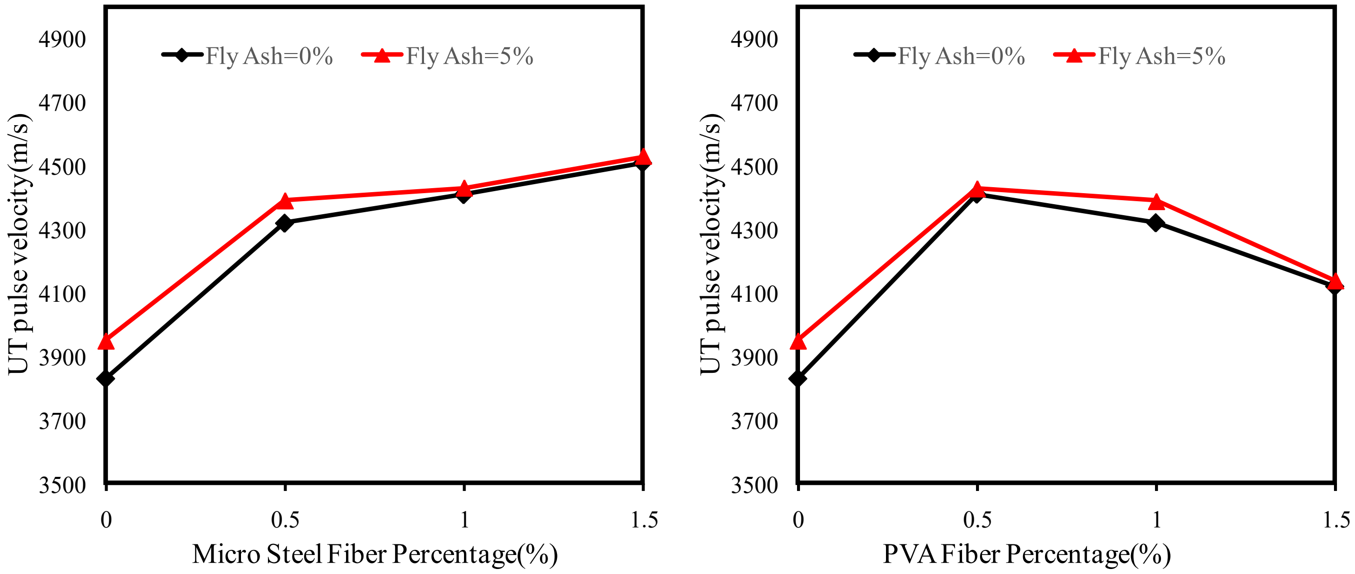
7. CONCLUSION

In this research, a comprehensive study was conducted on the mechanical properties of fiber cement composites. Cement composites have Micro Steel and PVA fibers both separately

Table 9. Ultrasonic pulse velocity test results

Specimen No	Specimen	UT pulse velocity(m/s)
1	FA0-MS0-PVA0	3830
2	FA0-MS0-PVA1.5	4120
3	FA0-MS0.5-PVA1	4320
4	FA0-MS1-PVA0.5	4410
5	FA0-MS1.5-PVA0	4510
6	FA5-MS0-PVA0	3950
7	FA5-MS0-PVA1.5	4140
8	FA5-MS0.5-PVA1	4390
9	FA5-MS1-PVA0.5	4430
10	FA5-MS1.5-PVA0	4530

Fig 12. Ultrasonic pulse velocity test instrument



(a) (b)

Fig 13. Ultrasonic pulse velocity versus fiber percentage

and in combination. A total of 10 different mixtures were designed as cement composite. The following results were obtained from different tests conducted on the specimens:

Adding PVA fibers alone did not have significant effect on the compressive strength of composites. The maximum increase of compressive strength by using micro steel fibers was 16% compared to non-fibrous specimen. The use of fibers higher than 1.5% reduced compressive strength. The reduction in compressive strength was higher in specimens with PVA fibers (compared to micro steel fibers).

According to the results obtained from the tensile test, it was observed that the micro-steel fibers can have a great effect on the tensile strength of the cement composite. Adding 1.5% of the micro-steel fiber to the composite increased the tensile strength by approximately 2.08. Using PVA fibers had much less influence on the tensile strength of the specimens compared to micro steel fibers. Adding 1.5% of PVA fibers increased the tensile strength by 37%.

Tensile strengths varied expansively among the laboratory steel fibers specimens with Code values. However, the difference was lower in specimens containing only PVA fibers. The reason for this difference is disregarding the effects of fiber in the Code relationships.

The results of bending test of the beams showed the high influence of the micro-steel fiber on the flexural strength. Adding 1.5% of the micro-steel fiber could increase the flexural strength by 143%. This increased resistance for 1.5% of PVA fibers was 47%. Also, the micro-steel and PVA fibers by stitching bending crack created in the beams resulted in a significant increase in ductility.

In all experiments, hybrid specimens had higher flexural strength and tensile strength (as compared to those with PVA fibers only). This trend for specimens with micro steel fibers was contrary to PVA fibers. Therefore, according to the results, it is clear that the micro-steel fibers have a much greater effect on the strength of the specimens (in hybrid specimens).

In all experiments it was determined that using fly ash has exerted a negative effect on the resistance of the specimens. By increasing the percentage of fly ash in the specimens, compressive, tensile and flexural strength of the specimens decreased.

According to the results of an ultrasonic test, it was determined that wave velocity in specimens with 5% fly ash is higher than those without fly ash. The average wave velocity in the specimens with 5% fly ash was 4288 m/s, which was about 2% higher than the average wave velocity in the group without fly ash.

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[24] ASTM C597, Standard Test Method for Pulse Velocity through Concrete.

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