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Research Article

Investigation of Flexural, Compressive Strength and Microstructure of Silica Fume Added Steel Fiber Concrete

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Abstract

Concrete is the most extensively used construction material today, and cement is used as the bonding agent in the concrete production. Use of silica fume in steel fiber concretes is suitable for high-strength and high-quality concrete production. In this study, tests were conducted using silica fume in steel fiber concretes by 0 %, 5 %, 10 % and 15 % via replacement with cement. CEM I 42.5 N cement and steel fiber were used in the concrete produced during the tests. Samples were selected from C 25 class in which water/cement ratio was 0.50 and produced by being subjected to vibration. Test samples were subjected to a flexural test from their midpoints and a compression test from the edges on prism samples produced at sizes of 100 mm x l00 mm x 500 mm. 7 day and 28 day flexural and compression strength tests of the concretes produced were measured. Besides, hydration products in concrete were observed with scanning electron microscope, energy dispersive spectrometry, and x-ray diffraction. As a result, it was determined that as the amount of silica fume increased, there was an increase in flexural and compressive strength.

Keywords: Concrete, silica fume, steel fiber, flexural and compressive strength, microstructure

Silis Dumanı Katkılı Çelik Lifli Betonun Eğilme, Basınç Dayanımı ve Mikro Yapısının İncelenmesi

Özet

Beton günümüzde en yaygın kullanılan yapı malzemesi olup, beton üretiminde bağlayıcı madde olarak çimento kullanılmaktadır. Çelik lifli betonlarda silis dumanının kullanılması yüksek dayanımlı ve kaliteli beton üretimi için uygundur. Bu çalışmada çelik lifli betonlarda silis dumanı kullanılarak %0, %5, %10 ve %15 oranlarında çimento ile ikame edilerek testler yapılmıştır. Testler sırasında üretilen betonda CEM I 42,5 N çimento ve çelik elyaf kullanıldı. Numuneler su/çimento oranı 0,50 olan C 25 sınıfından seçilmiş ve vibrasyona tabi tutularak üretilmiştir. Test numuneleri 100 mm x 100 mm x 500 mm ölçülerinde üretilen prizma numuneler üzerinde orta noktalarından eğilme testine, kenarlarından ise basma testine tabi tutuldu. Üretilen betonların 7 günlük ve 28 günlük eğilme ve basınç dayanım testleri ölçüldü. Ayrıca betondaki hidratasyon ürünleri taramalı elektron mikroskobu, enerji dağılımlı spektrometri ve x-ışını kırınımı ile gözlemlendi. Sonuç olarak silis dumanı miktarı arttıkça eğilme ve basınç dayanımında artış olduğu belirlendi.

Anahtar Kelimeler: Beton, silis dumanı, çelik elyaf, eğilme ve basınç dayanımı, mikro yapı

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1. Introduction

Turkey is among the rapidly developing countries in terms of level of development. One of the typical characteristics of this fact is developments in the construction industry. Concrete is one of the construction materials that come to mind when it comes to the construction industry. Developments in the field of concrete directly affect the resistance of a construction. Factors that affect the concrete strength can be divided into two groups as internal and external factors. Internal factors arise from the type and rates of the material forming the concrete while external factors stem from effects that are exposed throughout the concrete production, maintenance and service life. Among the internal factors are the types of cement, aggregate features, water/cement ratio, and chemical and mineral admixtures, whereas external factors include concrete casting and curing temperatures, curing conditions and compressive strength test conditions.

To bring new features to the concrete and upgrade some of its features markedly, chemical and pozzolanic admixtures are added to the concrete apart from steel, glass and polypropylene films. Fibers used in concretes increase the tensile and flexural strength and decrease shrinkage cracks (Afroughsabet & Ozbakkaloglu, 2015; Atiş & Karahan, 2009; Babu & Babu, 2003; Bagherzadeh et al., 2012).

The concrete does not break apart into two pieces due to the presence of fibers in the fiber-reinforced concrete obtained through the addition of steel fibers into the concrete, as distinct from normal concrete, and keeps carrying loads, albeit in little amount (Balendran et al., 2002; Behnood & Ziari, 2008; BENTUR & M. D. COHEN, 1987). Steel fibers substantially reduce crack widths, the number of cracks and joist displacement where measures are taken against the coagulation of fibers during the admixture. However, lifting the load again and repairing cracks in the joist at an early age may be considered as an important advantage for buildings exposed to repeated loads such as seismic loads (Doğruyol, 2017; Duval & Kadri, 1998).

The reduction rate of the load is much slower in fiber-reinforced concretes than in normal concretes as a result of increasing deformation following the maximum load. Therefore, energy absorption is at a fairly high level in fiber-reinforced concretes as fibers separate from the internal structure of the concrete and extend. Huge increases are maintained in the ductility and toughness of fiber-reinforced concretes compared to non-fibrous concretes (Ahmed Ezeldin & P. Balaguru, 1989; Doğruyol, 2017; Ferrara & Meda, 2006).

Steel fibers that are used in the concrete production are produced in various sections and sizes. Elements that define the fiber are the fiber length, the fiber diameter and the tensile stress of the fiber. In all studies ever conducted, it has been determined that there is a significant decrease in workability and a decrease in void measurement after fiber is added into the concrete(Gao et al., 1997; Hadi, 2009; Ivorra et al., 2010; Karahan & Atiş, 2011).

In general fly ash and silica fume are used as pozzolanic materials in the concrete production. As silica fume is a material finer than cement, it tightens and reinforces aggregate cement paste interfacial zone to minimize the void and increase the compressive strength of the concrete. Silica fume prevents the segregation in concrete and positively affects the homogeneity (Kamal Henri Khayat & Pierre-Claude, 1992; Kilinçkale, 1996). Use of silica fume up to 20 % instead of cement in concrete increases the adherence of the concrete to the steel (Choo & Newman, 2003; Kilinçkale, 1996). Besides, silica fume decreases pores in the cement paste, increases adhesion and maintains a more impermeable structure. Silica fume decreases the drying rate and diffusion coefficient of the concrete (Doğruyol, 2017). Serving as both filler and pozzolan, silica fume forms a dense structure from grains, cement paste and aggregate. As silica fume absorbs surplus water molecules, it reinforces the adherence between the cement paste and aggregate and limits the corrosion of the reinforcement (Kamal Henri Khayat & Pierre-Claude, 1992).

Concrete blocks produced with cool and lightweight aggregates were examined and it was determined that silica fume addition increased the strength at low doses and early age(Nili & Afroughsabet, 2010b; Serin, 1999).

It was determined that silica fume and fly ash improved the shrinkage and freeze-thaw properties of lightweight concretes, while silica fume increased the 28-day compressive strengths, while fly ash decreased their compressive strength (Nili & Afroughsabet, 2010a; Pinto & Hover, 1997).

The pozzolanic activity of artificial pozzolans such as blast furnace slag, fly ash and silica fume was investigated. Among these pozzolans, it was observed that silica fume had the highest pozzolanic activity (Regmi et al., 2011; Scrivener et al., 1988; Özcan and Güngör, 2019).

It was stated that the strength of cement systems increased with the addition of silica fume; that the preparation time of mortar shortened, and that normal water demand increased along with silica fume addition (Panjehpour et al., 2011; Şener et al., 2002; Al-Mashhadani, 2021).

The effects of silica fume substitution were investigated at two different rates (6 % and 10 %). Experimental results showed that the optimum silica fume addition was 6 % (Serin, 1999).

It was studied the effect of silica fume on the mechanical behavior of concrete in compression. They identified that use of silica fume in concrete changed the micro-structural features of the aggregate-mortar contact area and that the material exhibited a looser behavior (Siddique, 2011; Song & Hwang, 2004).

2. Material and Method

2.1 Material

Calcareous crushed aggregates are the majority in concrete design and divided into grain sizes of 0-4, 4-16, 16-32 mm. The densities of these aggregates are 2600, 2650, 2680 kg/m3 respectively. During the concrete production, portland cement 42.5 type portland cement, silica fume obtained from electrometallurgy plants, the one recommended in Turkish Standard 10514 were used in concrete production. ZC 60/100 coded steel fiber was also used. Crimped and hooked steel fiber with a diameter of 1 mm and a length/diameter ratio of 60, Figure 1. Emphasis information on silica fume and cement amounts used for fresh concrete, in the first sample, only 320 kg cement was used. In the second sample, 8 kg of silica fume and 312 kg of cement were used Table 1. In the third sample, 16 kg of silica fume and 304 kg of cement were used. In the fourth sample, 32 kg of silica fume and 288 kg of cement were used.

Its density is 7800 kg / m3 and its tensile strength is 1100 MPa. Concrete design did not include any extra additive and was prepared using tap water at the concrete laboratory University along with the production of 36 prism samples in total in sizes of 100 mm x 100 mm x 500 mm. 9 of the concretes those were produced of steel fiber and used as witness samples. 27 samples that remained constituted the fiber-reinforced concrete with additive silica fume at rates of 5 %, 10 % and 15 %.

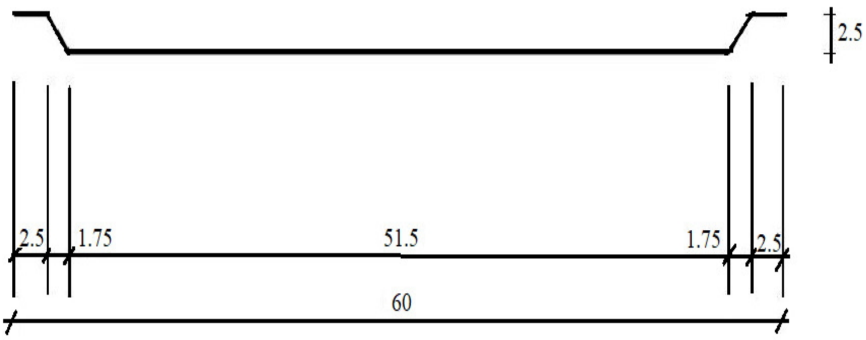


Figure 1. Sizes of Steel fiber (mm).

Table 1. Amounts of materials for Brand New Concrete.

Admixture Number	Concrete Type	Silica Fume (kg)	Cement (kg)	Water (Lt)	Steel fiber (kg)	Aggregate Grain Sizes (mm)		
						0-4	4-16	16-32
1	LB	0	320	138	50	893	903	204
2	SDLB-5	16	304	138	50	893	903	204
3	SDLB-10	32	288	138	50	893	903	204
4	SDLB-15	48	272	138	50	893	903	204

2.2 Method

C25 concrete was taken as basis in preparing the admixtures in which water/cement ratio was taken as 0.50. It was important that the slump value of the concrete produced be 7 ±1. Cement was replaced by silica fume by 5 %, 10 % and 15 % by weight. The steel fiber was added in accordance with Turkish Standard 10514 in concrete admixture, and remixing was carried out after initially each set of admixtures was subjected to dry-mix with mixer and then subjected to another dry-mix for one and half minute following the addition of the steel fiber on the same day to ensure a homogenous distribution of the steel fiber. Silica fume was added after it was turned into slurry with mixing water. Samples prepared were subjected to curing at 20 ± 2 °C and in the same environment. During the flexural test, the gap between bearers was 450 mm and the loop was installed from the point of ½ on the prism. The loading speed was 74 N/s. The loading mechanism is 3-point, Figure 2.

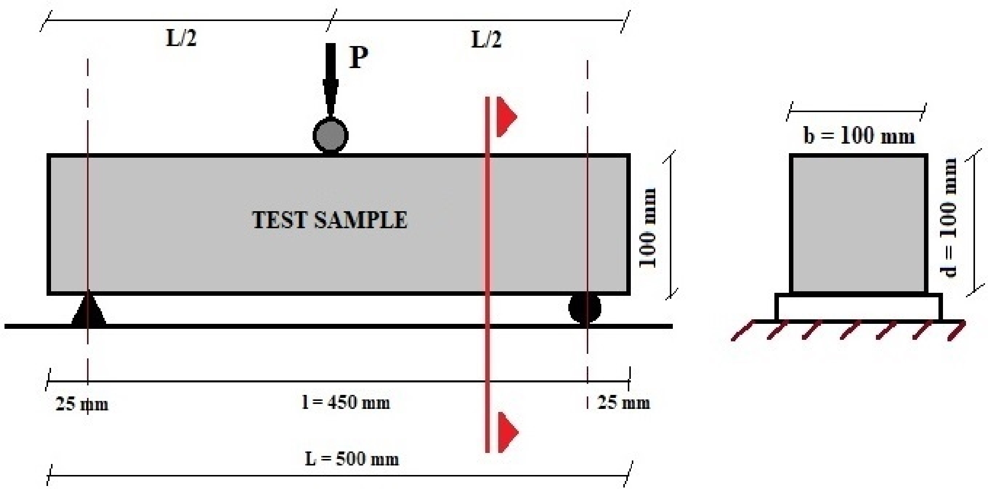


Figure 2. Test Loading Mechaism.

It has been determined that the flexural strength stress diagram of fiber reinforced concrete cannot be explained as in normal concrete (Behnood & Ziari, 2008), Figure 3.

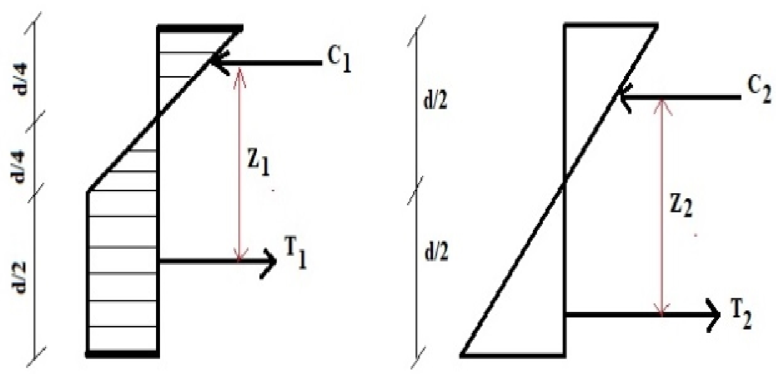


Figure 3. (a) Stress diagram of the fiber-reinforced (b) and non-fibrous concrete in beam bending.

Following assumptions were used to determine the distributions on the beam axis:

a. Stress-strain is not proportional in tensile.

b. As the fiber-reinforced concrete behaves distinctively in tensile and compression, the neutral axis is not the centre of gravity.

c. The flexural tensile obtained through the elastic behaviour assumption is about three times as much as the direct tensile.

d. It is enough to use the elastic behaviour in design though it does not exist in reality (Babu & Babu, 2003; Behnood & Ziari, 2008).

In addition, consistency water, flexural tensile strength (single point) and compressive strength results were determined for concrete samples on 7 days and 28 days. Cement hydration products were observed with the scanning electron microscope test of the 5 % silica fume substituted sample and calcium, chlorine and alkali ions, allite (Ca-Si O), combeite (Na-Ca-Si) and wadeite (K-Si-O) compositions were calculated with the x-ray diffraction and energy dispersive spectrometry tests, and the effect of concrete silica fume in concrete was revealed.

3. Experimental Outputs and Discussion

3.1 Strength of Blended Concrete

XAs a result of the flexural test conducted on the concrete prisms that were produced, cracking occurred in fiber-reinforced concretes; however, they did not break apart and go into two pieces instantly but collapsed with elastic behaviour to a degree and kept carrying load, albeit at low levels.The flexural strength values of fiber reinforced concrete are good, Table 2. Brittle fracture is more manifest in silica fume concretes with the abovementioned occasion in concretes produced. As silica fume concretes have an additive adherence effect, the tensile occurring in concretes has concentrated in areas where cracking has the maximum flexural stress.

Table 2: Flexural Strength Values of the fiber-reinforced Concrete.

Concrete Age (days)	Rate of Silica Fume (%)	Flexural Strength (MPa)	Standard Deviation
7	0	5.23	0.11
	5	5.31	0.12
	10	6.11	0.08
	15	6.41	0.05
28	0	8.98	0.12
	5	9.01	0.48
	10	10.08	0.12
	15	10.05	0.13

It was observed that the strength of concrete at 7 days increased as the amount of silica fume increased. It was observed that as the amount of silica fume increased, the strength of concrete at 28 days increased and the strength value started to decrease when silica fume was added over 10 %, Table 2. The compressive strength of silica fume concrete increases as the amount of silica fume increases and it reaches the maximum level by 10 % to 15 % (TS 10514, n.d.).

The flexural and compressive strength of the concrete varies depending on the silica fume included in it. The flexural strength of the concrete increased in parallel with the rate of the silica fume, Figure 4.

There was an increase by 1.52 % in the 7 day fiber-reinforced concrete in which silica fume addition was 5% compared to fiber-reinforced concretes in which there was no silica fume addition. Accordingly, there was an increase by 14.4 % where silica fume rate was 10 % and an increase by 18.5 % where silica fume rate was 15 %. While compared to the additive-free fiber-reinforced concrete, there was not a change related to the 28 day flexural strength in the fiber-reinforced concrete which contained 5 % of silica fume, the fiber-reinforced concrete with 10 % and 15 % of silica fume increased by 12.24 % and 16.88 % respectively compared to the 28 day additive-free fiber-reinforced concrete, Table 2 and Figure 4.

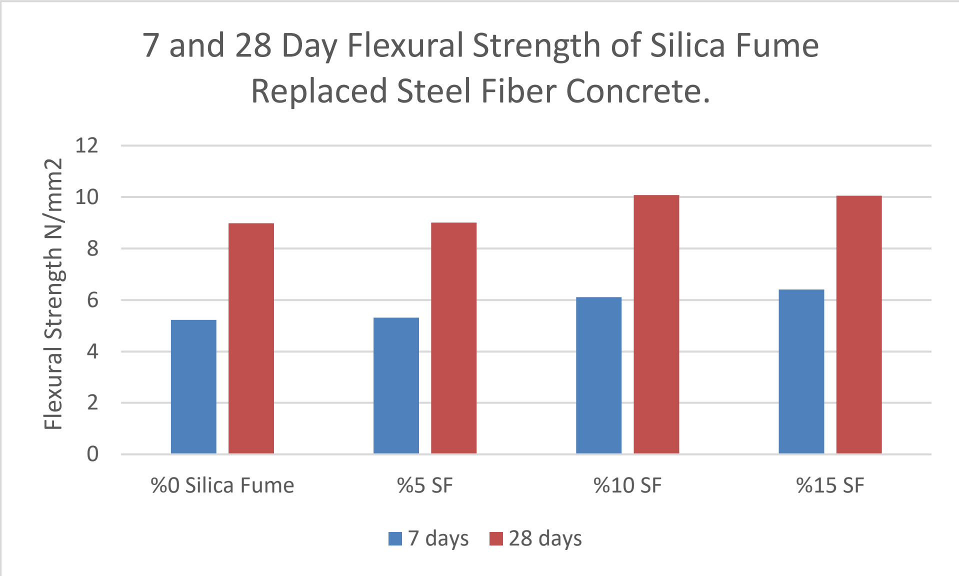


Figure 4. Silica Fume Rate and Flexural Strength Relationship in Steel fiber Concretes.

The compressive strength increases depending on the silica fume included in the fiber-reinforced concrete as it is in the flexural strength.

There was no increase where silica fume was 5 % compared to the 7 days additive-free fiber-reinforced concrete. However, silica fume with a rate of 10 % did give rise to an increase by 10.68 % while silica fume with a rate of 15 % led to an increase by 12.8 %.

In the 28 day compressive strength, there was an increase by 1.63 %, 15.7 % and 11.2 % where the fiber-reinforced concrete contained silica fume by 5 %, 10 % and 15 % respectively compared to the additive-free fiber-reinforced concrete Table 3. and Figure 5.

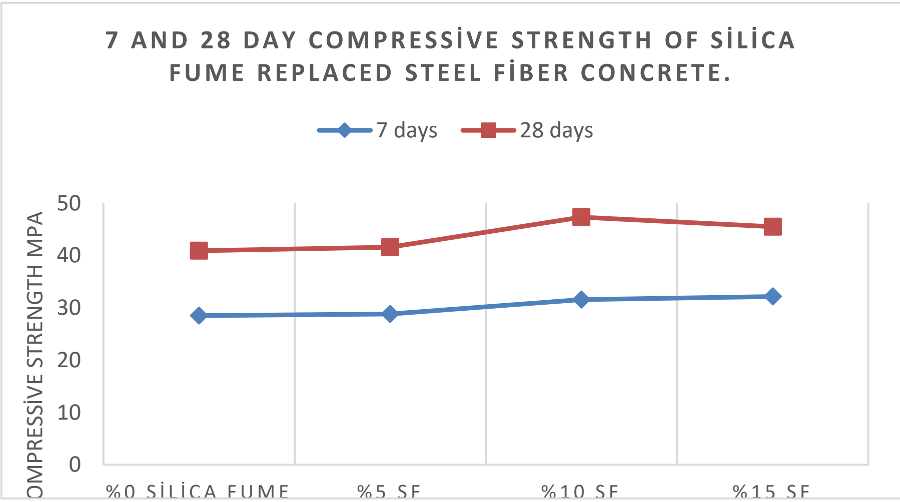


Figure 5.Silica Fume Rate and Compressive Strength Relationship in Steel fiber Concretes

Table 3. Silica Fume Rate and Compressive Strength Relationship in Steel fiber Concretes.

.Age of Concrete (days)	Silica Fume substitution amount, %	Compressive Strength, MPa
7	0	28.50
	5	28.80
	10	31.54
	15	32.15
28	0	40.90
	5	41.56
	10	47.32
	15	45.48

3.2 Microstructure of Hardened Specimens

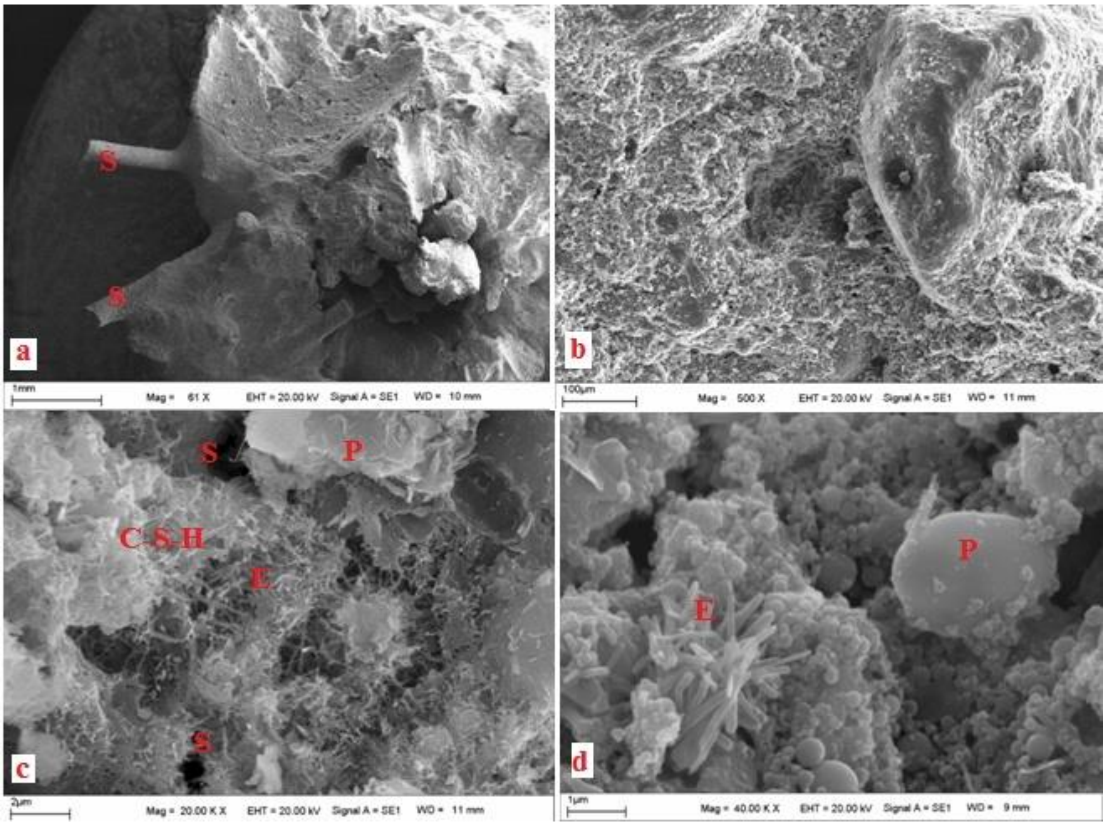


Figure6. Hydration products of 5 % Silica Fume substituted sample P: portlandite (CH), E: ettringite (C6AŚ3H32), Calcium Silicate Hydrate Gel (C-S-H: C3S2H3).

Figure 6a, The 61-fold magnified view. The concrete image of steel fiber reinforcement. Figure 6b, the 500-fold magnified image gives information about the surface topography of the sample. Figure 6c, the steel fiber top view and hydration products including portlandite, ettringite and calcium silicate hydrate gel (C-S-H) bonds, were intensely visualized with a 20.000 fold magnified image. Figure 6d. Hydration products such as ettringite crystal needles and portlandite were observed with the 40.000 fold magnified image. Ettringite is a product that is open to reaction with external influences and causes capillary cracks on the concrete surface by expanding volumetrically. This situation negatively affects the strength and durability.

It was observed in the study that silica fume substitution increased the 7 and 28 days compressive and tensile strength of steel fiber concrete, Figure 5. Silica fume substituted concrete showed the highest compressive strength performance in both water cure and sulphate solution in early and later ages, but the production cost is much higher than other types of concrete mixtures. In addition, it has an effect on the adherence of concrete (Yan et al., 1999).

Figure 6c, since steel fiber is opaque, it appears as black. A cement matrix was observed on the steel fiber surface. This shows that steel fibers have a good bond between cement hydration products. It can be seen that the steel fibers are heavily surrounded by hydration products, Figure 6c,

The peak of quartz was observed at the position of 2 theta = 29.040. In addition, predominant mineral phases (calcite) at different Bragg angle positions (2 theta = 31.020, 39.460) stand out in x-ray diffraction patterns (Yazıcıoğlu & Bozkurt, 2006) reported similar x-ray diffraction results in their study on concrete, Figure 7.

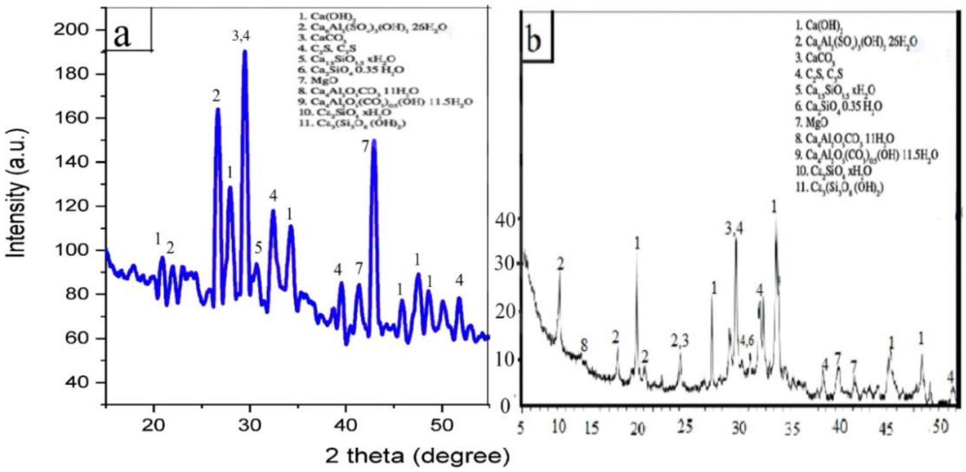
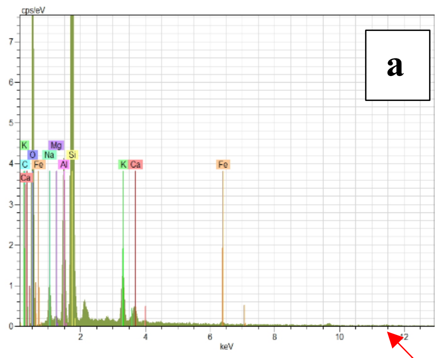


Figure 7. X-Ray Diffraction Analysis of the (a) 5 % Silica Fume. (b) CEM I 42.5N.

As seen in the energy dispersive spectrometry, the Si rate in the sample increased with the addition of silica fume to the concrete. It was observed that the high Si rate, which fills the inter-fiber spaces, increased the compressive strength and adherence. Calcium, chlorine and alkali ions, alite (Ca-Si-O), combeite (Na-Ca-Si) and wadeite (K-Si-O) compositions in oxide cement concrete with (energy dispersive spectrometry) experiments revealed the effect of silica fume in concrete Figure 8. The fine grain structure of silica fume reduced the permeability of concrete. Using 10% silica fume by weight instead of cement avoids the main factors causing alkali-aggregate reaction (Yoo et al., 2015).



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Elements	Weight, %
Si	17.43
Al	3.61
K	1.37
Na	1.75
Ca	0.43
O	75.17

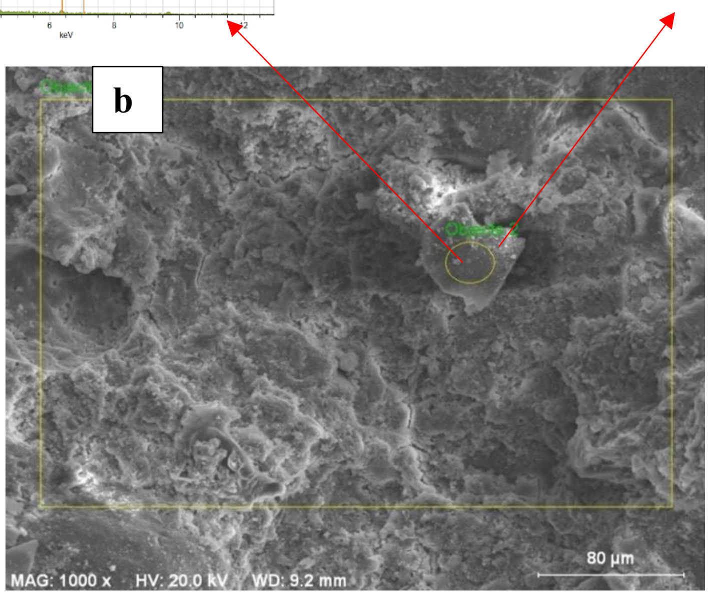

Figure. 8. (a) scanning electron microscope-energy dispersive spectrometry of 5 % Silica Fume (b) scanning electron microscope of 5 % Silica Fume (c)some elements in 5 % Silica Fume.

4. Concluding Remarks

As a result of the tests carried out on concrete prisms produced,

1. There was no immediate concrete fracture during the flexural test with the addition of steel fiber into the concrete. Initially, cracking occurred, and the concrete collapsed with slight elastic behavior and kept carrying some loads.
2. As the rate of silica fume in the fiber-reinforced concrete increased, there was an increase in the flexural and compressive strength as seen Figure 4 and Figure 5.
3. The addition of silica fume into fiber-reinforced concretes led to an increase in the adherence, and cracks in the flexure concentrated in areas where maximum stress was dense.
4. A 5% of addition of silica fume did not affect the flexural and compressive strength, but the addition of silica fume by 10 % and 15 % increased the flexural and compressive strength of the fiber-reinforced concretes.
5. It was observed that in the concrete with substituted silica fume, the formation of Alkali Silica Reactions decreased with the decrease in the amount of alkali in the concrete, Figure 8.
6. The recycling of environmental wastes has made an economically and environmentally beneficial contribution to reducing the greenhouse gases to be emitted to the nature in cement production due to the reduction of the amount of cement in the silica fume substituted concrete.

5. Benefits of Experimental Results

It has been observed by mechanical experiments that silica fume increases the flexural and compressive strength of steel fiber concrete, in addition, with the scanning electron microscope-energy dispersive spectrometry and x-ray diffraction analysis, it has been observed that occurs the calcium silicate hydrate gel (C-S-H) formation at the molecular level and decrease elements and minerals that to form alkali thanks to substitute the silica fume.

During the bending test with the addition of steel fiber to the concrete, there was no sudden concrete breakage. Initially, cracking occurred, and the concrete collapsed with slightly elastic behavior and continued to carry some load.

6. Acknowledgments

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