Improvement of hydration products for self-compacting concrete by using magnetized water

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ABSTRACT. Magnetized water (MW) is one of the most effective and economical ways to improve the properties of self-compacting concrete (SCC). Therefore, the aim of this study is to improve the fresh, mechanical, and microstructural properties of SCC using MW. For this purpose, a total of 12 mixes were produced with silica fume (SF) content (5% and 10% by weight of cement), and the mixing water passed through a permanent magnetic field (with a strength of 1.4 T) for 50, 100, and 150 cycles. Tests were performed for fresh properties (Slump flow, T50cm, V-funnel, and L-box), for mechanical properties (compressive, flexural, and tensile strength), and for microstructure properties (SEM, EDX, and TGA/DTG). The optimum result in compressive strength was achieved in the mix M8 using 5% silica fume and 150 cycles of MW. For fresh properties, the mix M4 using 150 cycles without SF had the workability enhanced by 11% compared to the control mix, and SEM and EDX tests indicated that SCC mixes prepared with MW had more C-S-H, less CH, and were denser. In addition, TGA/DTG analysis showed that the rate of hydration of mix M8 was reached by 61% at 28 days.

KEYWORDS. Self-Compacting concrete; Sustainable concrete; Magnetic water; Rate of hydration.

INTRODUCTION

Self-compacting concrete (SCC) is a very fluid concrete that may be easily replaced by its own weight in complex stirrup and rebar configurations. This method can assist in filling in the corners of a formwork without the need for a vibrator [1]. The production of self-compacting concrete requires the consumption of a large amount of superplasticizer, but the superplasticizer is expensive compared to the rest of the components, and this affects the final cost of self-compacting concrete. Therefore, one way to decrease superplasticizer dosage and to produce a more economical self-compacting concrete is to use magnetized water for enhanced concrete workability, where the superplasticizer dosage is decreased by 45% in specimens containing magnetized water and it nearly constitutes about 20% of the concrete cost. Given the reduction in superplasticizer consumption as a result of using magnetized water, it is possible to decrease material costs by 7% and produce more economical self-compacting concrete [2-4].

Water used in concrete has significant qualitative and physico-chemical properties that affect the properties of both fresh and hardened concrete [5]. Water is a polar substance whose molecules tend to form clusters by forming hydrogen bonds with one another [6]. Typically, each water cluster has roughly 100 molecules. As Fig. 1 shows, water that has been magnetized by an electromagnetic field or a permanent magnetic field is known as "magnetic field treated water" (MFTW). The magnetic field breaks hydrogen bonds, reducing the aggregation of water molecules in a cluster. It spreads water molecules [7]. The mechanical, electromagnetic, and thermodynamic properties of magnetized water differ from those of tap water. Because of these features, magnetized water has a wide range of industrial, medical, and agricultural applications [9]. The first experiments with magnetized water in concrete were undertaken by Velachofoski and Alnanma from the former Soviet Union in 1962 [10]. When water passes through a magnetic field, its structure is aligned in one direction after magnetization, and the sizes of the particles change after changing the angle of the bond. The viscosity and surface area increase, so the rate of hydration increases [11].
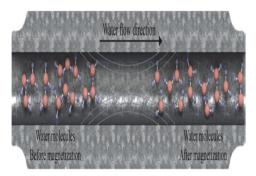

Figure 1: Effect of magnetic field on water clusters [7, 8].

A previous study stated that the improvement in workability and strength occurs when water passes through a magnetic field 15 times rather than once, so the effect of using magnetized water becomes more prominent as it passes through the magnetic field more times [12,13]. With an electromagnetic field intensity of 1.2 T and a water flow rate of 9 L/min, the highest increases in mechanical characteristics of the resulting self-compacting concrete were recorded [14]. When treating cement dough magnetically, it becomes more durable and also has an improvement in other properties of cement dough, such as compressive strength (54%), tension strength (39%), and adhesion (20%) and a decrease in initial and final setting time of about 39% and 31%, respectively [15]. Magnetized water's influence on high-strength concrete specimens with Compressive strengths ranging from 55 to 75 MPa [16]. Increased slump flows and compressive strengths were observed in the mixes, including magnetized water by as much as 45 and 18%, respectively [17]. Using magnetized rather than tap water in an SCC mix improved concrete workability, allowing less superplasticizer to be used to achieve a given workability value. Furthermore, in SCC with a given W/C ratio, using magnetized rather than tap water improved concrete mechanical properties such as compressive, bending, and tensile strengths [14]. Magnetic water causes a decrease in the viscosity of SCC mixes in V-funnel and T50 tests, and it can improve the passing ability of SCC mixes in the L-box test [18].

Fly ash (FA), limestone powder, ground blast-furnace slag, and silica fume (SF) are examples of Pozzolanic materials that effectively improve the strength properties of SCC [19, 20]. The inclusion of SF enhanced the pore structure of concrete and might operate as a filler to increase the density of concrete, resulting in a significant reduction in concrete porosity [21]. There was a loss in strength at a high silica fume content of 15%, compared to the maximum compressive at 5% silica fume with magnetic water [22]. When compared to the SCC control mix created with tap water, SCC incorporating magnetic water and 20% SF had the highest 28-day compressive strength with 49% [18]. Thermogravimetric analysis (TGA) is one of the most widely used methods to quantify the chemical reactions of mineral additives blended with cement [23-25]. Using TGA results, the ultimate chemically bound water should be determined in order to predict the hydration degree of mineral additives blended with cement. The latter is influenced by several factors, including particle size distribution, water/cement ratio, mineral addition type, and replacement level [26-29]. Pozzolans improve concrete performance by reacting with CH to form a secondary C–S–H gel, which decreases total porosity and refines pore structure, resulting in increased strength and impermeability. The atomic Ca: Si ratio of C–S–H depends on the types of pozzolanic material, mix proportion, and curing time [30]. It shows that lowering the Ca: Si ratio of C–S–H reduces microcrack width while improving macrolevel properties [31]. Scanning electron microscope (SEM) tests conducted showed that using magnetized water instead of tap water in concrete reduced the $Ca(OH)_2$ content and improved cement particle hydration, so compressive strength increased [7]. Using MW as the mixing water instead of TW reduced the number of pores [32], increased the amount of CSH [33], and produced smaller $Ca(OH)_2$ crystals [34] in specimens.

In this study, we will focus on the effect of magnetized water with silica fume on the fresh, mechanical, and microstructural properties of self-compacting concrete. For this purpose, twelve SCC mixes were produced by the inclusion of magnetic water at 1.4 Tesla and a flow rate of 9 L/min with 50, 100, and 150 cycles, as well as silica fume at 5% and 10% by weight of cement. Slump flow, T50cm, V-funnel, and L-box were used to evaluate the fresh properties. The hardened properties were evaluated, with compressive strength being evaluated at the ages of 7, 28, and 90 days, tensile strength, and bending strength at 28, 90 days. In addition to the mechanical properties, with SEM at 90 days, EDS at 90 days, and TGA analysis at 7, 28, and 90 days.

MATERIALS AND METHODS

Cement: CEM I class (42.5 N) was used throughout this study, and it was purchased from a local store (Suez Cement Company, Suez, Suez Governorate, Egypt). The cement had a specific gravity of 3.15 and was compliant with Egyptian standard specifications (4756-1/2007). The chemical analysis and physical properties of the applied cement, as confirmed by laboratory testing (per E.S.S No. 2421/2005) and Tab. 1 and 2 show the properties of the cement used in this research.

Oxide composition	Percent by Weight (%)
Silicon Oxide (SiO_2)	20.37
Aluminum Oxide (Al_2O_3)	5.14
Ferric Oxide (Fe_2O_3)	3.67
Calcium Oxide (CaO)	63.51
Magnesium Oxide (MgO)	1.03
Sulphur Trioxide (SO_3)	2.22
Loss on Ignition (L.O.I)	4.25

Table 1: Chemical composition of the cement.

Test	Test result	E.S.S Limits
Specific gravity	3.15	-----
Specific surface area (cm²/gm)	3295	≥ 2750
Setting time (min)	Initial	120
	Final	360
Compressive strength 3 days (MPa)	22.6	≥10 MPa
Compressive strength 28days (MPa)	57.1	≥42.5 MPa

Table 2: Physical and mechanical properties of the cement.

Fine aggregate: The sand utilized was siliceous natural sand; the sand was obtained from a local warehouse (Mansoura, Egypt). Testing of the used fine aggregate has complied with the Egyptian standard specifications E.S.S 1109-2008 [35]. Tab. 3 and Tab. 4 show the properties of used fine aggregate.

Property	Sand	Limits*
Specific weight	2.5	-
Bulk density (t/m³)	1.52	-
Fineness modulus	3	-
Material finer than No 200 sieve%	2.62	Less than 3%

Table 3: The physical properties of the fine aggregate.

Sieve size (mm)	0.15	0.3	0.6	1.18	2.36	4.75
Passing%	1.4	9.8	58.3	77.9	90.7	100
Limits of E.s.s(1109)	(0-15)%	(5-48)%	(25-80)%	(45-100)%	(65-100)%	(89-100)%

Table 4: Grading of used sand.

Coarse aggregate: The coarse aggregate used was rounded and was obtained from a local warehouse (Mansoura, Egypt). The used coarse aggregate tested in accordance with Egyptian standard specifications E.S.S. 1109-2008 [35]. Tabs. 5 and 6 show the properties of used coarse aggregate.

Property	Test result
Specific gravity	2.55
Bulk density (t/m³)	1.55
Maximum nominal Size	12.5
Absorption%	0.8

Table 5: physical properties of used coarse aggregate.

Sieve size (mm)	4.75	9.5	12.5	19
Passing%	2.15	64.1	96	100
Limits of E.s.s(1109)	(0-10)%	(50-85)%	(90-100)%	100%

Table 6: Grading of used coarse aggregate.

Silica Fume (SF): The silica fume used in this study as a mineral admixture was brought from Sika Company; the specific gravity of silica fume is 2.2. The chemical properties of silica fume are shown in Tab. 7 and the physical properties of silica fume are shown in Tab. 8 as derived from the manufacturer's data sheet.

SiO_2	C	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	R_2O_3	K_2O	SO_3	C1	LO1
96.0	0.6	0.25	0.6	0.3	0.6	0.2	-	0.65	0.18	0.02	0.6

Table 7: Chemical properties of Silica fume.

Result*	Property
170000	Surface area (cm²/gm)
8.00	Particle size, μm
2.20	Specific gravity

Table 8: The physical properties of the used silica fume (*by the manufacture data sheet).

Superplastizers (SPZ): Viscocrete-3425 meets the requirements for superplasticizer according to ASTM-C 494 Types G and F [36]. Tab. 9 shows the properties of the superplasticizer.

Result*	Property
Clear liquid	Appearance / color
1.08	Density (kg/lit)
4.0	PH value
40	Solid content (% by weight)

Table 9: Properties of the superplasticizer (*by the manufacture data sheet).

Water: Two types of water were used. (I) Ordinary tap water (drinking water) available in the laboratory was used in concrete mixes. (II), magnetic water (MW): To obtain the MW, water was passed through a magnetizing device with a magnetic strength of 1.4 Tesla. The water's surface tension was measured and determined to be 0.06624 N/m. The magnetizing device was manufactured by Delta Water Company in Alexandria, Egypt. It was set up by Mansoura University Laboratory. It consists of

(1) a water supply source, i.e., a container containing water that needs to be magnetized.
(2) The pump: it takes the water from the container and transfers it to the top through the pipes.
(3) The pipes: water is circulated through them to magnetize them.
(4) The calibrating valve: a 1.5' valve used to control the water's velocity as it passes through the magnetizing device.
(5) The water safety valve: it prevents water backflow.
(6) The Magnet: It magnetizes water.
(7) The Snout: It transports water from the device to another container. As shown in Fig. 1.
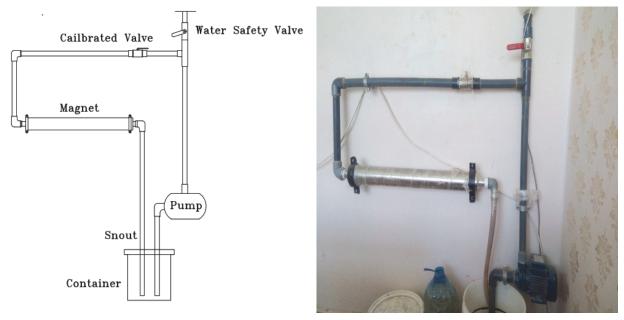

Figure 2: Magnetizing device components.

The magnetizing device is working in an acyclic way. The time of one cycle is calculated through Eqn. (1), whereas the water discharge rate is calculated to be equal to 9 lit/min and the volume of water to be magnetized is determined. Therefore, we determine the time of one cycle.

$$\text{Water discharge rate (Q)} = \text{Volume (Lit)} / \text{Time (min)} \qquad (1)$$

And to calculate the time required for the number of cycles is calculated by Eqn. (2).

$$\text{Cycles Time (min)} = \text{No of Cycles x One cycle time (Sec)} / 60 \text{ (Sec/min)} \qquad (2)$$

Mixtures proportions: To achieve the goals of this study, SCC mixes were produced with a W/C ratio of 0.35. The cement content was 550 kg/m³, the sand/cement ratio was 1:1 by weight, and by replacing silica fume (5% and 10%) by the weight of cement and the superplasticizer ratio of 3% of the total weight of cement content, the experimental work provided 12 mixes, which were divided into three groups, which are divided as follows: without SF, 5% silica, and 10% silica, each with four mixes. On an individual basis, TW water was applied in the first mix, whereas MW water was used in the second, third, and fourth mixes, with the number of cycles varying between 50, 100, and 150 on an individual basis to study the effect of the number of cycles of MW on the fresh, mechanical, and microstructural properties of self-compacting concrete. The proportions of the mixtures are displayed in Tab. 10.

Groups	Mix	Mix ID	No of cycles	Cement Kg/m³	SF Kg/m³	Coarse aggregate Kg/m³	Sand Kg/m³
1	M1	CTRL	0	550	-	818.345	818.345
	M2	CTRL	50	550	-	818.345	818.345
	M3	CTRL	100	550	-	818.345	818.345
	M4	CTRL	150	550	-	818.345	818.345
2	M5	5SF	0	522.5	27.5	813.35	813.35
	M6	5SF	50	522.5	27.5	813.35	813.35
	M7	5SF	100	522.5	27.5	813.35	813.35
	M8	5SF	150	522.5	27.5	813.35	813.35
3	M9	10SF	0	495	55	808.35	808.35
	M10	10SF	50	495	55	808.35	808.35
	M11	10SF	100	495	55	808.35	808.35
	M12	10SF	150	495	55	808.35	808.35

Table 10: Mix proportions of Concrete used in this study.

MIXING, CASTING PROCEDURE AND CURING

As illustrated in the process sequence, the mixing procedure for all mixes is as follows: Firstly, the measured amounts of cement and sand were carefully mixed for two minutes without the addition of water in a mechanical horizontal pan mixer. After that, add the silica fume and mix at low speed for two minutes. The water and superplasticizer were poured over the mixture for about five minutes, until it was distributed uniformly. Finally, pouring the mixture into samples without compacting it, allowing it to set for 24 hours, and keeping samples in a water curing tank for 7, 28, and 90 days for compressive strength and 28 and 90 days for bending and tensile strength tests.

Fresh Concrete Tests
Slump flow and T50cm Tests: Instead of using the conventional slump test, the slump flow test was used to assess the flowability of SCC. According to BS EN 12350-8[37], the test was carried out. The cone was filled with concrete and then

vertically removed. As a result, the concrete on the base plate was left to expand freely. Then, in two perpendicular directions, the average final diameter of spread out concrete was determined, and the T50cm Test is the time recorded in seconds for the concrete to reach a diameter of 500 mm. Decreased time (T50cm) gives evidence of increased fluidity and decreased viscosity.

V-funnel: The V-funnel test is used to assess the viscosity and filling ability of concrete according to BS EN12350–9[38] Concrete should be poured into a standard V-shaped funnel without compacting it so that the concrete surface is level with the edge of the funnel. Afterwards, the bottom valve is opened and the required time for concrete to empty the mould is reported as the outcome of the test.

L-box: This test consists of a rectangular-section box in the shape of an L, with a vertical and horizontal section separated by a moveable gate, in front of which vertical lengths of reinforcement bar are fitted. The vertical section is filled with concrete, and then the gate is lifted to let the concrete flow into the horizontal section. When the flow has stopped, the height of the concrete at the end of the horizontal section is expressed as a proportion of that remaining in the section (H2/H1). This is an indication of passing ability according to BS EN12350–10 [39].
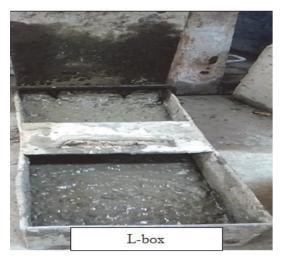
Figure 3: Fresh properties Tests.

Hardened Tests

Compressive strength Test: The compressive strength test was performed at 7, 28, and 90 days in compliance with the BSEN12390-3:2019 standard [40]. At each testing age, three specimens (10x10x10cm) from each mixture were tested, and the average was taken. All specimens were examined by utilizing a compression hydraulic testing machine with a capacity of 200 tones and an accuracy of 0.5 tons. The specimen must be positioned in the machine's center. This was done in the concrete laboratory of the faculty of engineering at Mansoura University.

Splitting Tensile strength: The splitting tensile strength test was conducted on three cylinders of diameter 100 mm and height 200 mm at 28 and 90 days, and the average was taken according to the BS EN 12390-6:2019 standard [41]. All specimens were examined by utilizing a hydraulic testing machine with a capacity of 200 tons. The specimen must be aligned with the center of the machine.

Flexure strength: Bending strength tests were carried out on beams measuring 100 x 100 x 500 mm using a flexure testing machine and subjected to incremental loading at a rate of 0.20 kN/s till failure according to BS EN 12390-5:2019 [42]. An average of three specimens was calculated for each mixture. Strength was tested for 28 and 90days.

Figure 4: Hardened properties Tests.

MICROSTRUCTURAL CONCRETE TESTS

Thermo Gravimetric Analysis (TGA) and Differential Thermal Analysis (DTG)

Thermogravimetric analysis (TGA) was done on around 50 mg of the resultant powder, which was made with a water to binder ratio of 0.35 and stored at 20 °C in 20 mL sealed plastic jars. To stop hydration and carbonization, it was broken into little bits and immediately immersed in acetone. At the ages of 7, 28, and 90 days after curing, differential thermal analysis (DTG) was found. Temperature peaks were investigated. The majority of endothermic peaks

appear at their highest temperatures. TGA investigations revealed the decomposition of cement hydrates by diminishing increments on TGA curves and endothermic peaks on the derivative TGA. The degradation of cement hydrates can be separated into three stages [43]. The first phase occurs between 25 and 400, and in the second phase, the hydrates decompose between 400 and 600 °C, corresponding to the dehydroxylation of Portlandite (Ldx). Between 600 and 800 C, the third phase owing to CaCO3 decarbonation was reported as (Ldc). The first peak, which occurs between 25 and 400 oC, can potentially be split into two parts. Within the temperature range of 25–105 °C, the first phase corresponds to free water, and the second phase between 105–400 °C represents the dehydration reaction (Ldh). According to Loukili [44] and Monteagudo [45].Four mixes, M1, M4, M8, and M12, were chosen to be used in the test.
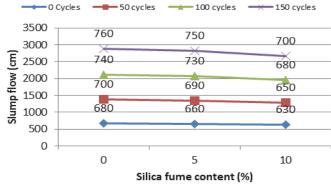
Scanning Electron Microscope (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDS)
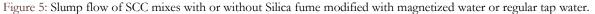The microstructure analysis was important because it simplified many of the concrete macrostructure's features and phenomena. Scanning electron microscopy (SEM) can be regarded as analyzing the CH and C-S-H layers in a concrete microstructure. The microstructure analysis was important because it simplified many of the concrete macrostructure's features and phenomena. Scanning electron microscopy (SEM) can be regarded as analyzing the CH and C-S-H layers in a concrete microstructure. The tested samples were collected from the innermost core of the crushed specimens after the compressive strength test at the age of 90 days. The test was carried out in the Faculty of Agriculture, Mansoura University, Egypt, using an electronic microscope of the type JEOL JSM-651OLV with a magnification capacity of 300,000 times. For the observation of specimens, five magnifications were chosen: 3000X, 1500X, and 1000X. Four mixes, M1, M4, M8, and M12, were chosen to be used in the test. An energy-dispersive x-ray spectroscopy (EDS) type (Oxford X-Max 20) was also used to determine the elemental composition of the observed specimens.

RESULTS AND DISCUSSION

Effect of magnetized water on the fresh properties of SCC
Slump flow and T50 cm tests: The slump flow and T50cm tests evaluate the self-consolidating concrete's deformability, flow-ability, and flow velocity in the absence of obstacles. [46] The results obtained are within EFNARC's acceptable limit. The results of the slump flow and T50 cm tests are shown in Figs. 2 and 3, respectively. According to EFNARC [47], the allowable slump spread for SCC is between 550 mm and 800 mm, and the time for the concrete to reach a diameter of 50 cm (T50) for all the mixtures was less than 5 s. All SCC mixtures showed flow time values in the range of 2–5. All results were within acceptable limits. Fig. 5 shows In comparison to the SCC control mix created with tap water, the use of magnetic water increased slump flow. This happens because the magnetized water molecules penetrate the layer more easily than tap water during hydration. As reported by [18, 48], cement particles repel each other due to the presence of magnetic water, which causes the production of hydration layers surrounding these particles, so the use of magnetized water had a positive impact on the mix's workability. As shown in Fig. 5, when water passes through the magnetic field 150 times rather than 100, a higher slump value is achieved in all SCC mixes. The effect of using magnetized water becomes more prominent as it passes through the magnetic field more often [49]. However, with the presence of silica fume, the workability decreases in comparison with control [50]. With increasing silica fume content, the workability decreases [51]. Fig. 6 depicts the T50 results, which show that magnetized waters cause T50 to decrease with increasing magnetization cycles [52].

Figure 5: Slump flow of SCC mixes with or without Silica fume modified with magnetized water or regular tap water.
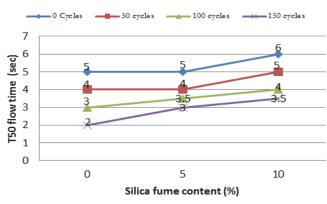
Figure 6: T50 results of SCC mixes with or without Silica fume modified with magnetized water or regular tap water.

V-funnel: Fig. 7 shows the results of the V-funnel test of all SCC mixes with magnetized water and regular tap water. The V-funnel test is usually used in order to assess the viscosity for the filling ability of SCC mixes as shown in Fig. 4, the flow time values for all of the SCC mixes were between 6 and 12 s, which were the EFNARC limit values [47]. Also shows that the magnetization of the mixing water reduces the flow time in the V-funnel test. This agrees with [18], which reported that SCC mixes become less viscous in the V-funnel as a result of magnetizing water. Fig. 7 also shows the V-funnel flow time decreases when the number of cycles increases.
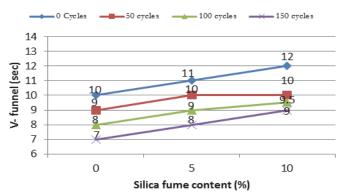

Figure 7: V-funnel test of all SCC mixes with or without Silica fume modified with magnetized water or regular tap water.

L-box Test: As given in Fig. 8, the result for all SCC mixes was 0.92 to 1, which was the EFNARC limit value [47]. and also showed that SCC mixes made with magnetic water had a better passing ability than those made with regular tap water. The SCC control mix created with magnetic water had a higher blocking ratio than the SCC control mix made with tap water, which had the highest blocking ratio of the control mix with 150 cycles of magnetized water.
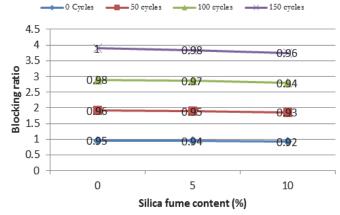

Figure 8: L-box test of all SCC mixes with or without Silica fume modified with magnetized water or regular tap water.

Effect of magnetized water on the hardened properties of SCC

Compressive strength: For all specimens, SCC mixes with and without silica fume. At all testing ages, the compressive strength of SCC mixes made with magnetized water is higher than that of mixes made with tap water, as it was improved by passing the mixing water via a permanent magnet. Because magnetized water has a larger specific area coMPared to tap water, when the water is subjected to a magnetic field, water clusters decrease [32, 49, and 53]. As a result, many water molecules are available in the hydration process; many reactions occur between them and the cement molecules, and the compressive strength increases [32, 49, and 33]. Fig. 9 depicts the compressive strength of SCC mixes with (0%, 5%, and 10% Silica fume) prepared with magnetized water and regular tap water. Fig. 9(a) shows that the compressive strength of all SCC mixes prepared with magnetized water is higher than that of those prepared with tap water at all curing ages when the number of cycles is increased. The strength increased from 0 to 150 cycles, where the strength increased by 20% with 150 cycles compared to tap water. This means that the use of magnetized water in the SCC mixes with or without any additives improves their compressive strength and is in direct relationship with the number of magnetization rounds as reported in Ghorbani et. al. [32]. Fig. 9(b,c) shows that, regardless of the type of mixing water used, the addition of 5% and 10% silica fume to concrete increases its compressive strength when compared to concrete without silica fume, as reported in [54].Fig. 9(b) shows that the highest compressive strength ever measured was at 5% Silica with 150 cycles at 28 days, where it increased by 32% compared to the control. Firstly, when the number of cycles increases, the water treatment also increases, and thus the compressive strength increases. Secondly, the hydration of cement is faster and more complete with magnetically treated water. Thirdly, magnetized water needs a small substitution ratio of cement in order to achieve the optimum reaction. Fourthly, the presence of amorphous silica that is highly reactive can react with CH to generate CSH, a key hydration product that provides cementitious materials with binding and strength properties. The small size of silica fume particles fills in the pores of the hardened cement matrix, improving the hardened paste's strength and density [54]. Fifth, the optimum replacement proportion of PC by SF is 5% to produce high strength and adequate workability. If the replacement level is exceeded, the strength decreases [55].
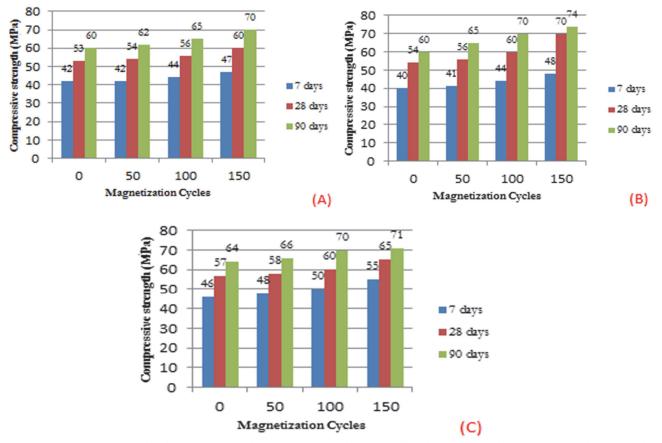

Figure 9: Compressive strength of SCC mixes with (a)0%, (b)5%and (c)10% Silica fume prepared with magnetized water and tap water.

Flexure strength: Fig. 10 depicts the results of the flexure strength test on SCC mixes with (0%, 5%, and 10%) silica fume prepared with magnetized water and tap water after 7, 28, and 90 days of curing in water. Fig. 10(a) shows that the flexure strength for all SCC mixes prepared with magnetized water is higher than that of those prepared with tap water at all curing ages, similar to the results of compressive strength. The flexure strength values for the control mix after 28 and 90 days of curing were (5.38–8.05 MPa), while these values for the magnetized water mixes were (6.44–9.052 MPa, 8.15–11.26 MPa), indicating that the use of magnetized water in SCC mixes with or without additives improves flexure strength and has a direct relationship with the number of magnetization rounds as reported by Ghorbani et al [32].According to [54], the use of silica fume in SCC mixes with either magnetized or regular tap water increased the flexure strength of SCC mixes compared to the mixes without silica fume, as shown in Fig. 10(b,c), and the flexure strength of SCC mixes increases with the increase in silica fume content, as shown in [56].
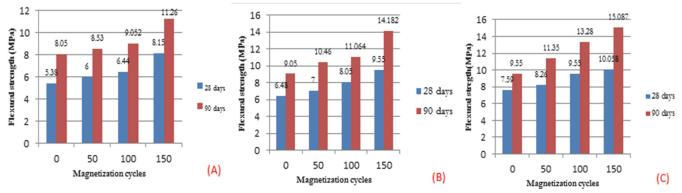

Figure 10: Flexure strength of SCC mixes with (a) 0%, (b) 5%and (c)10%Silica fume prepared with magnetized water and tap water.

Splitting tensile strength: Fig. 11 depicts the results of a split tensile strength test performed on SCC mixes containing (0%, 5%, and 10%) silica fume prepared with magnetized water and tap water after 28 and 90 days of curing in water. Fig. 11(a) shows that the splitting tensile strength for all SCC mixes prepared with magnetized water is higher than that of those prepared with tap water at all ages of curing, similar to the results of compressive and flexure strength. The splitting tensile strength values of the control mix after 28 and 90 days of curing were (3.05–4.14 MPa), while these values for the mixes with magnetized water were (4.15–4.65 MPa and 4.85–5.092 MPa). This means that the use of magnetized water in the SCC mixes with or without any additives improves their splitting tensile strength and is in direct relationship with the number of magnetization rounds as reported in Ghorbani et.al [32]. According to [54], the use of silica fume in SCC mixes with either magnetized or regular tap water increased the splitting tensile strength of SCC mixes compared to the mixes without silica fume, and it decreases with increasing silica fume content, as shown in Fig. 11(b,c).It was observed that a very high percentage of silica fume had no effect on splitting tensile strength, and the highest split tensile was observed in 5% of silica fume.
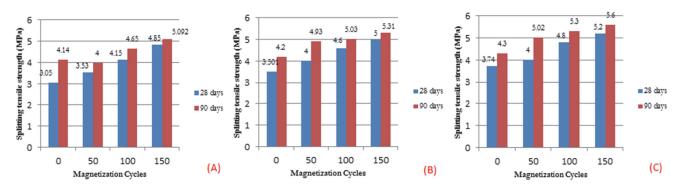

Figure 11: Splitting tensile strength of SCC mixes with (a) 0%, (b) 5%and (c)10% Silica fume prepared with magnetized water and tap water.

EFFECT OF MAGNETIZED WATER ON THE CEMENT PASTE OF SCC

Thermo Gravimetric Analysis (TGA) and Differential Thermal Analysis (DTG)

Thermo gravimetric analysis (TGA) was used to calculate the degree of hydration of various mixes based on the mass difference between 25 and 1000 °C. A traditional experiment (TGA) was used to obtain mass loss data on cement pastes, and the hydration degree of the pastes was then calculated [43].The calculated hydration degree of cement pastes is shown in Fig. 12. It shows that the rate of hydration enhanced with magnetic water is increased by 11%, 10%, and 7% for 7, 28 and 90 days compared with tap water. This is because water passing through a magnetic field prevents cement particles from accumulating and allows water molecules to penetrate more easily into the cement particles, enhancing the rate of hydration [18]. And they also showed that with 5% silica fume, the rate of hydration increased by 4%, 19%, and 13% for 7, 28 and 28 days because of the addition of silica fume improves the water absorption of concrete due to the high specific area of silica fume. Furthermore, there was an increase in the rate of hydration reaction [57]. The DTG thermograms of control specimens are shown in Fig. 13:16.
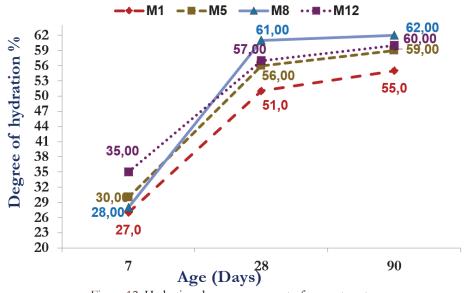

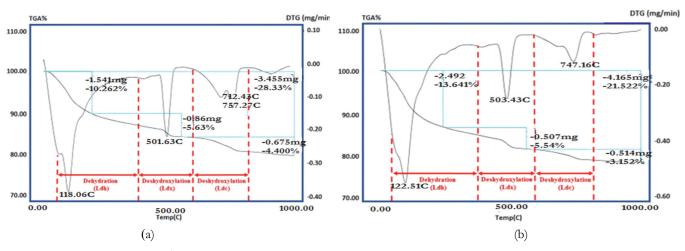Figure 12: Hydration degree assessment of cement paste.

Figure 13: TGA/DTG of cement paste of the control at the ages of (a) 28 days and (b) 90 days.
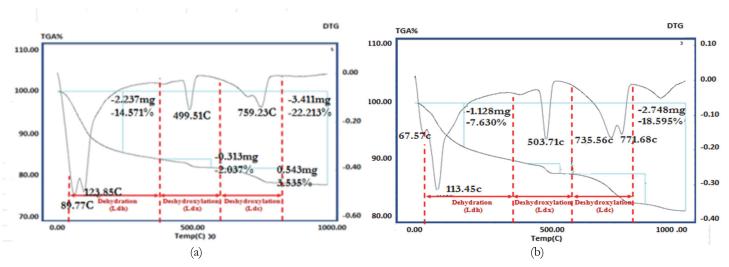
Figure 14: TGA/DTG of cement paste of the control with 150 cycles of MW at the ages of (a) 28 days and (b) 90 days.
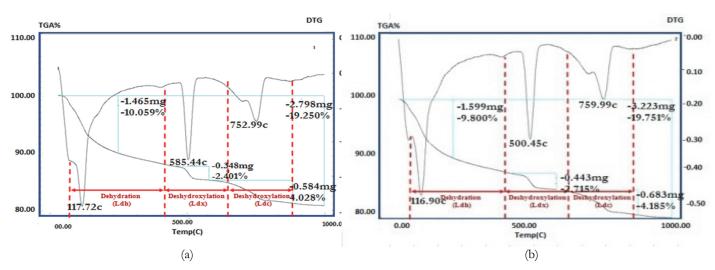

Figure 15: TGA/DTG of cement paste of 5% SF with 150 cycles of MW at the ages of (a) 28 days and (b) 90 days.
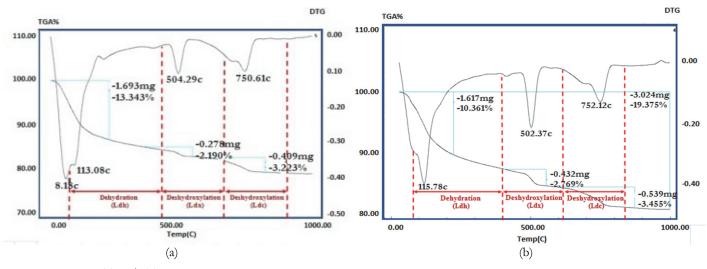

Figure 16: TGA/DTG of cement paste of 10% SF with 150 cycles of MW at the ages of (a) 28 days and (b) 90 days.
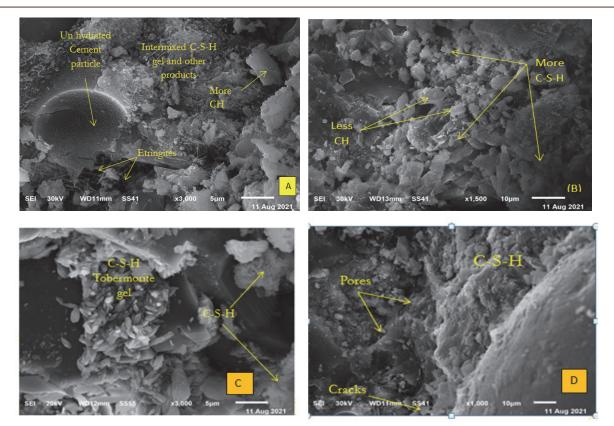
Figure 17: SEM images for (A) SEM image for the 100% OPC Mix1 at 90 days, (B) SEM image for the 100% OPC + 150 Cycles of magnetized water Mix5 at 90 days, (C) SEM image for Mix(5) the 100% OPC +5% silica fume + 150 Cycles of MW at 90 days and (D) SEM image for the Mix(D) 100% OPC+ 10% silica fume+ 150 Cycles of MW at 90 days.

EFFECT OF MAGNETIZED WATER ON MICROSTRUCTURAL PROPERTIES OF SCC

The Scanning electron microscope (SEM) tests

The SEM test was used to examine the microstructure properties in the transition zone and paste around aggregates in mixes M1, M5, M8 and M12. The SEM tests were carried out after 90 days of curing with a magnification of 1000X, 1500, and 3000X, and the results are shown in Fig.17, from this test, we can conclude two things.

(1) The effect of magnetized water on the microstructure of SCC: by comparing Figs. 17(a) and (b), we find that mixtures mixed with tap water, as shown in SEM images, represent the aggregation of poorly crystalline C-S-H gel particles with at least one dimension (1 to 100 nm). Also, there are intermixed C-S-H gel and other products, unhydrated cement particles, and ettringites (hexacalcium aluminate trisulfate hydrate)). However, by incorporating magnetized water, as shown in SEM images, we find that magnetized water plays an effective role in improving concrete, resulting in smaller calcium hydroxide (CH), allowing for more effective hydration of cement particles and a denser calcium silicate hydrate (C-S-H) gel. This is because when water passes through a magnetic field, part of the hydrogen bonds break, the number of single molecules or smaller clusters increases, and the cohesion forces between water molecules weaken, resulting in a larger average space of water molecules and improved water activity, allowing it to penetrate cement particles more deeply, effectively, and completely [58-59]. This difference explains why the magnetized water can increase the compressive, tensile, and flexural strengths of concrete.

(2) The effect of magnetized water with silica fume on the microstructure of SCC: comparing Figs. 17 (C) and (D), we find that the results are better at a lower substitution ratio of silica fume. As a result of the SEM image, we find at 5% silica fume there are two products of calcium silicate hydrate (C-S-H). Firstly, (C-S-H) is the primary product of the cement hydration process. Secondly, (tobermorite gel) secondary, resulting from the reaction of silica with calcium hydroxide resulting from the hydration of cement, As a result, the two products led to fewer calcium hydroxide (CH) pores and more calcium silicate hydrate (C-S-H) However, at 10% silica fume, there are a few pores and cracks because of

the reaction that occurs between water and cement, which needs the optimum cement particle dispersion using magnetization [60]; and for this reason, the same number of cycles has not been reached to gain the best results in mixtures of 10% SF because the content of cement has been reduced, so the compressive strength has decreased compared to 5% SF.

As mentioned in SEM results, we find that the magnetized water can protect the concrete internally and externally because there is more C-S-H, less CH, and the concrete becomes denser, so the cracks and pores decrease. In addition, the concrete will be protected from any attack from sulfates or chlorides and will not be prone to fracture. As reported in previous studies, with the use of magnetized water in concrete, an improvement was observed in the resistance of concrete to sulfuric acids and early-age shrinkage cracking. It was also reported that the initial fracture energy Gf and total fracture energy GF increased, so the fracture toughness improved [61-63].

Energy-dispersive X-ray spectroscopy (EDS) analysis

To obtain the elemental composition, the EDS results are obtained by combining M1, M5, M8, and M12. The ratio of the atomic percent of Ca/Si for tested mixes is one of the main indicators that has been observed. Wollastonite (Ca) and Silicon dioxide (Si) EDS test results are shown in Figs. 18, 19 and Tab. 11. EDS results show the atomic Ca/Si ratio for M1, M5, M8 and M12 is 2.65, 3.05, 2.01 and 2.21. The compressive strength of these mixes is in the same range, indicating there is a significant relationship between compressive strength and the atomic Ca/Si ratio, whereas the compressive strength at 28 days was 53 MPa, 60 MPa, 70 MPa, and 65 MPa, respectively. It can be confirmed that the lower Ca/Si ratio reflects the compressive strength enhancement. [64]. this confirms the results of previous tests.

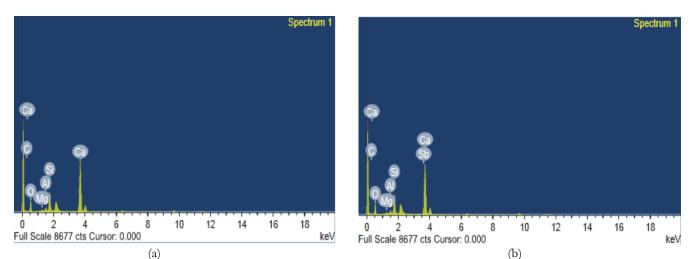Figure18: (a) EDS (X-ray) analysis of the mix(1) 100% OPC mix at 90 days and (b) EDS (X-ray) analysis of the mix(5) 100% OPC of 150 Cycles of magnetized water at 90 days.
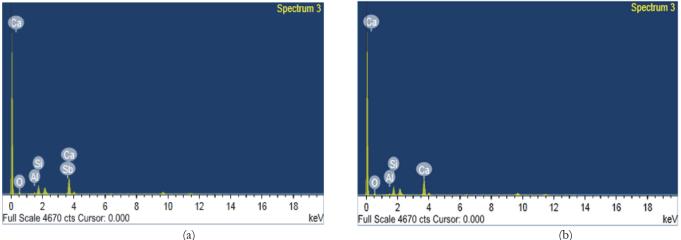

Figure19: (a) EDS (X-ray) analysis of the mix (M8)100% OPC+ 5% Silica fume mix with 150 Cycles of magnetized water at 90 days(b) EDS (X-ray) analysis of the mix(M12) 100% OPC+ 10% Silica fume mix with 150 Cycles of magnetized water at 90 days.

Element	M1		M5		M8		M12	
	Weight%	Weight%	Weight%	Weight%	Atomic%	Atomic%	Atomic%	Atomic%
O	47.55	39.84	35.24	47.00	66.34	59.13	58.67	62.55
Ca	34.92	33.50	35.22	37.54	21.15	23.59	19.69	18.34
Si	8.31	8.84	12.28	12.13	9.56	11.74	7.42	6.00
Al	1.59	1.54	2.23	2.33	1.95	2.22	1.34	1.24
C	5.80	5.12	-	-	-	-	10.04	10.17
Mg	0.90	0.88	-	-	-	-	0.85	0.78
Sb	-	10.28	15.04	-	-	3.32	1.99	-

Table 11: Elemental composition of mixes (M1, M5, M8, and M12).

CONCLUSION

In the present research, the effect of magnetized water on the fresh, mechanical, and microstructural properties of SCC mixes was investigated, incorporating different contents of silica fume. For this purpose, Slump, V-funnel, L-box, Compressive Strength, Tensile Strength, Flexural Strength, SEM, EDX, and TGA/DTG Tests The following conclusions can be drawn according to the results of this study:

1- In V-funnel and T50 tests, magnetized water causes a decrease in the viscosity of SCC mixes. It also improves the passing ability of SCC mixes in the L-box test.
2- Magnetized water significantly improved the workability where an increase of 11% was recorded compared to tap water.
3- The mixes containing magnetized water in all ages have higher compressive, splitting, and flexural strengths than their control mix.
4- The best results of magnetized water on the fresh, mechanical, and microstructural properties of self-compacting concrete were achieved at 150 cycles of MW. The better its treatment, the greater its magnetization.
5- The best results in the increase in compressive strength reached 32% compared to the control mix at 28 days in mix M8, which contains 5% SF with 150 cycles of MW.
6- The best results in the increase in tensile and flexural strength reached 22% and 40%, respectively, at 90 days.
7- Based on SEM results, using MW instead of TW as mixing water resulted in fewer pores, more C-S-H, and smaller Ca (OH) 2 crystals in the specimens.
8- Silica fume increases the additional formation of C-S-H, lowering the Ca: Si ratio based on EDS results and reducing microcrack width, resulting in improved mechanical properties.
9- Based on TGA results, the rate of hydration of a mix M8 including 5% silica with 150 cycles of MW was reached by 61% at 28 days.

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