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Effect of rock flour type on rheology and strength of self-compacting lightweight concrete

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Abstract. With the development of concrete technology, producing concrete products that have the ability to flow under their own weights and do not need internal or external vibrations is an important achievement. In this study, assessments are made on using travertine, marble and limestone rock flours in self-compacting lightweight concrete (SCLC). In fact, the effects of these powders on plastic and hardened phases of SCLC are studied. To address this issue, concrete mixtures with water to cementitious materials ratios of 0.42 and 0.45 were used. These mixtures were made with 0 and 10% silica fume (SF) replacement levels by cement weight. To achieve lightweight concrete, lightweight expanded clay aggregate (Leca) with the bulk density of about 520 kg/m^3 was utilized. Also two kinds of water were consumed involving tap water and magnetic water (MW) for investigating the possible interaction of MW and rock flour type. In this study, 12 mixtures were studied, and their specific weights were in the range of 1660-1692 kg/m^3. To study the mixtures in plastic phase, tests such as slump flow, *J*-ring, *V*-funnel and *U*-box were performed. By using marble and travertine powders instead of limestone flour, the plastic viscosities and rheology were not changed considerably and they remained in the range of regulations. Moreover, SCLC showed better compressive strength with travertine, and then with marble rock flours compared to limestone powders. According to the results of the conducted study, MW showed better performance in both fresh and hardened phases in all the mixes, and there was no interaction between MW and rock flour type.

Keywords: rock flour; self-compacting lightweight concrete (SCLC); rheology; magnetic water (MW); silica fume (SF); superplasticizer

1. Introduction

Concrete as a material of multi-phase heterogeneous is one of the major materials used in construction industry. The main problem in reinforced concrete is mixing method and pouring fresh concrete in the molds containing heavy reinforcement. To solve this problem, a type of concrete was produced by researchers that required no external or internal vibration and took the shape of the molds under their own weights easily and are not obstructed by the steel bars (Okamura and Ouchi 2003, Kurt *et al* 2016). In addition, the need for lightweight materials in the construction industry led to producing self-compacting lightweight concrete (SCLC) by combining the desirable characteristics of self-consolidating concrete (SCC) and lightweight aggregates concrete (LWAC) (Mazloom and Hatami 2015, Mazloom and Mahboubi 2017). Usually, all the materials that are used for the production of normal concrete are applicable for producing self-compacting concrete. But major difference is in the use of the superplasticizer for proper flow and the use of rock flours to build the required viscosity (Ahmad *et al.* 2014). The main challenge in SCC is creating a balance between sufficient rheology and segregation tolerance (Kim *et al.* 2012).

Wu *et al.* (2009) who have studied the performance of SCLC, considered the slump flow, *V*-funnel, *L*-box and *U*-box tests appropriate to evaluate SCLC performance. Khayat *et al*. (2004) reported that *L* and *U* boxes and *J*-ring tests can be used to assess the passing ability of SCC. Granata (2015) used *J*-ring, *U*-box and *L*-box tests to test flow and the ability of SCC filling in the plastic phase and also *V*-funnel test was used to check viscosity. Karahan *et al*. (2012) have used slump flow, compressive strength and tensile strength to check characteristics of fresh and hardened concrete, respectively. Also using slump flow test and *L* or *U* boxes in the workshops can provide favorable conditions for the quality control of SCC (Bartos 2005). This research confirms the use of tests such as slump flow, *U* and *L* boxes, and *J*-ring for evaluation of segregation tolerance, passing ability and uniformity in SCLC in accordance with the regulations of EFNARC (2002).

To achieve the desired properties in fresh and hardened SCC phases, fillers such as fly ash, silica fume (SF), rock flour and natural Pozzolans are required (Ahmad *et al.* 2014). These fine materials are necessary for maintaining uniformity in the samples and reducing the risk of segregation (Wu *et al.* 2009).The use of rock flour improved mechanical properties and durability of SCC through filling the pores and providing a denser structure (Felekog and

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Table 1 Physical properties of aggregate and stone powders

	Material	Water absorption (%)	density (kg/m^3)	Fineness modulus	Max diameter (mm)
	Leca	7	520	-	9.5
	sand	3.6	2530	3.2	4.5
Stone powders	limestone	1.09	2680	-	0.15
	travertine	2	2510	-	0.15
	marble	0.36	2710	-	0.15

Table 2 Physical and chemical properties of cementitious materials, leca and stone powders

Compositions	Weight %					
	Cement	SF	Leca	Stone powders		
				Limestone	Marble	Travertine
CaO	63.56	0.49	2.46	55.07	52.45	54.23
SiO_2	19.3	93.6	66.05	0.22	1.29	0.49
Al_2O_3	5.57	1.32	16.57	0.18	0.39	0.04
Fe_2O_3	3.46	0.37	7.1	0.44	0.78	0.08
$SiO2+Al_2O_3+Fe_2O_3$	28.33	-	-	-	-	-
MgO	0.86	0.97	1.99	0.34	0.54	0.33
SO_3	3.02	0.5	0.03	-	-	0.3
K_2O	0.8	1.01	2.69	0.11	0.11	0.03
Na_2O	0.13	0.13	0.69	-	-	0.12
L.O.I	1.95	-	0.84	42.86	43.9	43.82
Blaine (Cm^2/gr)	3294	20400	-	-	-	-
Specific Gravity (gr/Cm^3)	3.07	2.21	0.52	2.68	2.71	2.51
28-day compressive strength (MPa)	46	-	-	-	-	-

Baradan 2003). The mechanism of these fine materials in SCC is investigated by many researchers, and it is presented in the report of ACI Committee 237 (2007). Gesoglu *et al.* (2013) studied the properties of fresh and hardened SCC using a combination of limestone, marble and fly ash. In this study, mixtures have been made with 0, 5, 10 and 20 percent of fly ash replacement levels. The results showed that by increasing the amount of filler, the amount of superplasticizers increased, the amount of cement decreased, and flow properties were improved. In all mix designs, by increasing the amount of filler at the range of 5 to 20%, compressive strength at the ages of 28 and 90 days and28-day tensile strength of concrete increased from 6 to 10 percent. Also Granata (2015) used pumice powder as filler in SCC. The results showed that the use of this filler had a positive effect on the mechanical properties and compressive strength of SCC samples. Topcu and Uygunoglu (2010) have studied the properties of SCLC using three types of lightweight concrete and the effects of rock flour volume. Some researchers have studied the relationship between the rheology and strength of concrete too (Mazloom *et al.* 2004, Mazloom and Ranjbar 2010, Mazloom 2008).

Magnetic Water (MW) refers to water overtook through a magnetic field. The magnetic field can be produced by strong permanent magnets and also electromagnets (Mazloom and Miri 2016). Nowadays, MW is widely used in industry and agriculture (Surendran *et al.* 2016, Bogatin 1999). In fact, oxygen and hydrogen atoms of water molecules include negative and positive cores, respectively. An electrical dipole moment is formed in water as a result of asymmetric electronic allocation of water molecules. Liquefied salts involve negative and positive charges; they exist as dissolved ions draw to the water molecules. In accordance with Faraday's law, charged elements moving through a magnetic field with a velocity vertical to the magnetic field create a local electrical field perpendicular to both magnetic field and velocity. Moreover, if a conductive fluid is passed through a magnetic field, an induced electrical current is generated (Bernardin and Chan 1991).

Gabrielli *et al*. (2001) worked on the impacts of passing water through magnetic fields. One of the effects was dispersing the arrangement of water molecules which was more interesting for other researchers (Al-Qahtani 1996, Fu and Wang 1994, Mazloom and Miri 2017). In this condition, the magnetic force breaks apart water clusters into the smaller ones; therefore, the action of water improves. In fact, the magnetic field influences on the hydrogen bonds that alters the angle between the hydrogen atoms. Yan *et al*. (2009) say MW decreases the angle between the hydrogen atoms from 104.5 to 103 degrees. In fact, water clusters are produced by hydrogen bonds and these clusters cause the abnormal behavior of water in freezing (Fletcher 1970). This effect was investigated from several aspects by Szczes *et al.* (2011). In concrete technology, scattering of water clusters can cause better participation of them in the hydration process.

Another fact is that MW has a memory effect. It means, according to the intensity of magnetic field, the time duration of influence of magnetic field on water changes; as time passes, its magnetism weakens and finally it will be lost. Pang and Deng (2009) showed that when water is influenced by a 0.44 Tesla magnetic intensity, after about one hour, water is fully magnetized, and after about one hour, its effect on water is lost. Some researchers believe that MW can be kept in reservoir for 0-12 hours (Fu and Wang 1994, Su and Wu 2000, Su and Lee 1999). In present investigation, directly after making MW, it is used in concrete mixtures.

Numerous studies on the field of using MW in concrete show that MW can enhance the strength and rheology of concrete reduce the bleeding of it and improve its resistant 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). Moreover, MW reduces the amount of cement and chemical admixtures, thus it shrinks environmental pollution (Mazloom and Miri 2017). Also Wang and Wu (1997) say if concrete is cured in MW, its compressive strength develops. In fact, during the hydration of cement, MW can enter the core zones of particles more effortlessly than tap water. Therefore, MW can enhance the hydration process and grow concrete properties.

In this study, SF and limestone powder are used as the cement replacement material and the first filler in concrete. The use of limestone flour as a filler is quite common in concrete technology. The effects of powdered marble and travertine as fillers are studied in this research, and the replacement of limestone powder by them is investigated on SCLC. Also the interaction of MW and the rock flours above are studied. The water to cementitious materials ratios of the mixes are0.42 and 0.45. Slump flow, *J*-ring, *V*-funnel and *U*-box tests are use here to convene the rules in the plastic phase of SCLC. In the hardened phase, to determine the mechanical properties, compressive strength tests at the ages of 7, 28, and 90 days and also28-day tensile strength test are used.

2. Laboratory program

2.1 Materials

Physical properties of the utilized aggregate can be seen in Table 1. Cement used in this study was type 1-425. Its chemical and mechanical properties are provided in Table 2. Based on the conducted studies, it is decided to use 10 percent SF replacement level; the chemical properties of SF are presented in Table 2. To achieve lighter concrete, in this study, lightweight expanded clay aggregate (Leca) was used. The utilized Leca was produced according to the method of inflating clay through wet process within the battalion; its bulk density was 520-550 Kg/m^3 in accordance with ASTM C127 (2007). Karamloo *et al.* (2016) have worked on fracture parameters of self-compacting light weight concrete containing Leca aggregate.

Chemical characteristics of Leca are presented in Table 2. To prevent plugging and better uniformity of concrete, Leca size was considered 9.5 mm according to EFNARC (2002). The sieve analysis of Leca is presented in Table 3.

Natural sand with specific density of 2530 Kg/m^3 and water absorption of 3.6 percent was used. In this study, the superplasticizer was based on polycarboxylate ether; this material was liquid with light brown color and specific weight of 1.07 gr/cm^3. The three types of rock flours which were used as fillers in this study were limestone, travertine and marble powders. The chemical compositions of the rock flours are given in Table 2. In the construction of all samples, both tap water and MW were used.

Direct electric current was necessary to create a uniform magnetic field, which was supplied by a direct power supply. The adjusting of magnetic field strength could be prepared by changing the electric flow. The electric current through the device was two 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 quantity of magnetic field was 0.12 T. Therefore, two types of water were used, which were the tap water of Tehran (W0), and MW produced by the magnetic field of 0.12 T (W1). The water flow to move through the magnetic field was 18 L/h.

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

Table 3 Leca sieve size

Sieve size (mm)	Passing percentage
9.5	100
4.75	70
0	2.36

2.2 Concrete mixtures

In order to provide an observation for comparing the effects of powdered marble and travertine as alternatives of limestone powder on rheology, strength and segregation, some mixtures were made through trial and error. Then, to achieve efficiency and sustainability in accordance with the existing standards (EFNARC 2002, ACI 213 2014) the original concrete mixtures were modified and mixtures with water to cementitious materials ratios of 0.42 and 0.45 were made. Leca sieve analysis is presented in Table 3. It is worth noting that water absorption in Leca was high, thus to use the saturated with dry surface technique, it was placed in water for one hour to fully absorb the water (Mazloom and Mahboubi 2017). Mixtures were presented with and without SF. In fact, half of mixtures included ten percent SF replacement level in mass for mass bases of cement. Two different superplasticizer dosages were used in this research. By fixing most of the components of the mixtures, W/C ratio and kind of filler were changed as the alternatives of this investigation; some fresh and hardened characteristics of concrete such as workability (slump flow, *J*-ring, *V*-funnel and *U*-box), density, compressive strength and tensile strength were assessed. For the compressive strength test, cubic samples of 100×100×100 mm, and for indirect tensile strength, cylindrical molds with a diameter and height of 100 mm and 200 were used. Compressive samples at the ages of 7, 28 and 90 days and tensile samples after 28 days were tested. In this study, 12 mixtures were investigated that are shown in Table 4.

2.3 Rock flour

Since the most important usage of rock flour is in SCC and especially in SCLC compared with other types of concrete, knowing the influence of rock flour on these mixtures is very important. It is clear that increasing the superplasticizer dosage, leads to more segregation of SCLC. To resist segregation, it is needed to increase the amount of cement or to use viscosity modifiers, which increase the concrete production cost (EFNARC 2002, Skarendahl and Peterson 2001). To fix this instability, researchers should consider effective parameters such as powdery materials in concrete (Daczko 2002). It is one of the features that exist in limestone flours, which accelerates the hydration process at early ages, and therefore, it increases the hydration temperature. This type of powders considerably increases the reactions of cement phases. Hydrates of carbon-aluminates can be seen in their chemical makeup, which is caused by $CaCO_3$ reaction with C_3A. It has also been shown that by the reaction of $CaCO_3$ with silica phases, hydrates of carbosilicon are created (Vuk *et al.* 2001). In this study, the feasibility of replacing limestone by available powders such as powdered travertine and marble is discussed to achieve better performance and sustainability as well as better mechanical properties. It should be mentioned that all the powders passed through sieve No. 100.

Table 4 Mix designs

Mixtures		BL1	BL2	BT1	BT2	BM1	BM2	CL1	CL2	CT1	CT2	CM1	CM2
		Unit: (Kg / m^3)											
Cement		420	378	420	378	420	378	400	360	400	360	400	360
SF		-	42	-	42	-	42	-	40	-	40	-	40
Superplasticizer		6.1	6.1	6.1	6.1	6.1	6.1	4.9	4.9	4.9	4.9	4.9	4.9
Water		176	176	176	176	176	176	180	180	180	180	180	180
W/C		0.42	0.42	0.42	0.42	0.42	0.42	0.45	0.45	0.45	0.45	0.45	0.45
Stone powders	Limestone	220	220	-	-	-	-	225	225	-	-	-	-
	Travertine	-	-	220	220	-	-	-	-	225	225	-	-
	Marble	-	-	-	-	220	220	-	-	-	-	225	225
Sand		615	615	615	615	615	615	610	610	610	610	610	610
Leca		248	248	248	248	248	248	242	242	242	242	242	242
Specific gravity		1691	1682	1684	1679	1692	1684	1663	1660	1669	1665	1671	1669

Table 5 Class of viscosity

Class	VF1	VF2
V funnel (s)	Up to 8	9 to 25

3. Experiments

3.1 Fresh concrete tests

With slump flow test, the time in which SCLC reaches the diameter of 500 mm (T_{500}) that shows the flowability, and the final diameter distribution (D_f), which presents the ability of filling the molds are measured. *J*-ring test is used to determine the ability of concrete to pass through the compacted reinforcement in the mold. *V*-funnel test is designed to assess the final time for flowability and passing through limited places without obstruction. The results of this test must be within the specified ranges of EFNARC (2002), which are shown in Table 5. *U*-box test is used to estimate the passing and filling ability of SCLC. The results of the flowability of fresh SCLC are presented in Table 6. According to this table, all the mixes pass the requirements to be considered self-compacting.

3.2 Hardened concrete tests

For testing the hardened phase of SCLC, the specimens were placed in molds according to ASTM C192 (2014), and after 24 hours they were placed in water. The compressive strength tests were performed after taking 100 mm cubic samples out of water according to ASTM C39 (2012) at the ages of 7, 28 and 90 days. For indirect tensile strength, the cylindrical molds of 100×200 mm height were used and each of the samples were processed according to ASTM C496 (2011) after 28 days.

4. Analyses of the results

4.1 Fresh concrete tests

For different mixtures containing marble powder, the final diameter of slump flow increased with improving the W/C. This increase in diameter reflects the increased rheology. Travertine powder compared to other powders had shorter diameter of flow, but it was according to the limits set by regulations. According to Fig. 1, the final diameter of the slump flow for marble powder was between 750-820 mm for W0, and 880-990 mm for W1. Also for travertine and limestone powders, it was between 740-800 mm and 740-810 mm for W0 and 850-990 and 870-990 mm for W1, respectively. It is clear that MW improved the slump flow of all the mixes about 20% in average and type of powder did not affect this percentage considerably. Therefore, it may be said that, there was no interaction between MW and powder type in this case.

Analysis of variance (ANOVA) tests can be used to investigate whether the kind of stone powder and the type of water can have some interaction in rheology results or not. For this reason, the results of slump flow test, which is quite popular in the world, is considered. In ANOVA tests the stone powder had three kinds of limestone, travertine and marble denoted by 1, 2 and 3. Type of water had two levels of W0 and W1for tap water and MW that are denoted by 1 and 2 in ANOVA tests. Table 7 gives the results of two way ANOVA analysis using the significance of 0.05 for slump flow. In this table, P-value is a coefficient that indicates if a factor is important or not, F-value is an issue, which can be determined by dividing each MS value to the error of MS values, MS is mean square, SS is sum of squares, and DF

Table 6 The results of fresh SCLC

Mixture	Unit	Water type	BL1	BL2	BT1	BT2	BM1	BM2	CL1	CL2	CT1	CT2	CM1	CM2
Slump flow	mm	W0	760	740	750	740	755	750	810	780	800	800	820	810
		W1	940	870	910	850	910	880	990	920	990	920	990	960
Time of slump Flow	s	W0	4.9	5.8	5.1	5.1	5.9	5.6	5.5	5.8	5.7	5.6	5.2	5.4
		W1	4.2	5.3	4.3	4.7	5.1	5.1	4.7	5.3	4.8	5.1	4.4	5
J-ring height	mm	W0	8	10	10	9	10	11	11	13	9	11	10	13
		W1	6	7	7	6	7	8	8	9	6	7	7	9
V-Funnel flow	s	W0	9.9	13	10.3	14.2	10.4	14.3	7.8	12.4	10.2	10.6	9.7	11.6
		W1	7.7	10.2	7.9	11.4	7.6	11.2	6.6	9.7	6.8	8	7.7	8.7
U-box height	mm	W0	26	30	25	29	24	33	24	29	25	30	25	28
		W1	22	25	20	25	20	27	20	25	20	26	20	24

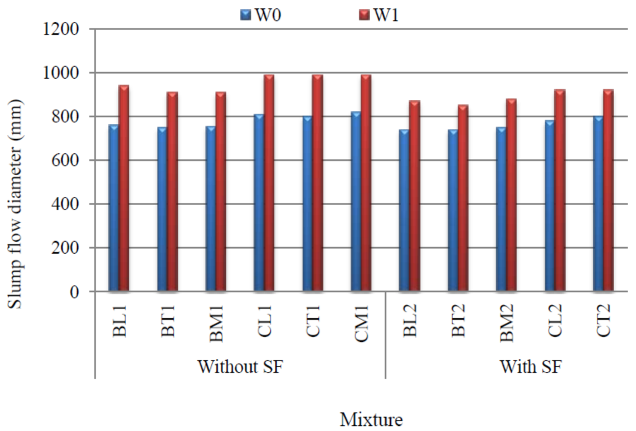

Fig. 1 Effect of stone powder, W/C, MW and SF on final diameter of slump flow

Table 7 Results of ANOVA tests for slump flow

Source	DF	SS	MS	*F*-value	*P*-value
MW	1	137259	137259	72.04	0.000
Powders	2	44	22	0.1	0.979
Interaction	2	944	472	0.25	0.783
Error	18	34294	1905		
Total	23	172541			

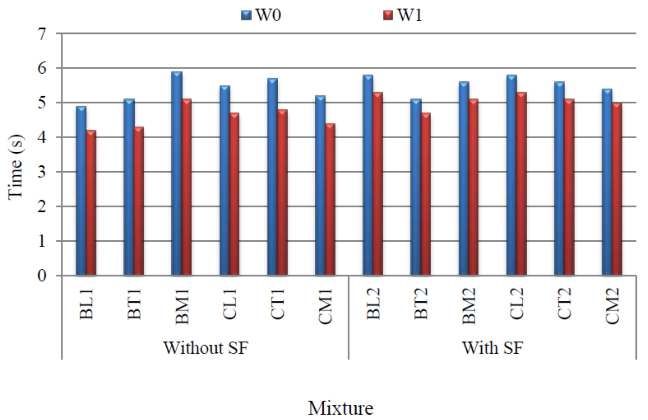

Fig. 2 Comparison of the effect of powder on slump flow time to *D*=500 mm (S)

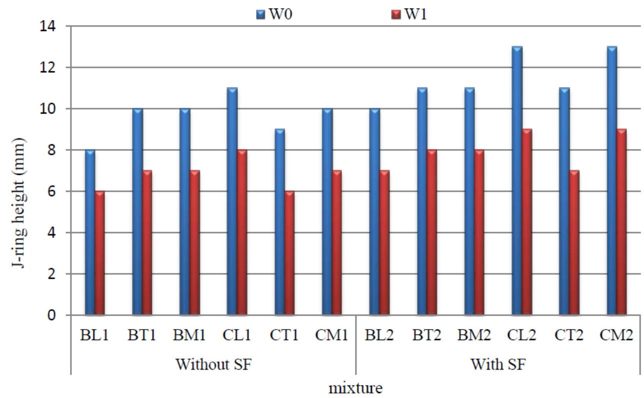

Fig. 3 Comparison of the effects of stone powders on *J*-ring height (mm)

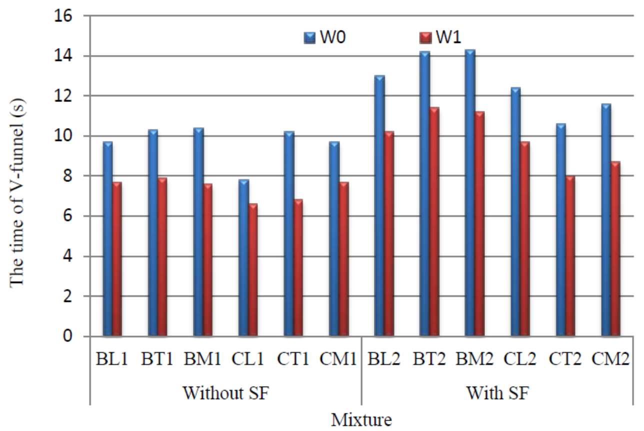

Fig. 4 Comparing the effects of different stone powders on *V*-funnel test

characterizes the degree of freedom of each supply.

It can be seen in Table 7 that *P*-value for MW is 0.000 (<0.05). This observation means that type of water is significant in the variation of slump flow. This is in agreement with the initial laboratory results that show MW improves the rheology of SCLC. Also *P*-value for powders is 0.979 (>0.05) and for interaction of MW and powders is 0.783 (>0.05).These *P*-values mean, the type of stone powder is not significant in the results of slump flow test and there is no interaction between type of water and kind of stone powder in the case of rheology. In other words, the initial laboratory finding about having no interaction between MW and powder type in fresh properties of concrete is proved by ANOVA analysis. It is worth adding that ANOVA analysis proved the independence of the effects of MW and powder type, considering the other fresh and hardened tests conducted in this research, on SCLC.

For all mixtures, the increase in W/C ratio led to an increase in the final diameter of slump flow according to Fig. 1. For the W/C ratio of 0.42 and 0.45, it was 740-760 mm and 780-820 mm for W0 and 850-940 and 920-990 mm for W1, respectively. As final diameter increases in slump flow, shear stress and viscosity of fresh concrete is reduced (Kurt *et al.* 2016). As shown in Fig. 1, with the addition of 10% SF in all mixtures, the final diameter was reduced. It can be said that by the addition of SF, the viscosity of the mixes increased. Travertine and marble rock flours in combination with SF had acceptable performance on SCLC flow. Smoother mixtures could be made with travertine and marble powders compared to limestone flour.

As shown in Fig. 2, the time in which the slump reaches the diameter of 500 mm was 4.9-5.9 s for W0 and 4.2-5.3 s for W1, in all the mixtures. They were in the classification of the viscosity of EFNARC (2002). MW decreased slump flow time to *D*=500 mm about 14% in average and this percentage was not changed considerably by altering the kind of stone powder. In other words, it could be concluded that there were not significant interaction between MW and the kind of rock flour in this case. In fact, the duration of reaching the diameter of 500 mm, shows flowability and plastic viscosity of fresh concrete. By using marble and travertine powder instead of limestone, the plastic viscosity were not changed much in both W0 and W1.

To evaluate the passing ability of the mixtures, *J*-ring test was used. The results can be seen in Fig. 3. According to the results, all mixes had suitable passing ability. In the mixtures of CL2 and CM12 due to higher altitude mean differences, there was the possibility of obstruction. In BL1, BT2 and CT1, the passing ability according to EFNARC (2002) was suitable and the possibility of obstruction was low. Also according to Fig. 3, in high W/C ratios that were without SF, the rheology of concrete was quite high. In other words, they had lower viscosity and higher probability of segregation. It is worth noting that MW decreased *J*-ring height about 45% in average.

Time of *V*-funnel ranged from 7.8-14.3 s in W0 and 6.6-11.4 s for W1 that are shown in Fig. 4. The *V*-funnel results of all mixtures that contained SF were more flowable than those without SF. This indicates that the addition of SF affected the viscosity. Also using marble and travertine

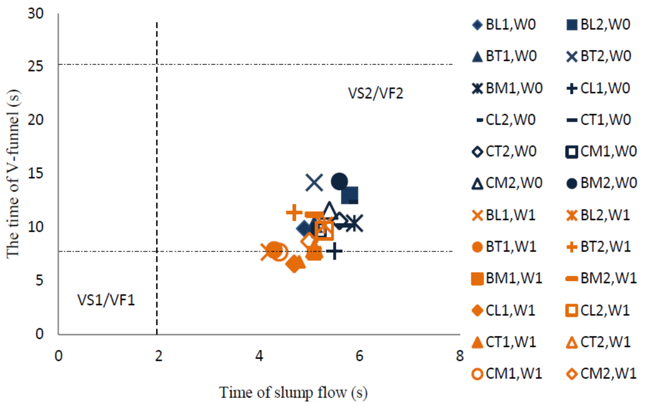

Fig. 5 Relation between *V*-funnel and slump flow time

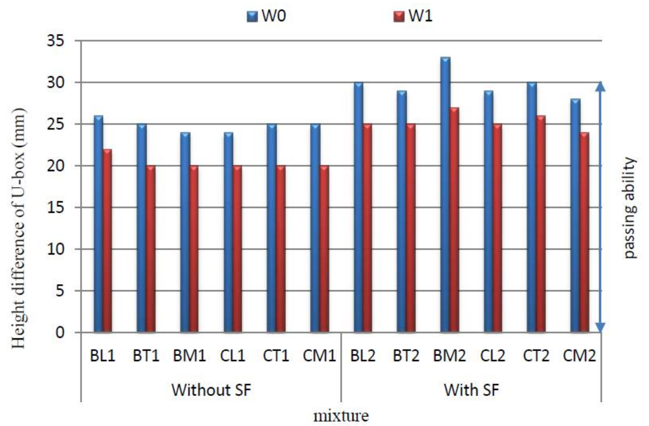

Fig. 6 Effects of stone powders, SF and W/C ratio on the height difference of *U*-box (mm)

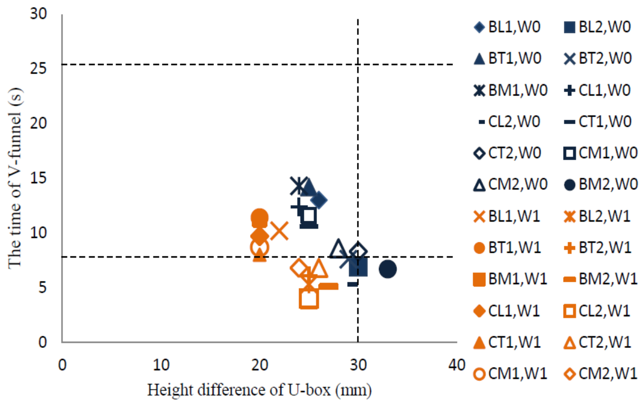

Fig. 7 Relation between the height difference of *U*-box and the time of *V*-funnel tests

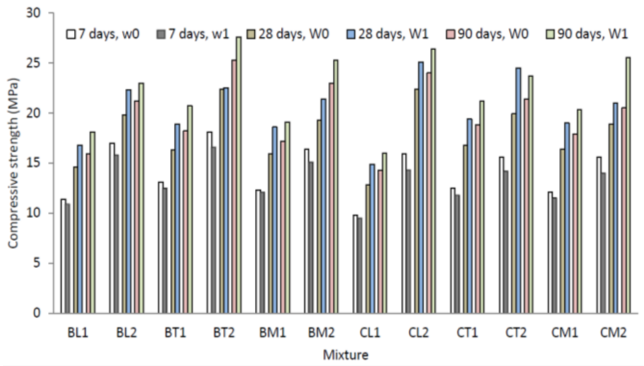

Fig. 8 The Compressive strengths of 7, 28 and 90 days samples

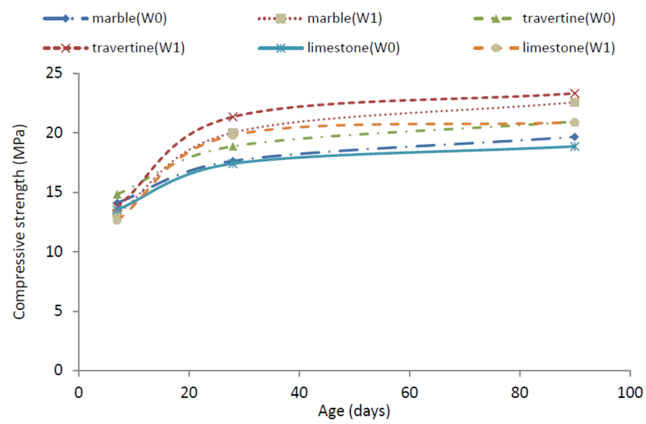

Fig. 9 The compressive strength of 7, 28 and 90 days samples made with rock flour

powders indicated better viscosity than limestone flour. It is worth noting that MW decreased the result of *V*-funnel test about 30% in average.

Fig. 5 shows the relationship between *V*-funnel flow time and the time of slump flow reaching the diameter of 500 mm. According to this figure, all the mixes containing MW and without SF gave the most flowable results. In other words, changing the rock flower type was not important in this field.

U-box test results can be seen in Fig. 6. Except BM2 with tap water (W0), all the mixtures had acceptable passing ability. In fact, they gained the height difference of $\Delta h \leq 30$ mm. the results of this test were compared with the results of *V*-funnel, which can be seen in Fig. 7. This figure shows that replacing tap water with MW could solve the passing ability of the mixes containing marble stone powder and SF. Also MW improved the average passing ability about 20%. This improvement for travertine flour was marginally better than marble and limestone powders.

4.2 Hardened concrete phase

According to Fig. 8, the ranges of compressive strengths at the ages of 7, 28 and 90 days were 9.8-18.1 MPa, 12.8-22.4 MPa and 14.3-25.3 MPa for W0, and 9.5-16.6 MPa, 14.9-25.1 MPa and 16-27.6 MPa for W1, respectively. Regarding this figure, the compressive strengths of 7-day samples made with travertine and marble compared to limestone increased about 10 and 4 percent respectively. These results at the age of 28-days increased about 12 and 5 percent, and for 90-day samples, they improved about 11 and 4 percent. Also MW decreased the 7-day compressive strengths in all specimens about 6 percent. However, the 28-day and 90-day compressive strengths of the samples containing MW increased about 12 percent. This issue can be improved by increasing the magnetic field intensity (Mazloom and Miri 2016, Su *et al.* 2003).

As shown in Fig. 9, it can be concluded that adding

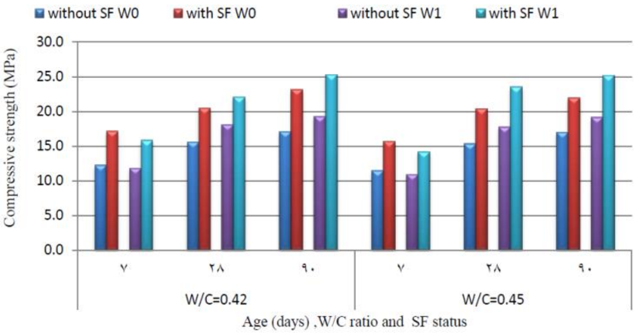

Fig. 10 Average compressive strenght based on W/C ratio and SF status

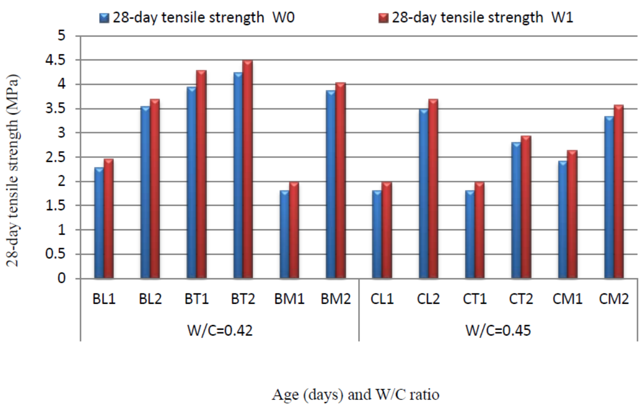

Fig. 11 28-day tensile strength test results

powdered marble and travertine instead of limestone, increased the compressive strength, and there was no interaction between MW and rock flour type in this field. It means, the rate of increase in compressive strength in specimens with and without MW was almost the same.

Fig. 10 shows the average compressive strength of specimens on different ages based on W/C ratio and SF status. As shown in this figure, the mixtures containing SF gained the highest compressive strength. In other words, the mixtures containing SF and lower W/C ratios had higher compressive strength. This positive effect of SF was presented earlier in SCC too (Mazloom *et al*. 2015). Also the positive effect of using MW on specimens with SF was lower than the ones without it.

The values of 28-day tensile strengths are given in Fig. 11. According to this figure, the mixtures containing SF had higher tensile strengths compared to the ones without it. This finding was observed in SCC earlier (Mazloom and Yoosefi 2013). Moreover, using SF and travertine powder at the W/C ratio of 0.42, gave the highest tensile strength. Marble and limestone powders had almost the same effects on tensile strength of concrete. Using MW improved the 28-daytensile strength of specimens about 7 percent in average. This value was not changed considerably by changing the kind of rock flour.

5. Conclusions

From the consequences existing in this paper, the main conclusions are:

- Limestone powder can be replaced by travertine and marble rock flours, to make SCLC in accordance with the existing regulations. These powders had considerable positive effects on the fresh and hardened properties of SCLC.
- Travertine and marble rock flours in combination with SF had acceptable performance on SCLC flow. Smoother mixtures could be made with travertine and marble powders compared to limestone flour.
- The 28-day compressive strength of samples with and without SF containing travertine powder were about 12% higher than the samples having limestone powder. Marble powder could improve this value about 5%.
- The mixtures containing SF had higher tensile strengths compared to the ones without it. Moreover, using SF and travertine powder gave the highest tensile strength. Marble and limestone powders had almost the same effects on the tensile strength of concrete.
- Magnetic water (MW) improved the final diameter of slump flow of all the mixes about 20% in average and the type of powder did not affect this percentage considerably. Moreover, MW decreased slump flow time, in which the slump reaches the diameter of 500 mm, about 14% in average, and similar to final diameter of slump flow, the kind of stone powder was not very important in this case. This positive effect of MW was observed in *V*-funnel, *J*-ring and *U*-box test results with different percentages too. In other words, MW could improve the workability of all the mixes and also there was no considerable interaction between MW and the kind of stone powder in the case of rheology.
- The rate of increase in compressive and tensile strength of specimens with and without MW was the same. In other words, there was no interaction between MW and the kind of stone powder in this issue. The 7-day compressive strengths of the samples containing MW decreased marginally, but it was not significant and could be ignored. The28-day and 90-day compressive strengths of the samples containing MW increased about 12 percent. Also MW improved the 28-daytensile strength of specimens about 7 percent.

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