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Influence of Mixing-Water Magnetization Method on the Performance of Silica Fume Concrete

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Abstract: The aim of this study is to experimentally investigate the mechanical characteristics of concrete combining silica fume (SF) and magnetized water (MW). A total of nine concrete mixes were prepared and tested for workability, compressive strength, splitting tensile strength, and flexural strength. Ordinary tap water (TW) and MW that was prepared with five proposed different methods were utilized in the concrete mixes. The MW was prepared by passing TW through a permanent magnetic field (having intensities of 1.4 Tesla and/or 1.6 Tesla) for a different number of cycles, namely 100, 150, and 250 cycles. Water characteristics were analyzed after being magnetized using the proposed different methods and compared with the TW characteristics. Non-destructive concrete testing (ultrasonic pulse velocity, and Schmidt hammer) was also conducted to determine the effect of MW on the prediction of concrete compressive strength. Scanning electron microscopy (SEM) analysis and energy dispersive X-ray (EDX) analysis were carried out on the produced mixes. Regardless of the method utilized to prepare the MW, the results revealed a considerable improvement in concrete compressive strength, splitting tensile strength, and flexural strength by up to 80%, 98%, and 22%, respectively, when MW was prepared with 150 cycles. The best water magnetization method found in this study was the passing of water through magnetic fields of 1.6T then 1.4T intensities for 150 cycles. The ultrasonic pulse velocity test resulted in good prediction of the concrete compressive strength with overall error ranged between −12.6% and +5.8%. MW significantly improved the concrete microstructure and produced a denser structure in comparison to the control conventional concrete.

Keywords: magnetized water; silica fume; concrete strength; non-destructive testing; microstructure

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1. Introduction

Silica fume (SF) is a cementitious material that can effectively replace a part of concrete cement [1,2]. SF has relatively smaller particle size compared with cement in which it can easily fill the pores in the concrete matrix. It also reacts with the calcium hydroxide (Ca $(OH)_2$), produced from the cement hydration reaction, and forms calcium silicate hydrate (C-S-H) [3,4] that is able to enhance the concrete strength. Using SF in concrete has an environmentally friendly feature as it reduces industry by-product waste, and uses less energy to make cement [5,6].

The usage of SF in concrete mixtures has increased during the past few decades. The compressive strength, splitting tensile strength, and modulus of elasticity of concrete were shown to increase when SF was used in partially replacing concrete cement [7–9]. Abbass et al. [10] and Singh [11] recommended an SF content of 10% by weight for optimum concrete properties. According to Gholhaki et al. [12], SF in concrete enhances its pore structure and could function as a filler to increase the density of concrete, which causes significant reduction in its porosity. The use of micro and nano silica materials can help to improve the mechanical, durability, and microstructural characteristics of high-performance self-compacting concrete (SCC) [13]. Sabet et al. [14] noted a decrease in absorbed water from 4.5% to 2.76% when using 10% SF and from 4.5% to 2.57% when using 20% SF in SCC mixes. They also demonstrated that the addition of SF increased the need for high range water reducer (HRWR) in the SCC mixes.

Magnetized water (MW) can be produced by magnetizing normal tap water (TW) in a magnetic field [15]. The breaking effect on the structure of the water crystal is amplified by magnetization, which enhances negative ionic hydration [16]. When magnetization occurs, the properties of the water molecules alter in which hydrogen bonding allows the molecules of TW to remain connected to one another. They frequently create clusters by joining forces [17]. The size of these water clusters and the quantity of clustered molecules decrease as TW passes through a permanent magnetic field [18,19]. As a result, the water molecules become more active. According to Toledo et al. [19], the magnetic fields reduced the hydrogen bonds within the intracluster, causing the larger clusters to disintegrate and produce smaller clusters with stronger intracluster hydrogen bonds. Figure 1 shows how the water molecules can be changed after magnetization.

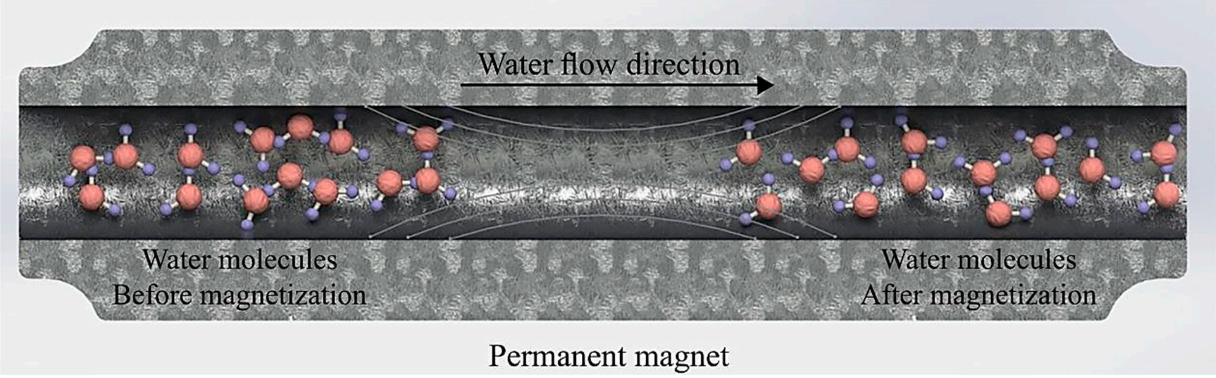


Figure 1. Water molecules before and after magnetization [17].

In recent years, several studies have employed MW in concrete mixing and observed its effects on workability, compressive strength, and other mechanical characteristics [20]. They reported that an initial hydration reaction occurs on the cement particles' surface during the mixing of TW and cement. Thus, a thin layer of hydration products is created on the cement particles, inhibiting further hydration and, consequently, the development of the strength of concrete. However, if MW is utilized, water molecules can quickly enter cement particles, allowing a more thorough hydration process to take place that improves the strength of concrete [21–23].

The influence of using MW on enhancing the mechanical characteristics of high-strength concrete was investigated by Afshin et al. [24]. They discovered that concrete mixed with MW has a relatively higher slump value than that of TW concrete. The compressive strength improved by 18% when MW was used in concrete. Additionally, the cement content could be decreased by 28% for the same slump and compressive strength values. The use of MW in concrete has a huge potential for decreasing the amount of water needed in the concrete mix, as demonstrated by Abdel-Magid et al. [25], in which they reported that MW effectively enhances concrete workability by up to 400%. Thus, the amount of water required for mixing can be significantly reduced when using MW to obtain the same concrete workability compared to using ordinary TW. Su et al. [26] reported that using MW instead of TW increases compressive strength by about 10%, reduces the amount of cement used by 5%, enhances freezing resistance, and minimizes concrete bleeding. Gholhaki et al. [12] reported that the splitting tensile and flexural strengths of concrete can be increased by using MW. The splitting tensile strength values at 28 days ranged from 3.7 to 4.15 MPa for concrete prepared with MW, compared to 3.5 MPa for the control mix. Additionally, all concrete mixes made with MW had higher flexural strengths than that of the control mix, with respective values of 15%, 11%, 6%, and 3% for mixes made with

MW that were prepared by exposing TW to permanent magnetic field for 10, 20, 40, and 80 cycles.

By using scanning electron microscope (SEM) analysis, Soto-Bernal et al. [27] showed how MW in concrete results in increased density, C-S-H gel production, and compressive strength. They also discovered that the use of MW caused the water's temperature to increase, and they also reported that the cement setting time is a function of the intensity of mixing water magnetization. Wei et al. [19] mentioned that the MW in concrete reduces its drying shrinkage. According to Yousry et al. [28], using MW rather than TW to prepare the concrete mixes could result in a noticeably greater early concrete strength.

The combination of SF and MW in concrete can result in an environmentally friendly product with reduced cement production and reduced CO_2 harmful impacts. In addition, the water magnetization method still needs to be optimized for practical use. This research is designed to assess the mechanical properties of concrete containing SF and MW using different water magnetization methods. Concrete workability, compressive strength, splitting tensile strength, and flexural strength were measured and compared for the assessment. Non-destructive concrete testing was also conducted to determine the effect of MW on the prediction of concrete compressive strength. SEM and EDX analyses were used to measure the percentage of the elements' intensity in concrete mixes.

2. Experimental Plan

2.1. Materials

In accordance with ASTM C150 (2019) [29], Blended Portland Cement (BPC) CEM II 42.5 N (specific gravity of 2.9) was used as the binder of concrete mixes in this experimental study. SF with specific gravity of 2.25 that complies with ASTM C1240-05 (2019) [30] was used partially as a cementitious material in all mixes. Table 1 shows the composition of both cement and SF. According to BS EN 12620:2002 [31], dolomite with a nominal maximum size of 12.5 mm and specific gravity of 2.62 was used as a coarse aggregate and 5 mm siliceous natural sand that has 2.59 specific gravity was used as a fine aggregate in this study. The water absorption of the dolomite and the sand were 1.2% and 0.76%, respectively. A polycarboxylate superplasticizer (SP) type F with a specific gravity of 1.08 was used in all mixes. SP conformed to ASTM C494-08 (2008) [32].

Table 1. Physical and chemical properties of BPC and SF.

Element	CaO	Al_2O_3	SiO_2	MgO	Fe_2O_3	K_2O	SO_3	Na_2O	CL	TiO_2	LOI
BPC	63.43	4.62	20.61	1.56	3.58	0.24	2.48	0.43	0.07	-	2.47
SF	0.013	0.91	96.2	0.38	1.44	0.272	0.00	0.25	-	0.01	1.04

Two permanent magnets with intensities of 1.4T and 1.6T were used to magnetize the water used in this study. Five different methods were used to prepare the MW by passing TW through the permanent magnetic fields for a number of cycles, namely 100, 150, and 250 cycles. In the first method (MW 1.4), the TW was passed through the 1.4T magnetic field only. The second method (MW 1.6) was similar to the first one but used a 1.6T magnetic field only. In the third method (MW 1.4 to 1.6), the TW was passed first through 1.4T then through 1.6T magnetic fields. The fourth method (MW 1.6 to 1.4) was similar to the third one but the TW was passed first through 1.6T then through 1.4T magnetic fields. In the fifth method (MW 1.4 with 1.6), the TW was passed through both 1.4T and 1.6T at the same time. The TW magnetization using the five methods was carried out using a designed water flow system that consisted of a water tank, water pump, some water tubes, and some valves, as shown in Figure 2. The water pump was used to ensure steady flow circularization of the water. The valves were used to control the water flow direction to set up the required magnetization method. Table 2 shows the details of the opened or closed valves in each method.

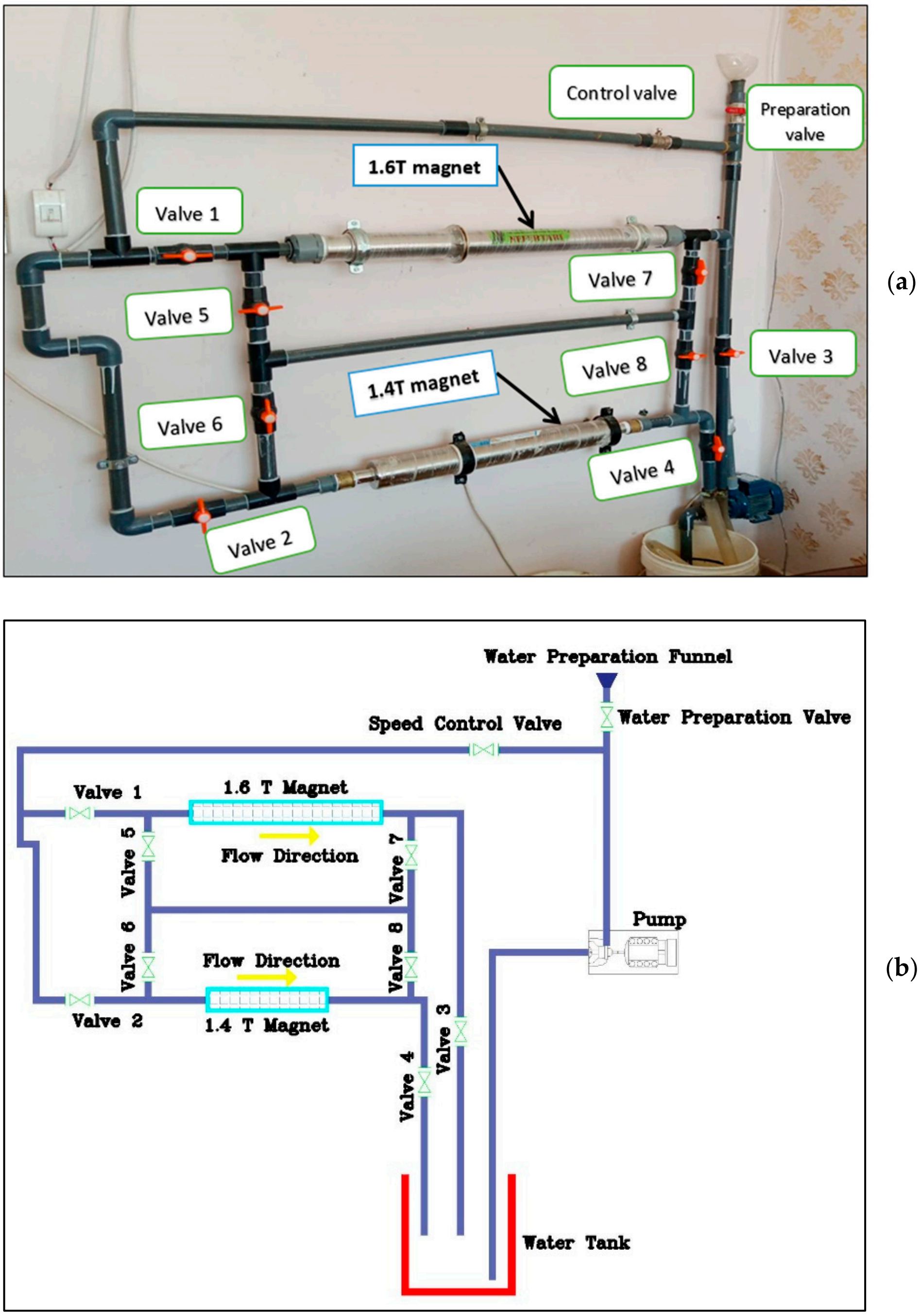


Figure 2. Water magnetization flow system: (**a**) real system, and (**b**) schematic drawing.

Table 2. Details of the water magnetization methods used (10 L water).

Method	Description	Time Per Cycle (s)	Opened Valves	Closed Valves
MW 1.4	Exposed to a 1.4T magnetic field only	50.0	2 and 4	1, 3, 5, 6, 7, and 8
MW 1.6	Exposed to a 1.6T magnetic field only	55.6	1 and 3	2, 4, 5, 6, 7, and 8
MW 1.4 to 1.6	Exposed in sequence to 1.4T then to 1.6T magnetic fields.	54.1	2, 3, 5, and 8	1, 4, 6, and 7
MW 1.6 to 1.4	Exposed in sequence to 1.6T then to 1.4T magnetic fields.	50.0	1, 4, 6, and 7	2, 3, 5, and 8
MW 1.4 with 1.6	Exposed to both 1.4T and 1.6T magnetic field at the same time.	54.1	1, 2, 3, and 4	5, 6, 7,and 8

2.2. Mixes and Variables

All mixes in this study were designed according to ASTM C192 (2018) [33]. The mixes were divided into three groups (A, B, and C) to investigate the effect of each applied parameter on the concrete properties, see Table 3. Group A consisted of two mixes and was designed to determine the effect of using SF as a partial replacement of cement by 10% weight ratio with using ordinary TW. Group B consisted of five mixes and was designed to determine the effect of the water magnetization method with a constant number of magnetization cycles of 150. Group C consisted of two mixes and was designed to determine the effect of magnetization cycles (100, 150, and 250) with using only one magnetization method "MW 1.6 to 1.4".

Table 3. Mix proportions for each group.

Group	Mix No.	Magnetization		Mix Composition (Kg/m^3)						
		Method	Cycles	Cement	Sand	Dolomite	TW	MW	SP	SF
A	1	–	–	500	457	1218	179	–	2.6	0
	2	–	–	450	457	1218	179	–	2.6	50
B	3	MW 1.4	150	450	457	1218	–	179	2.6	50
	4	MW 1.6	150	450	457	1218	–	179	2.6	50
	5	MW 1.4 to 1.6	150	450	457	1218	–	179	2.6	50
	6	MW 1.6 to 1.4	150	450	457	1218	–	179	2.6	50
	7	MW 1.6 with 1.4	150	450	457	1218	–	179	2.6	50
C	8	MW 1.6 to 1.4	100	450	457	1218	–	179	2.6	50
	9	MW 1.6 to 1.4	250	450	457	1218	–	179	2.6	50
TW	Tap water				SP	Superplasticizer				
MW	Magnetized water				SF	Silica fume				

2.3. Test Techniques and Procedures

2.3.1. Water Properties

Physical and chemical properties were measured for the two types of water in the current investigation. Temperature, surface tension, density, total dissolved salts (TDS), electrical conductivity (EC), and pH were the conducted measurements. The water temperature and electrical conductivity were recorded using a portable meter (EC/TEMP-913) according to [34]. The pH values of water were measured using a digital pH meter (PH-009) according to [35]. The TDS in water were measured using a portable TDS meter (TDS-3) according to [36]. The water density was calculated by measuring its volume using a graduated beaker and then measuring its weight using a sensitive scale. In order to calculate the water surface tension, capillary tubes were used and the capillary rise was recorded according to [37].

2.3.2. Mechanical Properties

Using three 150 mm cube specimens per mix per day, the concrete compressive strength was measured at 28, and 120 days according to BS EN 12390-3: 2009 [38]. The splitting tensile strength was measured using two 150 × 300 mm cylinders per mix per day at 28 and 56 days according to ASTM C496 (2017) [39]. Using two concrete prisms 100 × 100 × 500 mm per mix per day, the concrete flexural strength was measured at 28 and 56 days according to ASTM C293-79 (2016) [40]. The measured mechanical properties were averaged and reported for the required comparison.

2.3.3. Non-Destructive Tests

Ultrasonic pulse velocity and Schmidt rebound hammer non-destructive concrete tests were conducted to determine the effect of MW on the prediction of concrete compressive strength. These tests were carried out on all mixes in this study. The PUNDIT pulse velocity apparatus, was used to conduct the ultrasonic pulse velocity test in accordance with ASTM C597 (2016) [41]. A specific steel reference bar was used to confirm the calibration of the device before testing each concrete specimen. The essential component of this apparatus is a transducer, which transmits an ultrasonic pulse through the concrete to a receiving transducer. By dividing the recorded concrete path's length by the instrument's display of the wave's duration of passage, the pulse velocity can be calculated. On each concrete cube specimen, the pulse velocity was measured three times before testing the cube under conventional destructive compression, and then the concrete compressive strength was predicted.

Using a Schmidt rebound hammer type N made by ELE International, the surface hardness test was conducted in accordance with ASTM C805 (2018) [42] on the same concrete cube specimens prepared for the destructive compression test and after conducting the ultrasonic pulse velocity test. The cube specimens were first axially loaded with an axial load equal to 10% of the average concrete strength. This was to fix the specimens during the test to eliminate test-related bouncing and to simulate concrete being loaded in reality. For each cube specimen, the hammer was applied laterally 10 times, and then the concrete compressive strength was predicted.

2.3.4. Microstructural Analysis

SEM and EDX analyses were carried out on concrete samples taken from tested specimens of mixes 1, 2, and 6. These mixes were selected for the microstructural analysis to closely investigate the effect of SF without MW in mix 2, and the effect of SF with MW in mix 6 that showed the best magnetization method (as will be described in the results section) and then compare those mixes with the control mix (mix 1). In the SEM analysis, the concrete samples were coated by a 12 nm gold layer before being scanned with a JEOL JSM 6510 lv microscope at an acceleration voltage of 30 kV to describe and study the surface structure of the selected concrete mixes. The EDX analysis was carried out using an Oxford X-Max 20 device to determine the atomic percentage of each element in the selected concrete mixes.

3. Experimental Results and Analysis

3.1. Water Properties

The characteristics measured for the tap water and magnetized water (using different methods) are shown in Table 4. As can be observed, the water properties changed after the magnetization in which the temperature, pH, TDS, and EC increased by averages of

15%, 11%, 12%, and 6%, respectively. The water density did not show significant change after magnetization; however, the water surface tension decreased by an average of 4%. The temperature increase after water magnetization might be attributed to the friction between the water and the device's internal body while passing it for many cycles through the magnetic field. The greatest temperature rise was observed when water was exposed to magnetic fields of 1.6 T then 1.4 T which was the best magnetization method to improve the concrete strength (as will be discussed later). The increase in water pH after magnetization means that more H+ ions are absorbed and more OH- ions are present in the water [43–45]. The largest increase in TDS was seen after 250 cycles of the water being exposed to 1.6 T then 1.4 T intensity fields which was a result of breaking the large water clusters by the magnetic force. A material's EC reveals how well it transmits electricity. The water magnetized using 1.6 T to 1.4 T method achieved the maximum rise in the EC. As magnetization time increases, the EC rises. The EC is impacted by ion concentration. The decrease in the water surface tension is attributed to the increase in its temperature and the dispersing of its molecules when subjected to magnetic fields which causes changes in the distribution of molecules and the polarization effect in MW, hence the water surface tension decrease [45].

Table 4. Measured physical and chemical properties of water.

Water Type	**Magnetization**		**T (°C)**	**pH**	**TDS (ppm)**	**EC (µs)**	**D (gm/cm^3)**	**ST (mN/m)**
	Method	**Cycles**						
TW	TW	–	25.4	7.2	195	394	0.977	70.67
MW	MW 1.4	150	29.4	8.1	214	415	0.973	66.96
MW	MW 1.6	150	28.9	8.1	221	418	0.970	67.65
MW	MW 1.4 to 1.6	150	29.7	7.8	212	413	0.975	66.89
MW	MW 1.6 to 1.4	150	29.2	8.2	222	419	0.973	68.05
MW	MW 1.6 with 1.4	150	28.8	7.8	220	418	0.970	67.23
MW	MW 1.6 to 1.4	100	28.3	8.0	215	414	0.973	69.03
MW	MW 1.6 to 1.4	250	30.8	8.1	229	422	0.970	67.44

T: Temperature, TDS: Total dissolved salts, EC: Electrical conductivity, D: Density, ST: Surface tension.

3.2. Workability

The concrete workability was determined by measuring the concrete slump according to ES 8411-2:2020 [46]. Table 5 and Figure 3 show the variation of slump values measured for all mixes in this study. As shown in the figure, there was no significant effect on concrete slump by using SF or magnetized water as the slump variations ranged between 5% and 7% only. Using 10% SF as a cement weight substitution (mix 2) decreased the concrete slump from 140 mm to 130 mm compared with that of the corresponding control mix 1. Using MW with SF in mixes 3–9 increased the concrete slump from 130 mm to an average of 136 mm. There was no remarkable effect on concrete slump when changing the water magnetization method or the number of cycles used in water magnetization.

Table 5. Concrete mechanical characteristics test results.

Group	Mix No.	Slump (mm)	Compressive Strength (MPa)		Splitting Tensile Strength (MPa)		Flexural Strength (MPa)	
			28 d	**120 d**	**28 d**	**56 d**	**28 d**	**56 d**
A	1	140	45.8	55.6	2.17	3.26	7.65	8.18
	2	130	58.7	66.7	3.35	4.18	7.99	8.81
B	3	135	79.3	79.8	–	–	–	–
	4	135	80.2	81.3	–	–	–	–
	5	130	68.6	76.2	–	–	–	–
	6	140	82.4	86.9	4.30	5.26	8.55	10.01
	7	140	68.2	79.6	–	–	–	–
C	8	135	71.3	77.7	–	–	–	–
	9	140	76.7	79.9	–	–	–	–

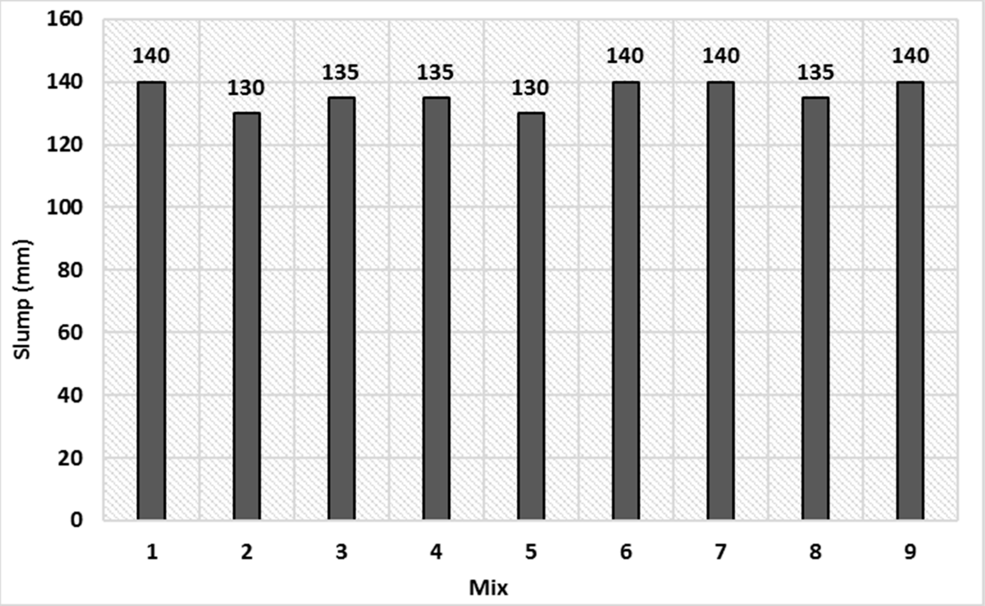


Figure 3. Measured slump values for all mixes in this study.

3.3. Compressive Strength

The compressive strength was measured for all mixes at 28 and 120 days. Table 5 and Figure 4 show the measured compressive strengths for concrete groups A and B that were designed to investigate the effects of SF and the water magnetization method, respectively. As shown in the figure, using 10% SF as a cement weight substitution (mix 2) increased the concrete compressive strength by 26% at 28 days and by 20% and 120 days, compared with those of the corresponding control mix (mix 1). This was due to the filling effect of the SF particles that are 100–150 times smaller in size than the cement particles, which makes the concrete relatively denser. In addition, SF reacts with calcium hydroxide, that is generated from the cement hydration reaction, to generate calcium silicate hydrate which results in an enhanced concrete compressive strength.

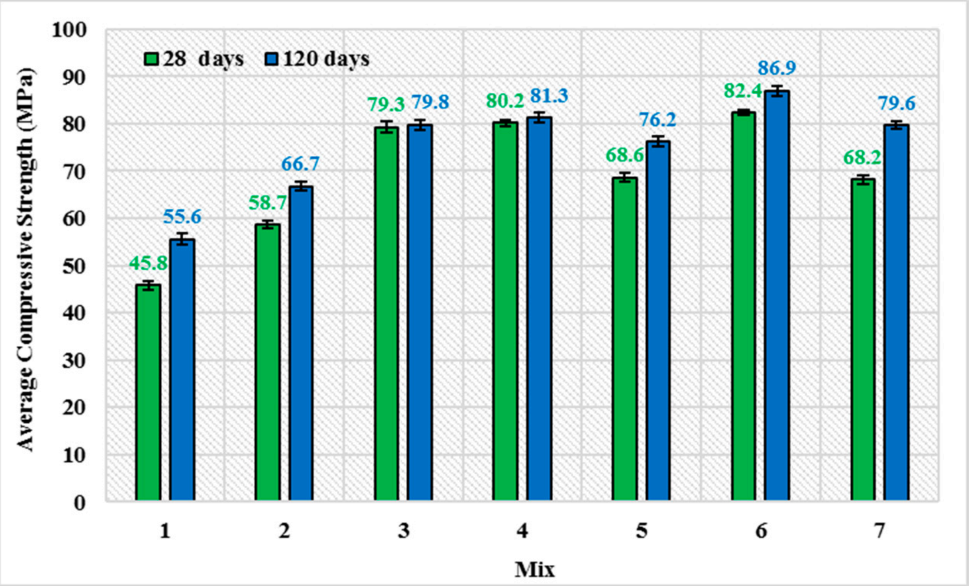


Figure 4. Effect of SF and water magnetization method on concrete compressive strength.

For mixes made with SF and MW (mixes 3–7), the increases in concrete compressive strength were 35%, 37%, 17%, 40%, and 16% at 28 days, and 20%, 22%, 14%, 30%, and 19% at 120 days for mixes 3, 4, 5, 6, and 7, respectively, compared with the corresponding control mix 2 that was made with SF and TW. The compressive strength increased by 73%, 75%, 50%, 80%, and 49% at 28 days, and by 44%, 46%, 37%, 56%, and 43% at 120 days for mixes 3, 4, 5, 6, and 7, respectively, compared with the corresponding control mix 1 that was made with TW and no SF. Generally, the enhancement of concrete compressive strength when using MW was due to the increase in water reactivity during the hydration reaction in which the cementitious materials could be penetrated easily by the relatively small molecules of water resulting from the magnetic field effect. The improvement in the water/binder hydration reaction resulted in increasing the formation of C-S-H and hence raised compressive strength [15]. Increasing the magnetic field intensity showed an insignificant effect on concrete compressive strength when using only one magnet (1.4T or 1.6T) to magnetize the water in mixes 3 and 4. The "MW 1.6" method could result in slightly better compressive strength by only 2% (at both 28 days and 120 days) more than what could be achieved with using "MW 1.4" method, when comparing them with the corresponding control mix 2. This might be attributed to the close intensity of both magnets and hence a similar resultant effect. It has been observed from the results that magnetizing the water by passing it firstly through a 1.6T magnetic field, then through 1.4T (mix 6) could show the best enhancement in concrete compressive strength at 28 days by 40% and at 120 days by 30%. However, reversing the water flow direction (from 1.4T to 1.6T in mix 5) or passing the water through both magnetic fields at the same time (mix 7) showed relatively less strength enhancements.

Figure 5 shows the effect of the number of cycles used in water magnetization on concrete compressive strength. The comparison in Figure 5 was carried out among mixes 6, 8 and 9 as all of them had the same magnetization method "MW 16 to 1.4". All applied number of cycles in this study could produce MW that was able to increase the concrete compressive strength at both 28 days and 120 days compared with those of mix 2. The 150 water circulation cycles (mix 6) yielded the best compressive strength outcomes in which the strength increased by 40% at 28 days and by 30% at 120 days. The 250 water circulation cycles (mix 9) showed the second best number of cycles as the strength increased by 31% at 28 days and by 21% at 120 days. The 100 water circulation cycles (mix 8) showed the relatively lowest strength increase among all other number of cycles as the strength increased by 21% at 28 days and by 16% at 120 days. At 100 cycles, the water exposure time to the magnetic field might not be enough to perfectly break and disperse the large water clusters, as could happen when using 150 cycles. The increase in the number of cycles to 250 resulted in a water temperature increase. The increase in mixing water temperature increases the rate of water evaporation from concrete, which results in shrinkage cracks and hence a less positive effect on concrete compressive strength.

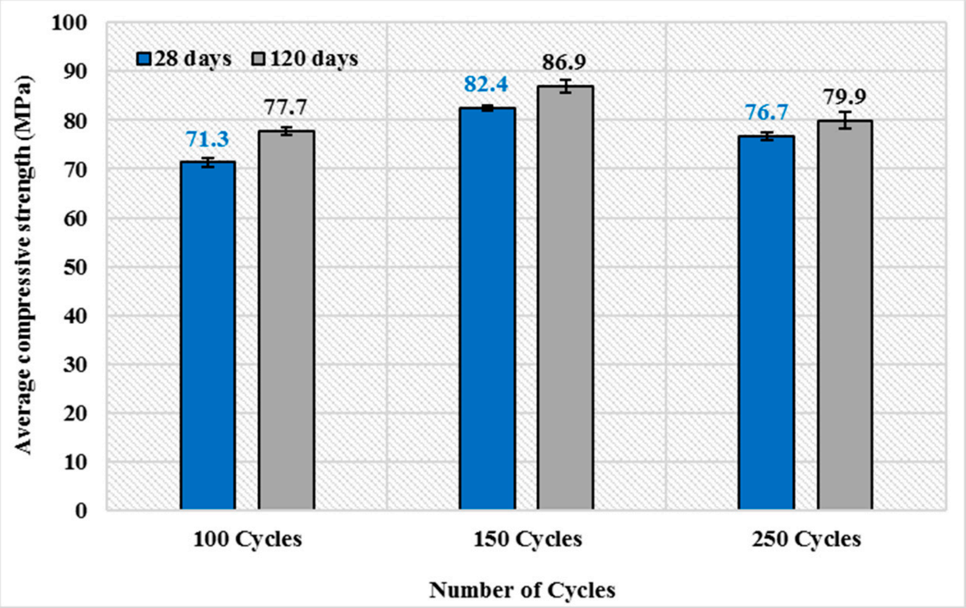


Figure 5. Effect of the number of cycles used in water magnetization.

3.4. Splitting Tensile Strength and Flexural Strength

The splitting tensile strength and the flexural strength were measured at 28 days and 56 days for mixes 1 and 2 to determine the effect of the SF, as well as for mix 6 to determine the effect of the MW. The selection of mix 6 from all mixes including MW was due to its superior compressive strength results compared with all comparable mixes. Table 5 and Figure 6 show the measured splitting tensile strength results. As shown, using 10% SF as a cement weight substitution (mix 2) increased the concrete splitting tensile strength by 54% and 28% at 28 days and 56 days, respectively, compared with those of the corresponding control mix 1. Using MW prepared with the "MW 1.6 to 1.4" method (mix 6) increased the splitting tensile strength by 28% and 26% at 28 days and 56 days, respectively, compared with those of the corresponding control mix 2. The existence of SF and MW in concrete (mix 6) showed the best splitting tensile strength results as this increased its splitting tensile strength by 98% and 61% at 28 days and 56 days, respectively, compared with those of the corresponding control mix 1. The increase in concrete splitting tensile strength when using MW and SF was due to the enhancement occurred in the corresponding compressive strength.

Table 5 and Figure 7 show the measured flexural strength of the tested concrete mixes 1, 2 and 6. As shown in the figure, using SF and MW enhanced the concrete flexural strength but with relatively lower rates compared with what occurred in the corresponding compressive and splitting tensile strengths. This was due to the applied testing method according to ASTM C293 [40] that uses a simple beam with center-point loading. In this testing method, at the failure location, the concrete specimens are under the combined effect of bending stresses and shear stresses. This might be the reason why the tested mixes did not show high increases in flexural strength as expected. Using 10% SF as a cement weight substitution (mix 2) increased the concrete flexural strength by 4% and 8% at 28 days and 56 days, respectively, compared with those of the corresponding control mix 1. Using MW prepared with the "MW 1.6 to 1.4" method (mix 6) increased the flexural strength by 7% and 14% at 28 days and 56 days, respectively, compared with those of the corresponding control mix 2. The existence of SF and MW in concrete (mix 6) showed the best flexural strength results as this increased its flexural strength by 12% and 22% at 28 days and 56 days, respectively, compared with those of the corresponding control mix 1. These findings are in line with those reported by Gholhaki et al. [12] and Ghorbani et al. [47]. The increase in concrete flexural strength when using MW and SF was due to the enhancement that occurred in the corresponding compressive strength.

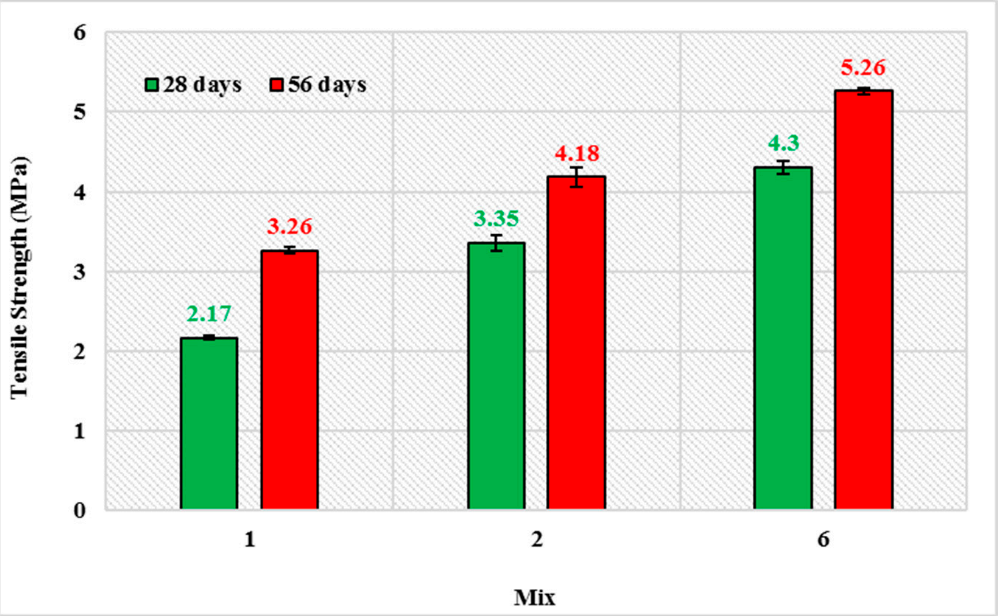


Figure 6. Effect of SF and MW on concrete splitting tensile strength.

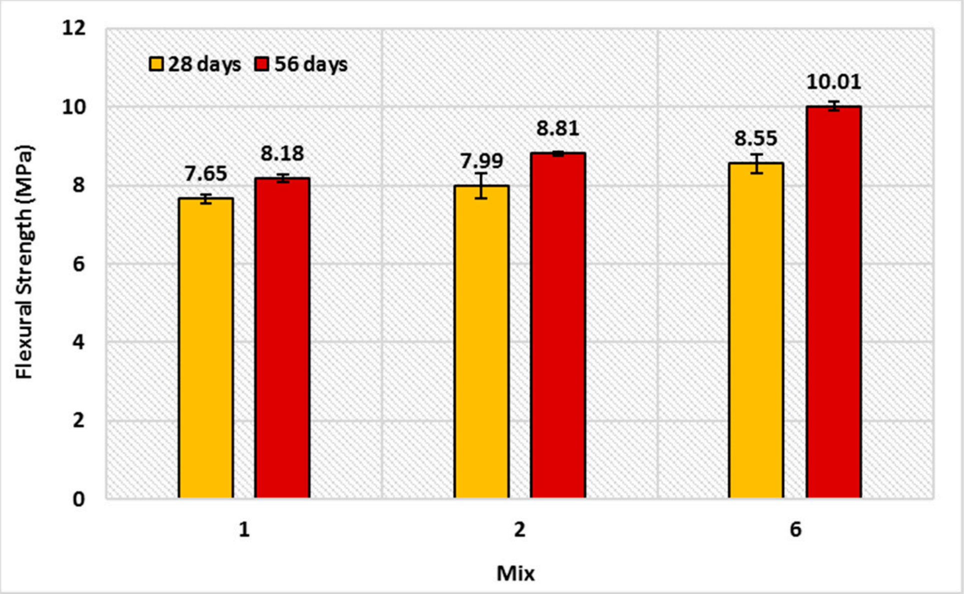


Figure 7. Effect of SF and MW on concrete flexural strength.

3.5. Non-Destructive Tests

Ultrasonic pulse velocity and Schmidt rebound hammer non-destructive concrete tests were conducted to determine the effect of MW on the prediction of concrete compressive strength of all mixes in this study. Table 6 shows the measured velocity, rebound number, and the predicted 28 day compressive strengths for each mix using the measurements of each non-destructive test. As shown in the table, mixes made with MW and SF have a somewhat higher average pulse velocity than those made with TW. This was because mixes having MW and SF have a relatively more uniform, denser structure due to the relatively higher hydration of cement particles when using MW and the formation of more C-S-H when MW and SF were presented. Figure 8 plots the measured versus the predicted compressive strengths using UPV test results. The UPV test resulted in good prediction of the concrete compressive strength for all tested mixes as the overall error in the prediction ranged between −12.6% and +5.8%. The existence of MW in concrete mixes positively affected the prediction of the strength using the UPV test as those mixes showed much less average error% than those shown by the mixes made with TW. Changing the water magnetization method or number of cycles during magnetization did not show any significant effect on the performance of UPV in predicting the concrete compressive strength.

Table 6. Concrete non-destructive test results.

Group	Mix No.	Measured Compressive Strength (MPa)	UPV		Schmidt Hammer	
			Velocity (km/s)	Comp. Strength (MPa) *	Rebound Number (R)	Comp. Strength (MPa) *
		28 d	28 d	28 d	28 d	28 d
A	1	45.8	4.4	27.0	32.2	27.2
	2	58.7	4.8	53.9	36.6	34.6
B	3	79.3	5.1	72.6	41.9	43.9
	4	80.2	5.4	78.4	43.8	47.5
	5	68.6	5.1	72.6	38.7	38.2
	6	82.4	5.4	78.4	43.9	47.7
	7	68.2	5.0	68.6	41.5	43.3
C	8	71.3	5.3	75.5	41.6	43.4
	9	76.7	5.2	73.5	42.5	45.1

* Predicted compressive strength.

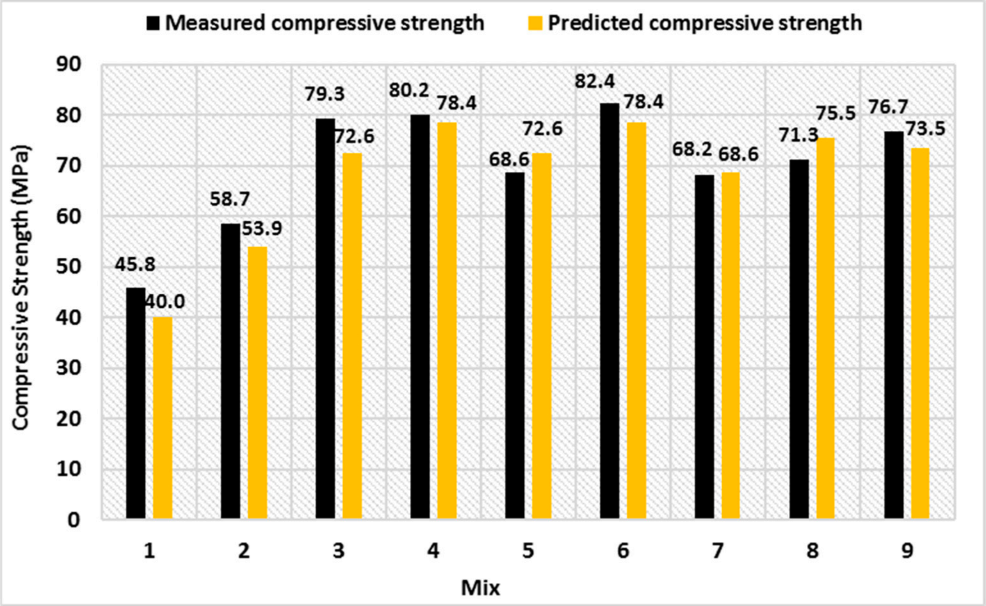


Figure 8. Measured versus predicted compressive strengths using UPV test results.

The Schmidt rebound hammer test failed to predict the concrete compressive strength accurately for the mixes in this study. Figure 9 plots the measured versus the predicted compressive strengths using Schmidt hammer test results. The average error in predicting the strength using this non-destructive test was about 40%. The measured rebound number reported in Table 6 shows higher average values for mixes made with MW than those shown by mixes made with TW. This can be attributed to the effect of MW in producing inner-hydrated cement particles during the hydration reaction which resulted in a more homogeneous, thicker structure than that of mixes made with TW [47].

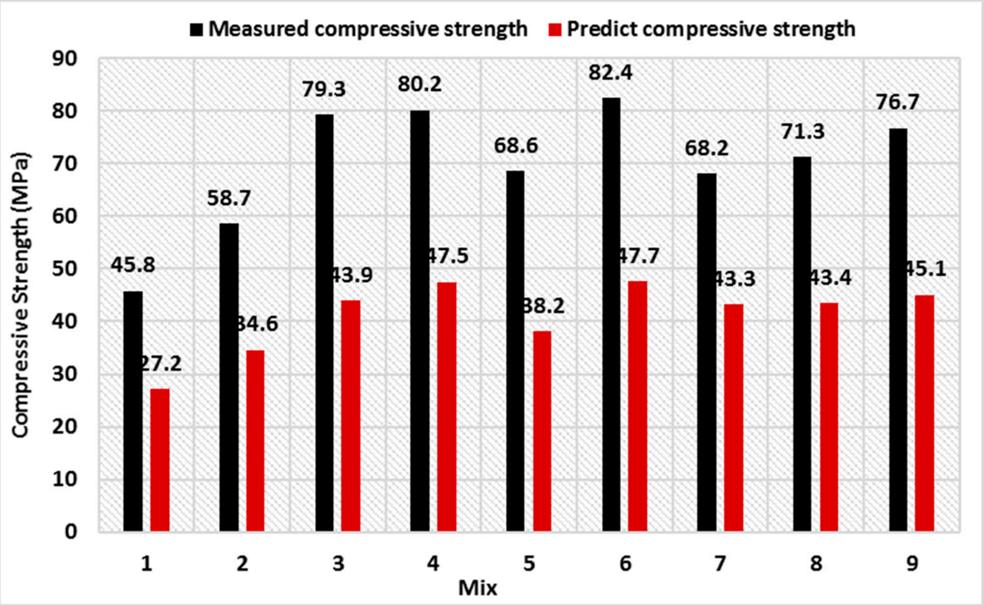


Figure 9. Measured versus predicted compressive strengths using Schmidt hammer test results.

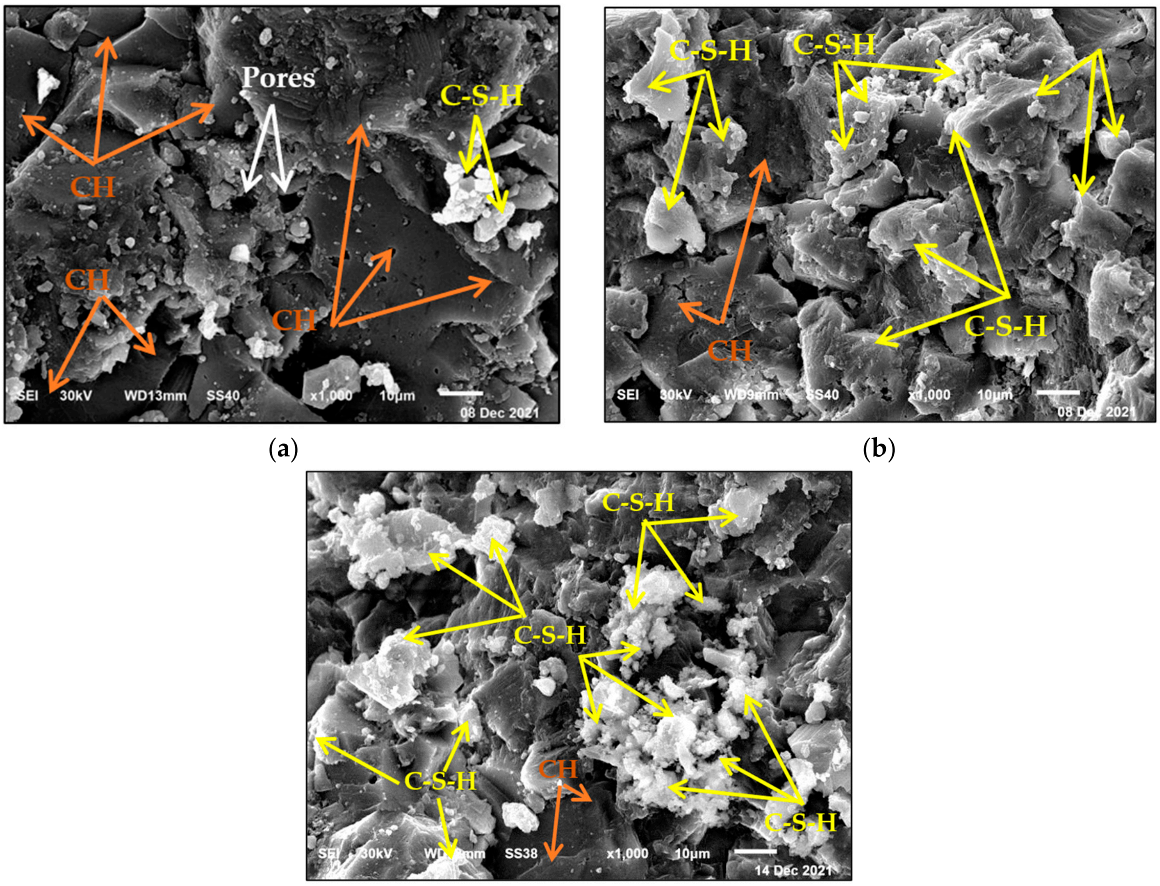
3.6. Microstructural Analyses

SEM and EDX analyses were carried out on concrete samples taken from tested specimens of mixes 1, 2, and 6. Figure 10 shows the SEM images taken for the three mixes. As shown in the figure, mix 1 prepared with TW and no SF has clear pores and calcium hydroxide signs, see Figure 10a. The use of SF in mix 2 decreased the calcium hydroxide formation and the number of pores within the concrete matrix, see Figure 10b. In addition, it increased the formation of C-S-H that may result in increasing the concrete compressive strength. Due to the relatively high fineness of SF particles, it can fill the void between the concrete ingredients. SF also reacts with the calcium hydroxide in concrete to produce C-S-H that is able to make the concrete microstructure denser [3,12,14]. The use of MW instead of TW in mix 6 relatively improved the microstructure of the concrete, as the structure became denser with fewer pores as shown in Figure 10c. The C-S-H in the concrete made with MW is larger and more noticeable than in concrete made with TW, which is a sign of an increased degree of cement hydration. The use of MW might result in more interaction and penetration of the cement particles by the water. Additionally, the cement may react with the smaller molecules of magnetized water more readily and cause a faster and more complete production of C-S-H. Density and water absorption measurements and analyses are recommended for future investigation to support the microstructure analysis findings in this study.

Figure 11 and Table 7 show the EDX analysis of mixes 1, 2, and 6. The presence of SF in mixes 2 and 6 increased the silica concentration by a significant amount compared with that in mix 1. This increased the amount of C-S-H gel, which is the primary byproduct of the pozzolanic reaction, and hence strengthened the concrete by adding this gel to the internal interstitial spaces. Compared to mix 2, that was made with TW, mix 6 made with MW has higher concentrations of C and O elements, which are directly related to the concentrations of calcium carbonate ($CaCO_3$) and silicon dioxide (SiO_2). In addition, the intensity of Ca, Al, and Si elements, which are directly related to the concentrations of wollastonite, aluminum oxide (Al_2O_3), and SiO_2, respectively, were relatively lower in the MW mix than that in TW mix.

Table 7. EDX analysis results.

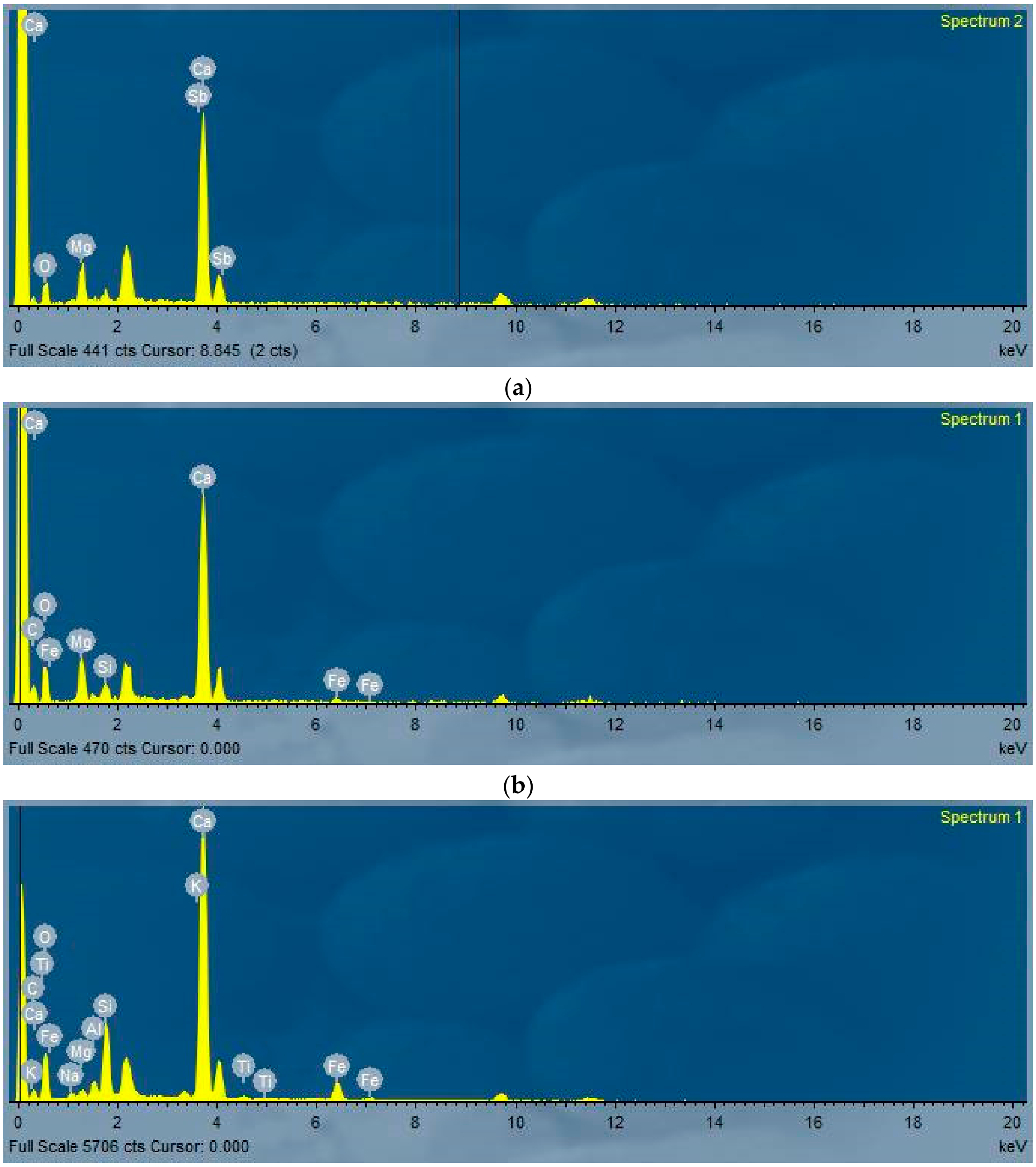
Element	Mix 1		Mix 2		Mix 6	
	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %
O	37.47	62.21	45.67	68.38	47.31	50.96
Si	-	-	0.65	0.23	3.57	2.96
Ca	31.90	21.14	23.93	14.31	19.48	8.38
Mg	11.39	12.44	13.59	13.80	6.74	4.78
Fe	-	-	0.43	0.18	0.73	0.23
Sb	19.25	4.2	15.37	3.10	-	-
C	-	-	-	-	21.18	32.70
Al	-	-	-	-	-	-



(**a**) (**b**)

(**c**)

Figure 10. SEM images of mixes 1, 2, and 6. (**a**) Mix 1 (TW, no SF); (**b**) Mix 2 (TW, SF); (**c**) Mix 6 (MW, SF).



(**a**)

(**b**)

(**c**)

Figure 11. EDX analysis of mixes 1, 2, and 6. (**a**) Mix 1 (TW, no SF); (**b**) Mix 2 (TW, SF); (**c**) Mix 6 (MW, SF).

4. Conclusions

In this work, the effects of MW on the mechanical properties of concrete incorporating SF were investigated. The MW was prepared using different methods and its physical and chemical properties were measured after magnetization. Concrete workability, compressive strength, splitting tensile strength, and flexural strength were the measured mechanical properties. Non-destructive tests and microstructure analysis were also conducted on the prepared mixes. The following points are the key conclusions of this study:

1. The water properties changed after the magnetization in which the temperature, pH, TDS, and EC increased by averages of 15%, 11%, 12%, and 6%, respectively. The water density did not show significant change after magnetization; however, the water surface tension decreased by an average of 4%.

2. Using MW with SF increased the compressive strength by up to 80%, the splitting tensile strength by up to 98%, the flexural strength by up to 22%, and did not significantly affect the concrete slump. The best results in the concrete mechanical properties were achieved when water was magnetized by passing it through magnetic fields of 1.6T then 1.4T intensities for 150 cycles.
3. The UPV test resulted in good prediction of the concrete compressive strength with overall error ranged between −12.6% and +5.8%. The existence of MW positively affected the prediction of the strength using the UPV test. However, the Schmidt rebound hammer test failed to predict the concrete compressive strength accurately for the mixes in this study as it showed a prediction error of about 40%.
4. The microstructural analyses revealed that employing MW instead of TW significantly improved the concrete microstructure and produced a denser structure in comparison to the control conventional concrete.

Overall, using magnetized water in silica fume concrete enhanced its mechanical and microstructural characteristics. It is recommended for future studies to employ the magnetized water (with the best magnetization method found in this study) in different types of concrete such as: self-compacting concrete, volcanic concrete, rubberized concrete, and lightweight concrete.

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