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Interaction of magnetic water, silica fume and superplasticizer on fresh and hardened properties of concrete

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Abstract. After passing through a magnetic field, the physical quality of water improves, and magnetic water (MW) is produced. There are many investigations on the effects of magnetic field on water that shows MW properties like saturation and memory effect. This study investigates the fresh and hardened properties of concrete mixed with MW, which contains silica fume (SF) and superplasticizer (SP). The test variables included the magnetic field intensity for producing MW (three kinds of water), SF content replaced cement (0 and 10 percent), water-to-cementitious materials ratio (W/CM=0.25, 0.35 and 0.45) and curing time (7, 28 and 90 days). The results of this study show that MW had a positive impact on the workability and compressive strength of concrete. By rising the intensity of the magnetic field which was used for producing MW, its positive influence on both workability and compressive strength improved. MW had greater positive impacts on samples containing SP that did not have SF. Moreover, the best compressive strength improvements of concrete achieved as W/CM ratio decreased.

Keywords: magnetic water; silica fume; superplasticizer; concrete

1. Introduction

Concrete is one of the most important materials in construction industry. Nowadays, the main Characteristics of concrete like compressive strength, workability and durability is widely considered by structural engineers. Increasing the compressive strength of concrete has many advantages such as downsizing the section of members and reducing the costs. Also workability of fresh concrete is very useful for concrete placing. Increasing durability of concrete has great impact on the life of structures and reduces production costs.

Utilizing pozzolans is one of the most common ways to increase the strength and service life of concrete structures. One of the most frequently used pozzolans in industrial projects is silica fume (SF). SF is a byproduct of the smelting procedure in the silicon and ferrosilicon industry. Its particles are tremendously fine, with more than 95% of the elements finer than 1μm and composed mainly of pure silica in non-crystalline shape. Excessive fineness and very high amorphous silicon dioxide content made SF a very immediate pozzolanic material. According to a number of studies, SF used at the suitable replacement level can piercingly enlarge the durability, strength of concrete

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and decrease its permeability (Saridemir 2013, Toutanji *et al*. 2004, Poon *et al*. 2006, Mazloom 2008, Soroushian and Alhozaimy 1995, Mazloom and Mahboobi 2017). Currently, SF is widely used to achieve high performance concrete mixtures (Elahi *et al*. 2010, Valipour *et al*. 2013).

Additionally, plasticizers and superplasticizers (SP) are used to increase the workability and reduce the amount of water in any type of concrete, but these materials also require multiple workshop needs. By induction of negative charge on cement particles, SP scatter the particles and guide them to move more comfortable and quicker between water molecules. The chemical composition of SP has significant effect on its performance (Janowaska-Renkas 2013, Mardani-Aghabaglou *et al*. 2013, Karamloo *et al*. 2016). The ones that are based on polycarboxylate are the newest and most effective types of them (Elżbieta 2013).

Magnetic Water (MW) refers to water passed through a magnetic field to improve its properties. The magnetic field is created by electromagnets and also strong permanent magnet. It is worth noting that MW is extensively used in agriculture and industry nowadays (Surendran *et al*. 2016, Bogatin 1999). Hydrogen and Oxygen atoms of the water molecules consist of positive and negative centers, respectively. Because of asymmetric electronic allocation of water molecule, an electrical dipole moment is formed. Dissolved salts involved negative and positive charges, exist as dissolved ions draw towards the water molecules. According to Faraday's law, charged particles moving through a magnetic field with a speed perpendicular to the magnetic field produce a local electrical field perpendicular to both particle the magnetic field and velocity. An induced electrical current is generated when a conductive fluid is passed through a magnetic field under the correct circumstances, and effectively oriented the charged particles is suspended in the solution (Bernardin and Chan 1991).

Some researchers have worked on the impacts of passing water through magnetic fields (Gabrielli *et al*. 2001). One of these effects is dispersing the arrangement of water molecules (Al-Qahtani 1996, Fu and Wang 1994). In this case, the magnetic force breaks apart water clusters into single molecules and produce the smaller ones; consequently, the action of water progresses. Furthermore, investigators show the magnetic field influence on the hydrogen bonds between water elements that alters the angle between the hydrogen molecules. MW decreases the angle between the hydrogen molecules from 104.5 to 103 degrees (Yan *et al*. 2009). Molecule clusters in water are produced by hydrogen bonds and these clusters cause the abnormal behavior of water in freezing (Fletcher 1970). This impact of the magnetic field was examined from several aspects (Szczes *et al*. 2011). Dispersion of water molecules can improve them to better participation in the hydration process.

Another research showed that MW had a memory effect. It means, depending on the intensity of magnetic field, the temperature and time duration of influence of magnetic field on water changes, and as time goes on, its magnetism will be lost (Pang and Deng 2009). This research showed that when water is influenced by a special magnetic intensity, for example 0.44 Tesla, after about 60 minutes, water will be magnetized completely, and after another 60 minutes, its effect on water will be lost. Pang and Deng (2009) believe that by increasing the intensity of magnetic flied, the magnetizing time will increase too. Some other researches claim that MW can be kept in reservoir for 0-12 hours (Fu and Wang 1997, Su and Wu 2000, Su and Lee 1999). In this study, immediately after producing MW, it is utilized in concrete mixtures.

There are extensive researches on the usage of MW in concrete that show MW can increase the compressive strength and workability of concrete, decrease bleeding of it and enhance the resistant of concrete to freezing and thawing (Su *et al*. 2000, Su *et al*. 2003, Honarmand Ebrahimi 2012, Reddy *et al*. 2014, Su and Lee 1999, Chau 1996, Abavisani *et al*. 2017). Some other benefits exist

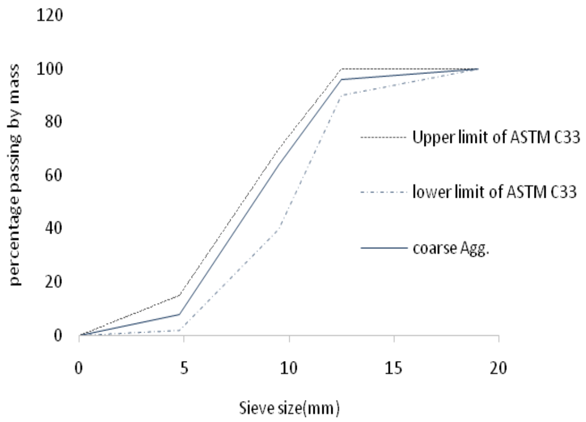

Fig. 1 Coarse aggregate grading

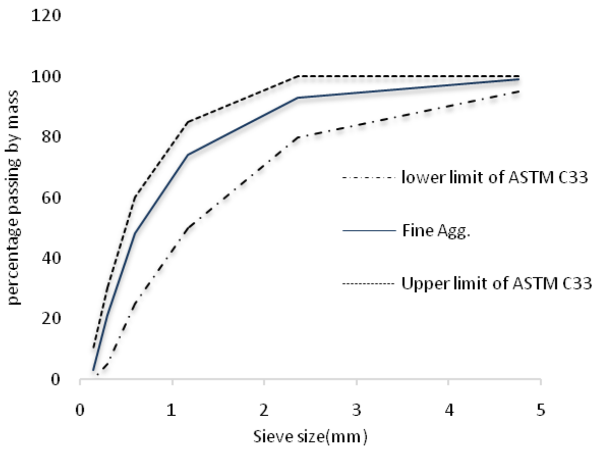

Fig. 2 Fine aggregate grading

in constructing concrete with MW. It decreases the quantity of cement and chemical admixtures, thus MW reduces environmental pollution. Some researchers also claim that when concrete is cured in magnetic field, its compressive strength improves (Wang and Wu 1997). While the hydration of cement is in progress, MW can penetrate the core zone of particles more easily. Therefore, MW can improve the hydration process and develop concrete properties.

In fact, the present study investigates the effects of MW on concrete mixes containing SF and SP. For this purpose, the magnetic field is produced by a current-carrying solenoid, which is a kind of electrical magnet. The advantage of these types of field compared to the magnetic fields produced by permanent magnets is their adjustability and possibility to produce stronger fields. Their main disadvantage is the cost of energy consumption. This study concentrates on three mix designs with W/CM ratios of 0.25, 0.35 and 0.45.

2. Experimental investigation

Table 1 Physical properties of aggregate

Aggregate	Water absorption (%)	Specific gravity	Maximum size (mm)
Coarse	1.42	2.64	12.5
Fine	2.63	2.55	4.75

2.1 Materials

Fine and coarse aggregate used in this study were graded according to the requirements of ASTM C33, as shown in Figs. 1 and 2. Table 1 shows the physical properties of coarse and fine aggregate. Water absorption and specific gravity of coarse and fine aggregate is respectively measured according to ASTM C127 and ASTM C128.

The samples were prepared using the municipal tap water of Tehran. Magnetization of water was carried out by passing the water through a magnetic field. Because of short magnetic memory of water, after producing MW in the laboratory, it was used immediately.

The utilized Portland cement type I was produced by Tehran Cement Company and SF was produced by Iran Ferrosilicon Company. The properties of cement and SF are shown in Table 2. In this study, SF was used to replace cement in mass-for-mass bases.

Also, the used SP was based on polycarboxylate ether. This product was a light brown fluid with the specific gravity of 1.07 g/cm^3 and alkali number from 5 to 6 that was produced by LG-Chem Company.

2.2 Mix proportions

The primary mix design for each W/CM ratio of 0.45, 0.35 and 0.25 was prepared according to ACI 211. These mixes were made and optimized to achieve appropriate concrete. By substituting 10% of the weight of cement by SF, six final mix designs were achieved as shown in Table 3.

2.3 Magnetic water

In order to produce MW, a current-carrying solenoid was used. The passage of water through the magnetic field was done by a 15-mm diameter copper pipe. In fact, the magnetic permeability of copper and water are very close, so there will be a chance that all of the magnetic flux passes through the water. With 6.8 cm length, the solenoid coil wrapped 3250 rounds around the copper pipe using lacquer coated wire with the diameter of 1 mm; so wire density per unit length of the pipe (N) was in maximum feasible level. In order to prevent damages, the coil protected by a special cover. The coil and schematic picture of MW device are shown in Fig. 3.

For creating a uniform magnetic field, direct electric current was necessary, which was provided by a direct power supply. The change of magnetic field strength was adjusted by changing the electrical flow. The current flows through the device were 1.5 and 2 amperes. Based on Eq. (1), parameters B, μ, N and I are magnetic field intensity, magnetic constant, wire density per unit length of pipe and electric current (Purcell and Morin 2009). The applied magnetic fields were 0.09 T and 0.12 T, respectively.

Therefore, three ranges of water were used, tap water of Tehran (W0), MW produced by the magnetic fields of 0.09 T (W1) and 0.12 T (W2). The water flow to pass through the magnetic field was 18 L/h.

Table 2 Physical and chemical properties of cement and SF

Chemical compounds (%)	Cement	SF
SiO_2	22.2	89.3
AL_2O_3	3.3	1.2
Fe_2O_3	3	0.7
CaO	60.3	0.6
SO_3	0	0.5
MgO	<5	4.5
Na_2O	0.15	1.1
K_2O	0.5	2.1
LOI	<3	-
Physical properties		
Special Weight (ton/m^3)	1.33	0.245
Blaine (cm^2/gr)	>2800	-

Table 3 Mix designs used in present research

Mix design	Aggregate		Water	Cement	SF	SP	W/CM
	Coarse	Fine					
	(kg/m^3)						
C1	1065	685	130	520	-	2.21	0.25
C2	1065	685	130	468	52	2.21	0.25
C3	1000	660	195	555	-	1.7	0.35
C4	1000	660	195	500	55	1.7	0.35
C5	960	640	220	485	-	-	0.45
C6	960	640	220	437	48	-	0.45

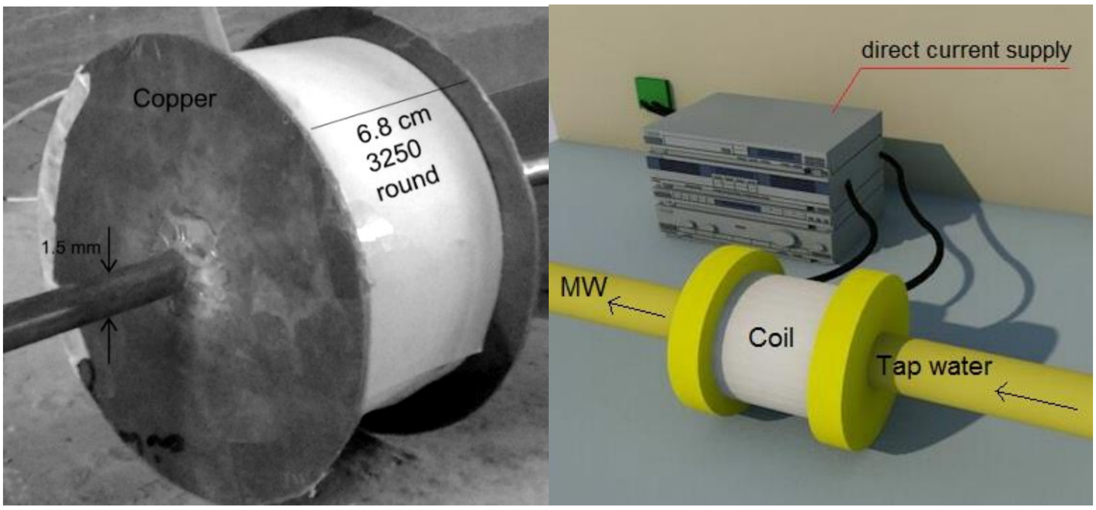

Fig. 3 Solenoid coil and schematic device used for producing magnetic water

Table 4 The results of slump tests

Mix design	W/CM	Slump for W0 (cm)	Slump for W1 (cm)	Slump for W2 (cm)
C1	0.25	17	19	20
C2	0.25	0	2	2
C3	0.35	17	20	23
C4	0.35	0	3	4
C5	0.45	9	11	9
C6	0.45	0	2	2

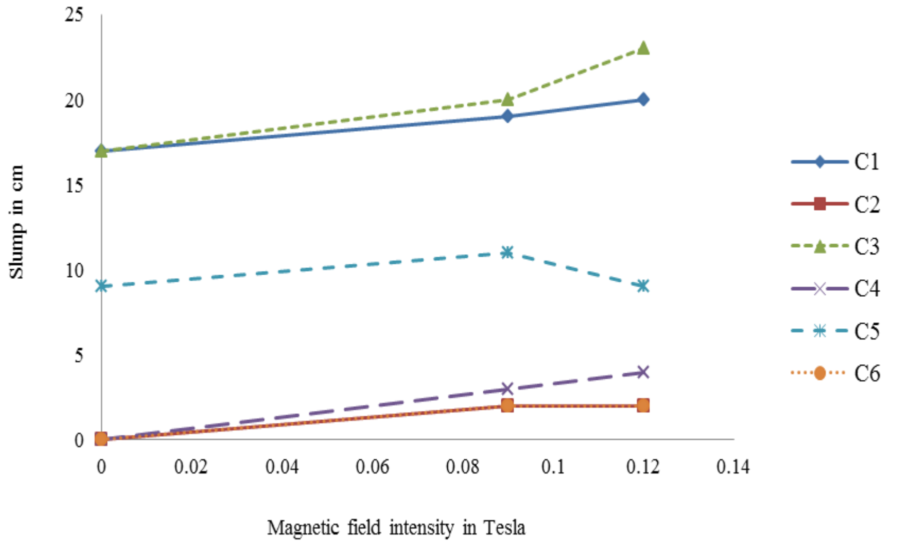

Fig. 4 Effect of magnetic field intensity on workability of fresh concrete

$$B = \mu \times I \times N \quad (1)$$

2.4 Experimental procedures

ELE 200-ton compressive test machine is used in this research. The compressive strengths of 10 cm cubic samples were measured after curing in water at 23±2℃ for 7, 28 and 90 days. Making and curing the specimens were according to ASTM C 31. Slump test was used according to ASTM C 143 for monitoring the consistency and workability of fresh concrete.

3. Results and discussion

In this part of the paper the effects of MW on fresh and hardened properties of the investigated concrete mixes are discussed.

3.1 Fresh concrete test results

Table 5 Compressive strength test results at different ages

Mix design	W/C	7-day compressive strength (MPa)			28-day compressive strength (MPa)			90-day compressive strength (MPa)		
		W0	W1	W2	W0	W1	W2	W0	W1	W2
C1	0.25	26(0.71)	34.4(1.77)	26.4(0.8)	47.8(0.99)	59.9(1.12)	61(1.63)	50.5(2.5)	67.4(1.22)	65.6(0.59)
C2	0.25	29(2.04)	26.8(0.8)	27.4(0.64)	53.1(1.49)	58(1.15)	60.2(1.56)	59.5(1.36)	63.7(1.26)	65.7(0.86)
C3	0.35	30.5(1.47)	28.3(0.74)	27.2(0.57)	50.9(1.93)	56.4(1.53)	59.1(1.35)	56.2(1.85)	61(1.49)	63.3(0.43)
C4	0.35	29.6(1.56)	28.6(0.59)	24.1(1.0)	51.8(1.02)	55.3(0.36)	58.7(1.45)	57.4(1.93)	60.2(0.8)	62.1(1.63)
C5	0.45	20.8(0.22)	17.5(0.31)	18.1(0.37)	44.8(1.12)	46.4(0.99)	47.3(1.64)	49(1.96)	49.3(1.20)	49.8(1.19)
C6	0.45	19.9(1.83)	19(0.78)	18.6(0.85)	42.1(0.78)	44.4(0.71)	46.2(1.85)	44(1.84)	46.3(0.62)	48.5(1.02)

As shown in Table 4, the slump of fresh concrete mixtures prepared with MW is higher than those produced with tap water. This may be because of the desperation effect of magnetic field on water clusters.

The results of tests on SF-free mixes indicate an average slump increase of 19%. The application of MW combined with SP showed about 38% improvement in slump test. Therefore, application of MW in combination with SP is more effective. In fact, they have different actions, in which the magnetic field affects the water clusters and disperse them, but the SP influences on the cement particles. As mentioned earlier, by inducting negative charge on cement particles, SP can separate them. In other words, MW and SP are parallel solutions for improving the concrete workability. As seen in Fig. 4, increasing the intensity of magnetic field in all specimen leads to slump improvement and the growth rates are almost identical.

3.2 Hardened concrete test results

Table 5, presents the compressive test results of the mixes at different ages and the standard deviations are presented in the parentheses for each result. Also, Fig. 5 shows all the compressive strengths of the samples for each type of water.

Univariate outlier is used for detecting maximum likelihood and verifying the scattered data of each sample in all curing ages, and all of them were in the range. In fact, the results should be in the range of [m-3s, m+3s] in this method, where m is the mean value and s is the standard deviation.

There are three main variables in this study (W/CM, SF, MW) and the outputs are slump and compressive strength. Analysis of variance (ANOVA) tests can be used to test whether W/CM, SF and MW can have some effects on compressive strengths results or not. In ANOVA tests W/CM ratios had three levels of 0.25, 0.35 and 0.45 denoted by 1, 2 and 3. The levels of SF were chosen as 1 for 0% and 2 for 10% replacement level. MW had three levels of W0, W1 and W2 that denoted by 1, 2 and 3 in ANOVA tests. Table 6 gives the results of one way ANOVA analysis using the significance of 0.05 for 28-day compressive strength. In this table, DF represents the degrees of freedom from each source, SS is sum of squares, MS is mean square, F-value is a factor, which can be determined by dividing each source-MS by the its error-MS, and P-value is a coefficient, which indicates whether a factor is significant or not.

It can be seen form Table 6 that the P-value for MW is 0.002 (<0.05) and for W/CM is 0.000 (<0.05). This observation means that MW and W/CM were significant in the variation of 28-day compressive strength. Also P-value for SF is 0.796 (>0.05) that means, Statistically SF was not

Table 6 Results of ANOVA tests for 28-day compressive strengths

Source	DF	SS	MS	F-value	P-value
MW	2	465.7	223.8	7.01	0.002
Error	51	1695.1	33.2		
total	53	2610.7			
SF	1	2.8	2.8	0.07	0.796
Error	52	2157.9	41.49		
total	53	2160.7			
W/C	2	1432.2	716.11	50.13	0.000
Error	51	7285	14.28		
total	53	2610.7			

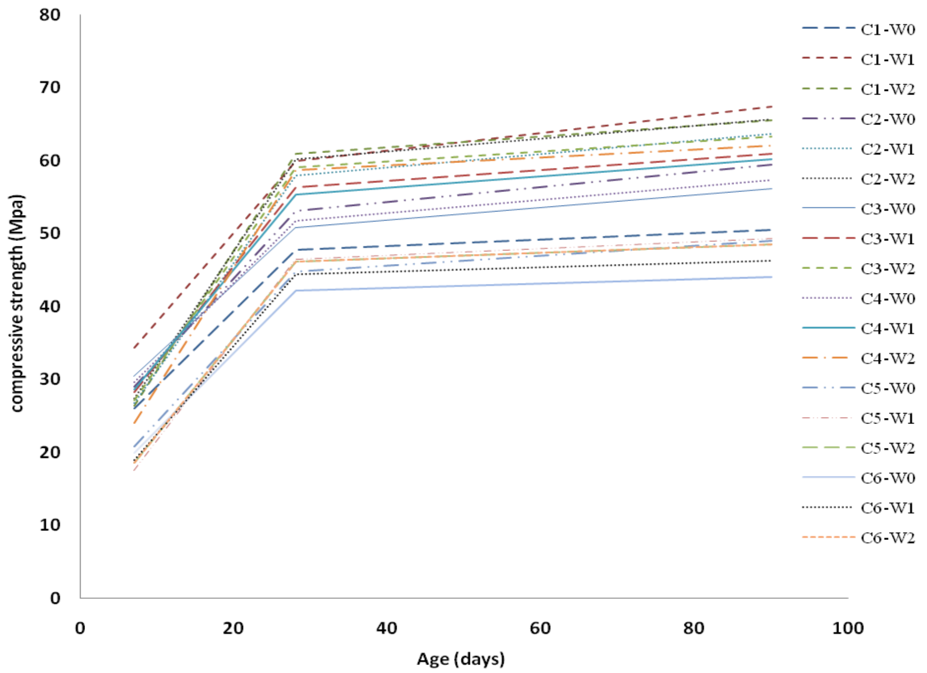

Fig. 5 Effect of age on compressive strength

significant in the variation of 28-day compressive strength. It could be due to the degree of freedom of SF, or laboratory errors in the tests.

As shown in Fig. 5, the compressive strength of samples mixed with tap water in 7 days was slightly better than the ones containing MW. This issue was improved by increasing the magnetic field intensity, and it has been reported in previous similar studies too (Su *et al*. 2003, Mazloom and Miri 2016).

However, a consistent pattern of increase of compressive strength by increasing the magnetic field intensity was found in samples at the ages of 28 and 90 days; but the rate of increase in compressive strength was more significant between the ages of 7 and 28 days than 28 and 90 days. Additionally, with longer curing age, the effects of increasing the magnetic intensity decreased. It

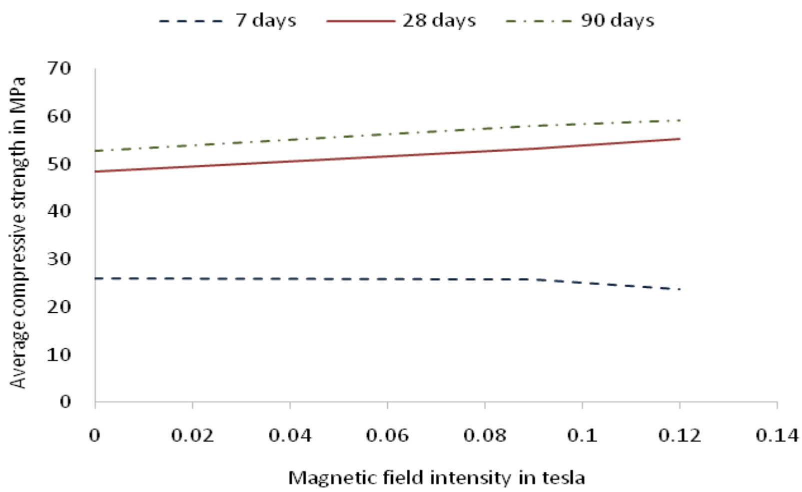

Fig. 6 Effect of magnetic field intensity on compressive strength

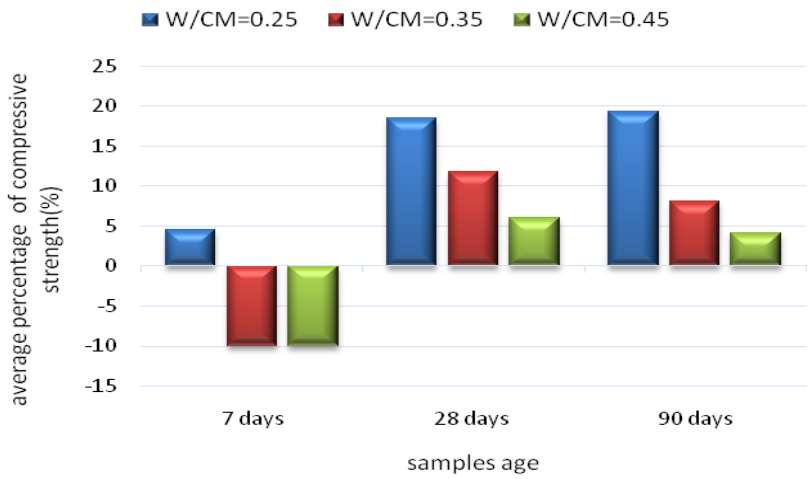

Fig. 7 Effect of W/CM ratio on compressive strength

could be explained by MW memory effect. In fact, by increasing the intensity of magnetic field, the rate of losing the memory effect in MW decreases (Pang and Deng 2009). So by passing the time, the intensity of magnetic field will lose its memory effect.

Fig. 6 shows the average percentage change in compressive strength of the samples at different ages based on magnetic field intensity. As seen in Fig. 6, increasing the intensity of magnetic field improves the compressive strength in 28 and 90 days and the growth rates are almost identical. Also by increasing the intensity of magnetic field, the negative effect of MW on 7-day compressive strength improves too.

Fig. 7 shows the average percentage change in compressive strength of the samples at different ages based on W/CM. As shown in this figure, the decrease of W/CM had a considerable impact on the effect of MW. Perhaps if lower amount of water is available in the mix, its quality becomes more important. This phenomenon is more visible in W/CM=0.25 because in this condition, the minimum amount of necessary water to complete the hydration process exists.

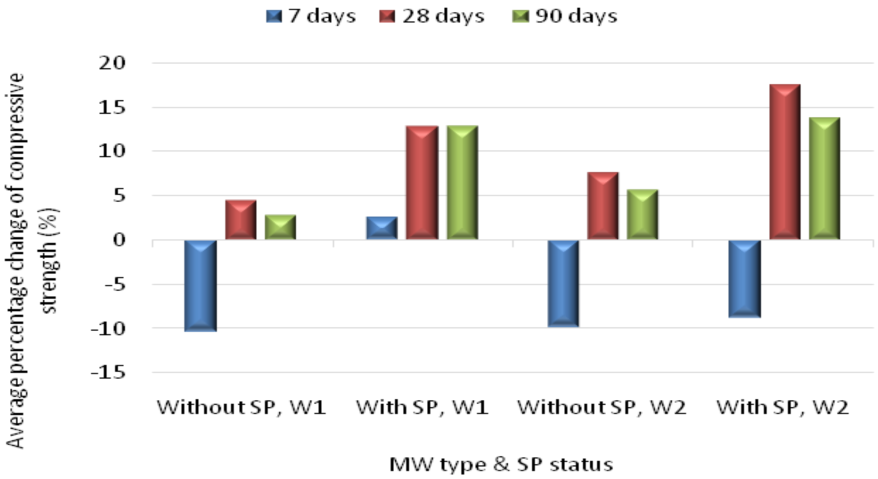

Fig. 8 Effect of SP on compressive strength

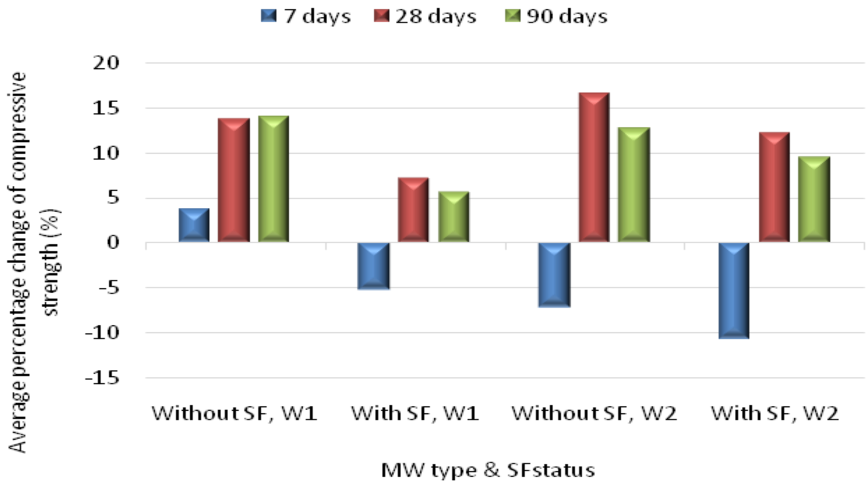

Fig. 9 Effect of SF on compressive strength

The greatest impact of MW on average compressive strength of samples was 20.1% for the specimen with W/CM=0.25 at the age of 28 days. Therefore, it can be said that there is an inverse relation between W/CM ratio and the MW effect.

Fig. 8 shows the average percentage change in compressive strength of samples made with MW and tap water. The samples are divided into two categories of with and without SP. The result for each type of MW is separated in this figure. According to Fig. 8, it can be said that both MW and SP improved the compressive strength of samples, excluding the 7 days results. As mentioned earlier, the magnetic field charged particles of water and dispersed water clusters but SP charged cement particles and helped them to move more easily between the constituent particles of concrete, so the hydration process would improve.

Also improving the intensity of the magnetic field increased the impact of SP on the concrete compressive strength. In particular, it can be said that MW and polycarboxylate SP had parallel effects on improving the compressive strength of concrete.

Fig. 9 shows the average change of compressive strength in samples made with MW and tap water. The samples are divided into two categories of SF-samples and SF-free ones in this figure. Similar to Fig. 8, the results for different types of MW are separated. Based on the assessment of Fig. 9, it can be concluded that there was a relative increase in the compressive strength of samples made with MW at 28 and 90 days. This increase was more in SF-free samples compared to the ones containing SF.

Generally, SF reduced the effect of MW on improving the concrete compressive strength. It should be noted that this reduction was not very significant. This result could be because of MW and SF electrical interactions. Also, the water absorption of very fine SF particles (Mazloom *et al*. 2004) may lead to amalgamation of MW particles. In fact, reducing the hydration process can decrease the compressive strength of concrete.

4. Conclusions

From the results presented in this research, the main conclusions are:

• The workability of all the fresh concrete mixes prepared with magnetic water (MW) was about 35% higher than the ones containing tap water. In this research, the applied magnetic fields for producing magnetic water were 0.09 T and 0.12 T. Also by increasing the magnetic field, the effect of MW on raising the workability of the mixes improved.

• The use of MW could improve the compressive strength of samples containing polycarboxilate ether superplasticizer (SP) up to about 15%. The amount of increase depended on the intensity of magnetic field. By increasing the magnetic field, the effect of MW on enhancing the compressive strength improved.

• The positive effects of MW on improving the compressive strength decreased at the age of 90 days compared to 28-day test results. It means, long-term mechanical properties of concrete are less affected by MW compared to the short ones.

• Silica fume (SF) reduced the effect of MW on improving the concrete compressive strength. This can be because of MW and SF electrical absorption. Also, the water absorption of very fine SF particles may lead to amalgamation of MW particles.

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