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Technical and Economical Approaches in Application of Micro Silica Gel and Calcium Carbonate Powder in Self-compacting Concrete

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A B S T R A C T

Effects of two admixtures, calcium carbonate powder (CCP) and micro silica gel (MSG) on self-compacting concrete (SCC) properties, such as workability, compressive strength, and durability are investigated. Results, show that, in some cases, concrete with MSG is unable to provide a stable condition, although flowability is higher. Experimental results indicate that the effect of CCP on sustainability, strength and durability of mixture is remarkable. Combo mix design is introduced to benefit from the positive characteristics of two admixtures. Results of decision making method show that this mix can be considered as a proper sample along with the sample containing the optimal dosage of CCP. Moreover, this method indicates the optimal dosage of CCP is 31.25%, which leads to the best improvement in characteristics of fresh and hardened concrete. In practical engineering, economic analysis demonstrates that using CCP is more cost effective, because is accessible and inexpensive in Iranian market.

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1. INTRODUCTION

Concrete vibrating is essential for consolidation and reducing the voids in normal concrete pouring process. But there are some problems using this process such as congested reinforcement, complex geometrical shapes and forms, and the cost. To overcome these problems, self-compacting concrete (SCC) was proposed by Okamura [1] for the first time and extended gradually from Japan to Europe and other parts of the world [2]. In this type of concrete, the higher dosage of superplasticizer is used in the mixture in order to gain more workability in comparison to use normal concrete; but, addition of superplasticizer has a risk of segregation and losing the integrity of SCC and as a result, the role of admixtures [3–5] and the grading of aggregates in SCC is more crucial in comparison to the normal concrete. It should also stress that, the extra fine aggregates are used in SCC because of filler role too. Moreover, in order to provide the required viscosity, it is necessary to use viscosity modifying admixture (VMA). VMAs increase the density of the mixture and capability of the cement paste in maintaining the floating ingredients which further lead to improvement of sustainability, viscosity, cohesion and internal friction of fresh concrete in microscopic scale. However, excessive dosage of VMA increases cohesion and duration of pouring in concrete, but normally, this effect can be compensated by adding more superplasticizer to the mixture [6–8]. Calcium carbonate powder (CCP) and micro silica (MS) are two VMAs which have all feature mentioned above amd also, have positive effects on improving the mechanical properties and concrete durability. For furthure information, see sections 1.1 and 1.2.

1. 1. Calcium Carbonate Powder

The most part of CCP used in industry is obtained through mining. CCP is produced from calcium oxide. The chemical reactions for

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obtaining calcium hydroxide and precipitated CCP are given by Equations (1) and (2), respectively [9].

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3\downarrow + H_2O \quad (2)$$

CCP as a cement substitute, has been used in concrete production for many years. CCP has many characteristics such as reduction in cement production, decrease in environmental pollution, and improving the workability and sustainability of fresh mixture. In addition, CCP increases the volume of cement paste, and this causes the better interlocking of aggregates and enhances the concrete durability [10].

Sua-iam and Makul [11] assessed the possibility of using CCP in SCC as a substitution for sand. The results showed that CCP with the amount of 30% by cement weight has the capability to improve the characteristics of SCC.

Justnes et al. [12] indicated that 20% of $CaCO_3$ as a replacement with Portland cement, considerably increases the compressive and flexural strengths of mortar. In other research, Okeyinka and Oladejo [13] showed that the application of CCP equal to 20% replacement, rises the compressive strength up to 43.9% at 28 days curing time.

Silva and Brito [14] conducted the durability tests of SCC's made with different dosages of CCP with respect to percentages of cement. They used Scanning electron microscopy (SEM) instrument for analyzing chloride penetration, electrical resistance, and carbonation. They revealed that, using CCP, improves the workability, sustainability, and durability.

Makul and Sua-Iam [15] studied the effect of rice husk ash and CCP on properties of SCC. Their investigation indicated that the workability of SCC containing CCP fall within an allowable range in accordance with EFNARC standard [16].

Lertwattanaruk et al. [17] investigated the impact of CCP on the characteristics of SCC. CCP was used as a cement substitute at percentage replacements of 20% and 40% by weight. They observed that the maximum compressive strength could be reached with 20% of CCP in the mix design.

Daoud and Mahgoub [18] evaluated the effect of CCP on fresh and hardened specifications of SCC. Mix designs with different replacement levels of 0%, 10%, 20%, and 30% by cement weight were prepared. The addition of CCP up to 30% by cement weight, decreased cost and improved the performance of SCC.

In the current study, CCP is used with the diverse weight percentages of cement 12.5, 25, 31.25, 37.5, 43.75, and 50.

1. 2. Micro Silica (MS) MS is a pozzolanic material. It was first used in Norway and then in the U.S, Canada, and Europe. Today, MS is considered as one of the most practical and beneficial admixtures for concrete production. Fundamentally, it is made of amorphous siliceous with a spherical shape. The application of superplasticizer is necessary for increasing workability and decreasing the water-to-cement ratio especially in concrete with pozzolanic materials such as MS. MS is becoming more popular in application. There are several advantages of using MS, one is filling and binding the gaps among cement particles, and simultaneously, increasing the adhesion between the cement paste and coarse aggregate; by that, when voids are reduced, MS considerably decreases permeability and increases lifetime of concrete. The other advantages are, replacing cement by MS, influences the viscosity of mixture and furthermore, this material improves mechanical properties of concrete [19–22].

Vikan et al. [23] indicated that replacement of cement with silica fume (up to10 vol.%) enhances the yield stresses of all mix designs.

Park et al. [24] understood that application of MS to substitute 5, 10 and 15% of the cement may lead to increase in compressive strength and plastic viscosity whereas decreases the segregation of mixture [25].

Bouzoubaa et al. [26], Gesoğlu et al. [27], Valipour et al. [28], Shaikh et al. [29], Zhang et al. [30, 31], Gupta et al. [32] and Barati et al. [33] investigated the effect of MS on improvement of mechanical properties and durability characteristics of concrete.

Micro silica gel (MSG) is actually the composition of Silica fume and a superplasticizer in a pasty form and ready-to-use which has not only the ability to enhance the chemical resistance and mechanical strength of concrete, but also does not have any breathing problems (the tiny particles of the silica fume are harmful).

Laboratory results of the Building and Housing Research Center (BHRC) [34]in compliance with ASTM C1202 [35], showed that using 7% to 10% MSG in the mix design, lead to the reduction of water consumption as well as enhancing the mechanical strength of concrete up to 30%. In addition, the properties and workability of concrete indicated, an increase of 10%, comparing to the mixture using of MS and superplasticizer. In other words, with high certainly, for improving the properties and workability, the system of silica fume and superplasticizer could be replaced by only MSG in the mix design.

Nandhini and Ponmalar [36] found that SCC with dosage of 10% MS, leads to the best performance regarding workability and compressive strength. Shashi [37] proposed that the adequate dosage of MS in SCC, is 7.5% to reach maximum compressive strength. In the similar research, Mohanraj et al. [38] obtained the dosage of 10% for MS. In this case, the compressive strength increased by 12% at 28 days of curing period.

Kumar et al. [39] investigated the effect of MS application in improving of normal concrete properties. They concluded that the optimal dosage of MS is 8% for reaching maximum compressive strength.

In the current work, the dosage of MSG, limited to 7% of the cement weight, was taken from conclusion of the study of BHRC [34].

1. 3. Innovative Significance of Research Overhauling literature review and perusing previous works, are shown that, they have studied the effects of using VMAs on characteristics of fresh and hardened SCC, separately. They have paid less attention on comparing the concrete properties containing CCP and MSG. It is expected MSG containing superplasticizer and MS, has positive effect on concrete flowability. Meanwhile, the prior researches (section 1.1) confirm that CCP is more effective on concrete characteristics such as sustainablity of mixtures, improving of mechanical property, and durability in comparison to MSG. The aim of current study is therefore to simultaneously benefit from the advantages of two admixtures in practical engineering.

In the most cases, prior investigations were focused on the effect of two admixtures on three significant concrete characteristics, namely, workability, strength, and durability, seperately. But, current study in a comprehensive approach, is considereding these characteristics, simultaneousley so as to provide a ground for practical application.

Besides, CCP is accesseble and more inexpensive than cement in the local market of Iran. On the other hand, CCP as a substitution for portions of cement dosage, is very important regarding impact of cement production in environment. Therefore, the design of concrete mixing compatible with Iran environment is crucial.

Above all, an economic analysis is considered to avoid concerning the practical approach of the current research.

2. METHODOLOGY

2. 1. Materials The following ingredients were used:

2. 1. 1. Cement Ordinary Portland cement based on ASTM C150 [40] with the cement content of 400 kg/m^3 was used. The chemical and physical properties of cement are given in Table 1.

2. 1. 2. Aggregates Sand and gravel aggregates were river type in accordance with ASTM C33 [41]. The sand sizes were ranged from 0 to 4.75 mm with density of 1270 kg/m^3 apparent weight in Saturated Surface Dry (SSD) state, and the 24-hour water absorption is 2.63%. The gravel sizes were ranged from 4.75 to 12 mm with 450 kg/m^3 apparent weight in SSD state and the 24-hour water absorption is 2.65%.

TABLE 1. Chemical and physical properties of cement

Physical properties						
Blaine cm^2/g	**Setting time (min)**		**Compressive strength (kg/cm^2)**			**Density (kg/m^3)**
	Initial	**Final**	**3 days**	**7 days**	**28 days**	
2910	154	195	205	288	411	3130

Chemical properties							
Property	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
Content (%)	20.82	4.98	3.57	62.84	2.79	2.27	0.63

Darvishvand et al. [42] stated that the maximum gravel size should be limited to 12.5 mm to reach the highest compressive strength and ductility of concrete. Therefore, in this research, this limit was chosen as the highest range of gravel size.

Figure 1 shows the gradation curves for sand and gravel aggregates.

2. 1. 3. Water Water to cement ratio of 0.45 was used through the entire experiment.

2. 1. 4. Calcium Carbonate Powder (CCP) CCP is a substitute for the part of cement content used in the mix design. Chemical and physical properties of CCP are given in Table 2. Variety of percentages of this material, 12.5%, 25%, 31.25%, 37.5%, 43.75%, and 50% by

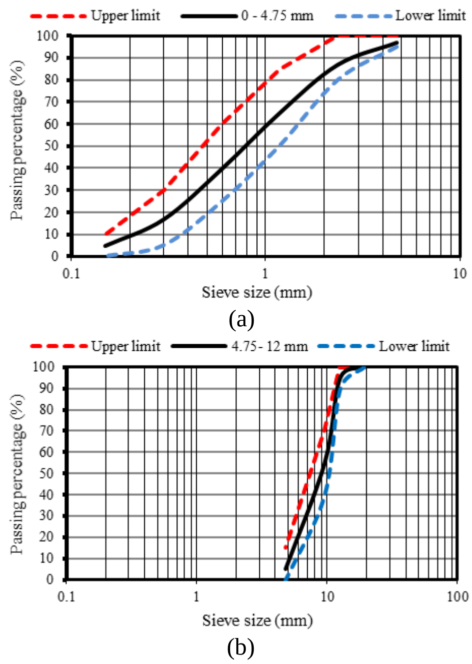

Figure 1. Gradation curves for aggregates: (a): sand aggregate, (b): gravel aggregate

TABLE 2. Chemical and physical properties of $CaCo_3$

Physical properties					
Form	**Particle size**	**Color**	**Humidity (%)**	**Specific surface area (m^2/kg)**	**Density (g/mL)**
powder	≤150 µm	Light brown	0.08	1540	2.93

Chemical properties													
Property	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	TiO_2	Mno	P_2O_5	S	L.O.I	$CaCo_3$
Content (%)	0.9	0.06	0.03	54.69	0.03	0.02	0.86	0.019	0.002	0.142	0.011	43.89	98.5

weight of cement, were used which are equivalent to 50, 100, 125, 150, 175 and 200 kg in one cubic meter of the concrete, respectively. The particle size of CCP utilized, was less than 150 microns in this experiment (see Figure 2).

2. 1. 5. Micro Silica Gel (MSG) The image of MSG is shown in Figure 3 and according to the technical specification of MSG product [43], this material was used to 7% of cement weight (28 kg/m^3) in the mixture. Table 3 presents physical and chemical data of the MSG.

Figure 2. Image of calcium carbonate powder used in mix design

Figure 3. Image of micro silica gel used in mix design

TABLE 3. Chemical and physical properties of MSG

Physical properties		
Color	**Physical state**	**Density (g/cm^3)**
Gray	Gel	1.45

Chemical properties								
Property	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
Content (%)	93	0.4	0.2	1.2	1.2	0.3	1.1	0.1

2. 1. 6. Superplasticizer The trade name for superplasticizer (SP) was Powor plast W/A. The archetypal of SP is given in Table 4. In this research, the amount of SP was 1% of cement weight (according to manufacturer 2018 [44]) which is 4 kg/m^3 of entire mix designs with the except for the control sample 1 (see section 2.2).

2. 1. 7. Air Entrainment Air entrainment (AE) materials were used in samples containing MSG as an adherent agent to bond the cement particles and aggregates. This ensures the enhancement of concrete sustainability. According to the technical specification of product [45], 0.08% of the cement weight of this material was used. Technical data of the material is reported in Table 5.

2. 2. Mix Design Table 6 is designated with 10 mix designs which are labeled with specific abbreviation codes.

The following is the description for the codes. Characters C and M followed by the numbers represent samples containing CCP, MSG, and the weight dosage of materials per cubic meter of the mix design.

TABLE 4. The archetypal of superplasticizer at 20˚C

Description	Specification
Name	Power plast W/A
Ingredient	Modified poly carboxylate
Color	Light brown
State	Liquid
Density (g/mL)	0.02 ±1.06
pH	1±6

TABLE 5. Air entrainment specifications at 20˚C

Specification	Description
Type	Surface active agent
Color	Brown
State	Liquid
Density, g/mL	0.01± 1.01
Ion chlorine	None (based on standard BS 5075)

TABLE 6. Mix designs used for different ingredients

Mixture code	Cement (kg/m^3)	Water (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	CCP (kg/m^3)	MSG (kg/m^3)	SP (kg/m^3)	AE (kg/m^3)
Control1	400	180	450	1270	-	-	-	-
Control2	400	180	450	1270	-	-	4	-
C50	350	180	450	1270	50	-	4	-
C100	300	180	450	1270	100	-	4	-
C125	275	180	450	1270	125	-	4	-
C150	250	180	450	1270	150	-	4	-
C175	225	180	450	1270	175	-	4	-
C200	200	180	450	1270	200	-	4	-
M28	400	180	450	1270	-	28	4	0.32
Combo	275	180	450	1270	125	28	4	0.32

In this research, control samples were made as the reference samples for comparison of experimental data to ensure the reliability of the results. Control sample 1 does not contain any admixture to find out the role of SP and VMAs on SCC properties. Control sample 2 was planned to evaluate the effect of SP on the workability of mixture. The mix designs from C50 through C200 were selected to determine the optimal percentage of the consumed CCP. M28 mix design was utilized to evaluate the effect of the MSG on concrete behavior. The combo mix design was considered for the purpose of estimating the effect of simultaneous use of two admixtures, CCP and MSG.

The experimental data showed that the dosage of CCP corresponding the sample that leads to the maximum compressive strength, was 125 kg/m^3. This amount was used in the mix design with both admixtures.

2. 3. Mix Preparation The design of mixture was performed according to ACI-211-89 [46] and concrete was made according to ASTM C 192 [47]. Each component of the mixture was determined using the weighing balance. The mixing sequence of concrete was accomplished by adding aggregates, cement and 70% of water. The SP dissolved in the remainder of water and added to the mixture. Then, the VMA was added to the admixture and it was stirred for 10 minutes. Finally, the fresh characteristics of concrete were measured.

2. 4. List of Performed Tests along with Acceptance Criteria

2. 4. 1. On Fresh Concrete Several methods were used based on EFNARC standard [16] and European Guidelines for SCC [8] to determine the workability of concrete. List of methods and images of the process are shown in Table 7 and Figure 4 (a-e), respectively.

2. 4. 2. On Hardened Concrete According to BS 1881: Part 111 standard [48], cubic samples with dimensions of 15 × 15 × 15 cm were made and kept inside the molds for 24 hours and then were cured inside a water reservoir at the temperature of 20±2 ˚C. Figure 5 shows the final blocks of concrete samples.

TABLE 7. List of experiments for determination of SCC workability and acceptance limits in EFNARC standard

Test	Property	Unit	Typical range of values	
			Minimum	Maximum
Slump flow	Filling ability	mm	650	800
T_{50cm} Slump	Filling ability	s	2	5
J-ring	Passing ability	mm	0	10
V-funnel	Filling ability	s	6	12
V-funnel at T5 minutes	Segregation resistance	s	6	15
L-box	Passing ability	h_2/h_1	0.8	1.0
U-box	Passing ability	h_2-h_1(mm)	0	30

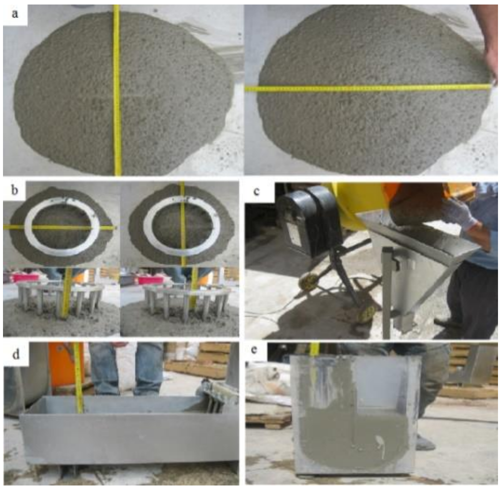

Figure 4. Different methods of SCC tests on fresh concrete: a. Slump-flow; b. J-ring; c. V-funnel and V-funnel at $T_{5minutes}$; d. L-box; e. U-box

2. 4. 2. 1. Compressive Strength Three samples were prepared for each mix design for this test. The experiment performed at the ages of 7, 28 and 90 days based on British Standard 1881: Part 108 [49].

2. 4. 2. 2. Water Absorption The amount of percentage of water absorption in a cement matrix composite, is an indication of volume and distribution of the capillary voids, and the porosity in material [50]. The test is a criterion to evaluate the durability of concrete for the long life. Two samples were prepared for each mix design. Samples were tested in compliance with ASTM C642 [51] for the age of 42 days. The test results were evaluated based on CEB-FIP reference [52]. The reference categorizes the quality and acceptance limit of water absorption. This is illustrated in Table 8.

Figure 5. Preparation of concrete blocks

TABLE 8. Categories of water absorption according to CEB-FIP reference [52]

Category	Acceptance limit (%)
Good	<3
Average	3-5
Poor	>5

2. 4 .2. 3. Electrical Resistivity This is to evaluate the durability of concrete for the long life. The test was performed on three samples at the age of 42 days. The experimental set up is shown in Figure 6. AC voltage was measured during the process and resistance was estimated using Ohm's law for each run [53]. Test evaluation was done according to ACI 222R-01 standard [54].

3. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, the results of each test from fresh and hardened concrete containing CCP and MSG, are presented and discussed.

3. 1. Fresh Concrete The followings are presentation of results and discussion based on explanation of methods in Table 5.

3. 1. 1. Slump Flow Test and T_{50cm} Test Figure 7 illustrates the slump flow measurement from diameter of each mix design. The results from this figure indicate that SP significantly improves the flowability of concrete. This can be seen by comparing control samples 1 and 2 in such a way that sample 1, doesn't extend to diameter of 500 mm and that's because of lack of SP in this mix design. Slump flow is slowed down in samples containing CCP in comparison to control sample 2 because of formation of higher viscosity in the sample, meanwhile the flowability is further declined for weight percentage of CCP over 37.5%, and this is passed beyond the limit of EFNARK standard [16]. Mixture containing MSG (i.e. M28), is shown improvement in concrete flowability which is higher than CCP mix designs and control sample 2. The dashed lines on Figures 7 and 8 are shown to stress the acceptance limits.

Similar results can also be deduced from Figure 8. The data in Figure 8 show that more dosage of CCP increases time for the mix designs to reach diameter of 500 mm, but if the percentage of dosage reaches 50%, the mix design C200, will not be within the acceptance limit of the EFNARK standard [16] due to formation of higher viscosity in the mixture. Data in Figure 8 reveal a shorter

Figure 6. Electrical resistivity apparatus

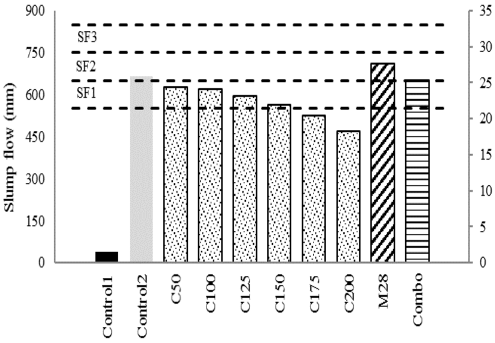

Figure 7. Results of slump flow test

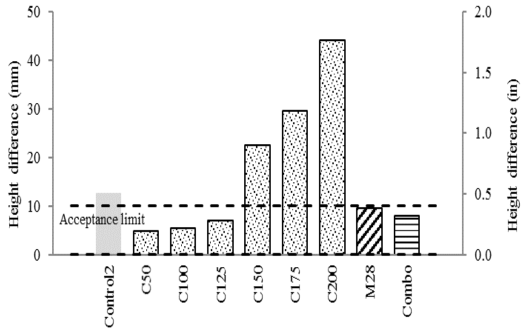

Figure 10. Height difference between the slump flow inside and outside of the J-ring

time for the mix designs to reach diameter of 500 mm. This indicates that mix design containing MSG, offers higher flowability of concrete in comparison to the mix designs with CCP. The word "infinity" in Figure 8, indicates the impossibility of mixture, reaching to diameter of 500 mm in practice. Although, study of mix design containing mixture of CCP and MSG, indicates that appearance of CCP causes relatively low reduction in the concrete flowability, but in general, the role of presence of MSG is dominant in the mixture.

3. 1. 2. J-ring Test and Height Difference between the Slump Flow Inside and Outside of the J-ring

Figures 9 and 10 present the test results for slump flow and height difference between slump inside and outside of the J-ring, respectively. The dashed lines in the figures illustrate the range of acceptance limit complying with the requirements of EFNARK standard [16]. It is impossible to illustrate the result of slump flow test for control sample 1 with the J-ring in which no SP is involved. Additional amount of CCP, leads to reduce the flowability of slump due to the higher viscosity in the samples and increases the height difference of slump of the ring. These are clearly demonstrated in Figures 9 and 10, respectively. Mixture shows more flowability when is containing MSG in comparison to samples with CCP. Similar results are drawn as in the previous section, the effect of using CCP and MSG, simultaneously, lead to a relatively low reduction in flowability, although the effect of CCP is not as tangible as the effect of MSG.

3. 1. 3. V-funnel Test and V-funnel Test at $T_{5minutes}$

The results of V-funnel test and increase of flow time in V-funnel test ($T_{5minutes}$), are presented in Figures 11 and 12, respectively. The dashed lines in the figures, exhibit the acceptance range of EFNARK standard [16]. Data in Figure 11 indicate that CCP increases the flow time with satisfaction whereas, it is shorter in control sample 2 in comparison to the acceptance limit of the standard and this can be attributed to the unsustainability of mixture. The figure also, reveals by adding MSG, there would be excessive flowability in the mixture, but doesn't meet the requirements of acceptance criteria based on EFNARK standard [16]. The data in Figure 12 clearly show that increasing of flow time in V-funnel test (5 min. waiting period) verifies that control sample 2 cannot be freely discharged due to the segregation of components of mixture which causes blocking the flow. The word "infinity in Figure 12, points out unlimited flow time. Figure also, provides that the mix design C125 has the minimum increase in flow time. This shows consistency and continuity of mix designs containing CCP, is much better in comparison to the mixture with MSG sample, M28. Data in Figures 11 and 12 illustrate that the addition of CCP, develops mixture sustainability when both admixtures are used simultaneously in comparison to use of only MSG.

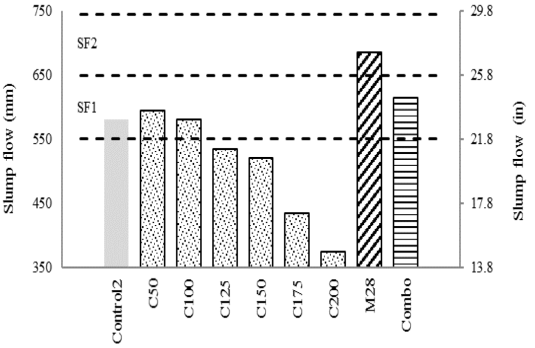

Figure 9. Results of J-ring test

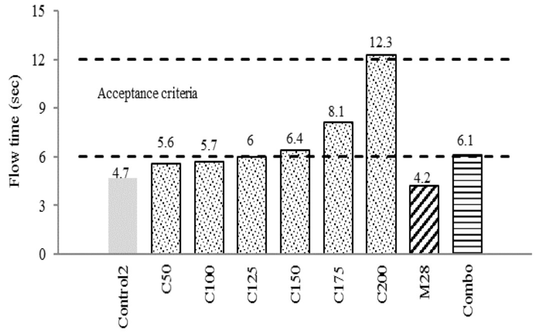

Figure 11. Results of V-funnel test

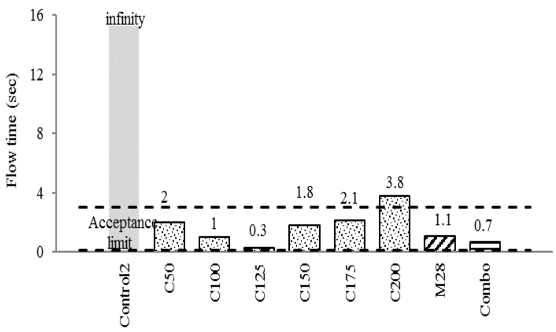

Figure 12. Results of V-funnel test at $T_{5minutes}$

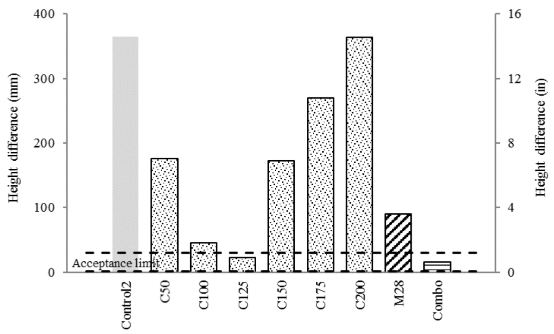

Figure 14. Results of U-Box test

3. 1. 4. L-box Test The results of this test is demonstrated in Figure 13. The dashed lines in the figure, illustrate the range of acceptance limit complying with the requirements of EFNARK standard [16].

The figure illustrates that addition of CCP in the mixture up to 125 kg/m^3, causes the rise in the concrete height ratio of the box defined as, concrete height at end of the box to the concrete height next to the rebar as shown in Figure 4d. The higher height ratio leads to the better passing ability of the concrete, however, the ratio will be out of allowable range if the dosage of CCP goes beyond the limit, and the reason for that is, occurrence of the dense viscosity in the mixtures. M28 sample shows a similar passing ability in comparison to C125 sample which shows MSG is more effective in flowability in mix design. The concrete height ratio is close to 1 when both admixtures are used at the same time, this means, the performance of the mixture is perfect, but it also shows that the concrete behavior is very similar to the condition when sample contains only MSG.

3. 1. 5. U-box Test The data from this test are shown in Figure 14. The dashed lines represent the acceptance limit of EFNARK standard [16]. In this figure, it is not possible to illustrate the data for the control sample 1 since concrete is unable to flow through the rebars. The figure also, indicates that, there is a significant height difference of concrete flow in case of control sample 2 with SP, and that is because of segregation and blocking of components. Therefore, this shows that the height difference is not within the allowable limit, and as a result, SP is unable to guarantee the desirable characterization of SCC by itself. Once again, using 125 kg/m^3 of CCP shows an observable increase in flowability and integrity of the concrete and of course, there is a decline in height difference, but the effect of CCP will be reversed if the dosage of CCP goes beyond the limit and, that is because of occurrence of high viscosity in the samples.

M28 sample shows poor passing ability due to the unsustainability of the mixture and stands out of acceptance standard range in comparison to sample containing 125 kg/m^3 of CCP. CCP admixture is considered as a proper choice in this type of test, because it provides a sustainable mix design and preserves the integrity of concrete and furthermore, the role of CCP can be distinguished when using both admixtures in the sample, in which, sustainability returns to the concrete.

3. 2. Hardened Concrete The followings are presentation of results and discussion on hardened concrete.

3. 2. 1. Compressive Strength Test Figure 15 shows the results of compressive strength and Figure 16 demonstrates the percentages of the growth of the samples at different ages. The values on the top of the bars in this figure, indicate the growth at the age of 28

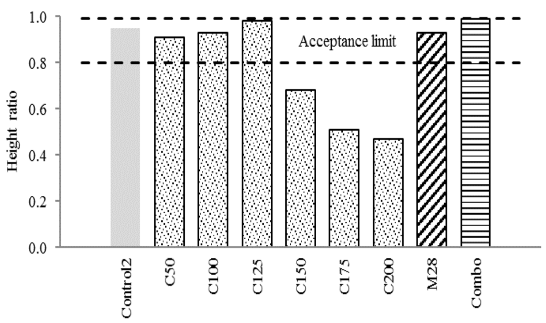

Figure 13. Results of L-Box test

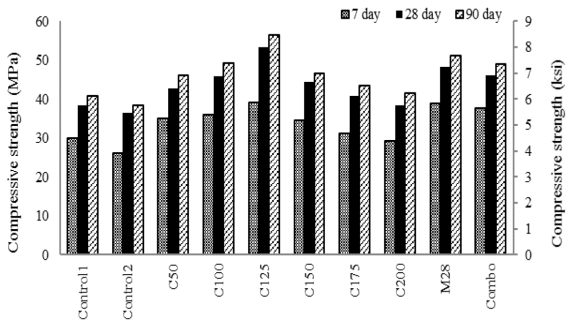

Figure 15. Results of compressive strength test

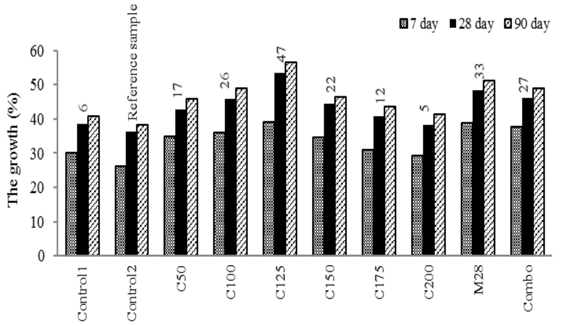

Figure 16. Compressive strength growth of samples at the different ages in comparison to control sample 2

days and they are compared to control sample 2. There are numerous points can be drawn from the data of Figure 16, one is using SP in control sample 2 reduces concrete strength by 6% in comparison to control sample 1. This can be attributed to unsustainability and loss of aggregate interlocking which may cause segregation of the components, the other one is, addition of CCP to the mix designs increases compressive strength of concrete in comparison to control sample 2. Figure 16 reveals the growth trend in compressive strength of mix designs with amount of 125 kg/m^3 CCP, has raised by 47% but, strength starts to reduce if the amount goes beyond the limit and this is because of reduction of cohesion in cement paste due to the presence of unreacted CCP in the mixture. Also, according to Figure 16, the percentage of growth in compressive strength is 47% and 33% for C125 and M28, respectively in comparison to control sample 2. Finally, using CCP and MSG in mixture simultaneously, have no significant effects on concrete strength and illustrate the similar behavior as the sample with only MSG.

3. 2. 2. Water Absorption Test Figure 17 demonstrates that by increasing the amount of CCP to 125 kg/m^3 in the mixture, percentage of water absorption has been reduced in comparison to control sample 2. The results are an indication of a desirable performance of CCP which lead to increase in consolidation and decrease in porosity of the mixtures, but percentage of water absorption starts to rise if the CCP amount goes beyond the defined limit, and that's due to the presence of floating of unreacted CCP in the mix designs which has a tendency to absorb water.

Percentages of water absorption of the samples are categorized based on CEB-FIP standard [52]. Samples containing 125 kg/m^3 CCP and MSG are in "good" and "moderate" categories, respectively. This shows a better performance of the sample containing 125 kg/m^3 of CCP in comparison to MSG sample. Use of MSG may provide a condition for extra water absorption due to the unsustainability and discontinuity of mixture. Also, the data in Figure 17 show that application of using CCP and MSG, simultaneously in the mixture, have a relatively low effect on the reduction of percentage of water absorption in comparison to the sample with only MSG, and the category remains in the moderate region.

3. 2. 3. Electrical Resistivity Test Data of this test are shown in Figure 18 which indicates affirmative effect of CCP and MSG on increasing of electrical resistance. Figure demonstrates that by increasing the amount of CCP to 125 kg/m^3 in mixture, specific electrical resistance rises, but resistance starts to reduce if the CCP amount goes beyond the limit, and this can be related to the role of free ions in atomic structure of material.

The categories on the figure, separated by the dashed lines, are the rate of corrosion in rebars in terms of electrical resistance. There are four levels of categories, low, low to moderate, high, and very high based on ACI 222R-01 [54] standard, and it can be seen that C125 and M28 samples have low and low to moderate corrosion rates, respectively.

Figure also shows, using CCP and MSG in mixture simultaneously, illustrate almost similar behavior as the sample with only MSG. It means that in this condition, the use of CCP illustrates no improvement in the mixture performance.

3. 3. The Statistical Variations The coefficient of variation (CV) Brown [55] is a measure for dispersion

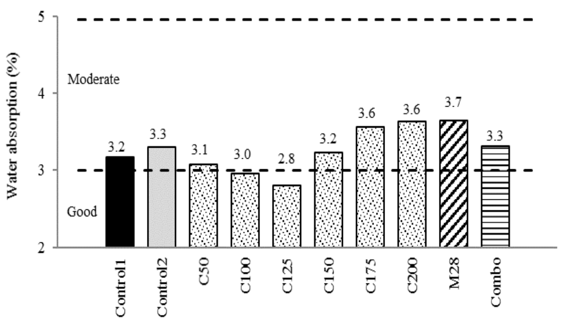

Figure 17. Results of water absorption test

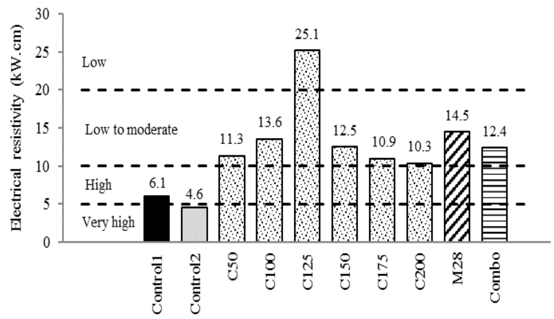

Figure 18. Results of electrical resistivity test

of probability distribution. It is often stated as a percentage, and is defined as the ratio of the standard deviation, σ to the mean value, μ.

Figure 19 shows the experimental data of variation coefficient for hardened concrete in comparison to fresh concrete regarding samples containing CCP. Observation of variation coefficients in Figure 19, indicates that there are more fluctuations in dispersion of probability distribution in fresh concrete in comparison to hardened concrete. This is indication of lower sensitivity in changing the dosage of CCP on hardened concrete with respect to fresh concrete tests. Figure 19 illustrates two distinguished results, the minimum effect of CCP on the properties of fresh concrete, is related to the slump flow and J-ring tests, whereas, this minimum effect on hardened concrete, is related to the compressive strength and water absorption tests. In contrast, the maximum effect of CCP on the properties of fresh and hardened concrete belongs to V-funnel $T_{5minutes}$ and electrical resistivity tests, respectively.

3. 4. Decision Making Method to Select the Optimal Mix Designs

In an overall approach, Table 9 is used to evaluate the effects of two applied admixtures on improving of fresh and hardened concrete properties. These properties were adopted from section 2.4. Mixture codes and concrete properties were tabulated in the table. The following steps in the table, explain the method of evaluation.

Step 1: Using the results from Figures 7 through 18, the evaluation was carried out to determine if any of the samples meets the requirements (i.e. falling within the acceptance criteria or having improvements in their properties relative to the control samples).

Step 2: For each property, samples meet the requirements are initially selected and listed.

Step 3: Frequency of selections for each mix design is counted.

Step 4: Finally, the samples are prioritized according to the frequency counted in step 3.

The results show that C125 (among the samples containing CCP) and Combo samples benefit from the highest improvement on concrete properties. M28 is next in the line.

CCP samples have higher mechanical property and durability in comparison to MSG sample. This is due to the stronger bond between aggregate and cement paste, as well as denser molecular structure in CCP. Appearance of superplasticizer in MSG sample, exhibits the improvement of the flowability in M28 sample, but on the other hand, superplasticizer can endanger the sustainability of the mixture. Whereas, CCP is able to eliminate this defect and sustains the mixture, since provides the sufficient viscosity for mixes. In the optimal dosage, C125 can be expected to have the best proportion in the components of the mixture. In the higher dosage, portion of CCP remains unreacted in the mixture and causes to reduce concrete characteristics.

In the Economic Analysis section, three selected samples, C125, Combo, and M28, are re-evaluated and finalized regarding cost- efficiency and practical engineering.

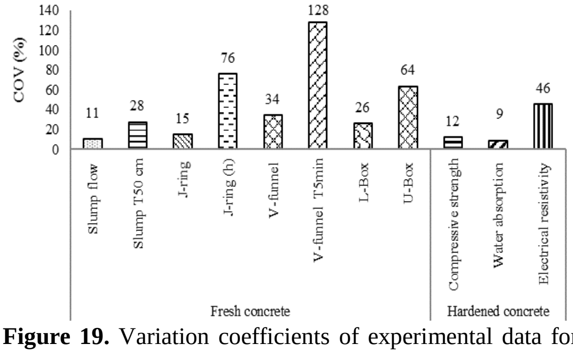

Figure 19. Variation coefficients of experimental data for samples containing CCP

3. 5. Validation of Results

Figure 20 shares the values of optimal dosage of CCP (31.25%) and MSG consumption (7%), and compares them with the literature values from other researchers, introduced in section 1. The dashed lines on the figure illustrate the estimation of average values of CCP and MSG which were suggested in the literatures. These values are compared with the values obtained from the current research, and indicated as maximum off percentages of errors which are 23% and 26% for CCP and MSG, respectively. It should be noted that the chemical components in these two types of admixtures are not exactly identical in different regions which can be certainly influential on optimal dosages and, for this reasoning, the errors are normal and can be justified and neglected.

3. 6. Economic Analysis

Economic analysis is performed to figure out which admixture is more cost-effective to use. Table 10 is a summary of economic analysis for four mix designs, control sample 2, C125, M28, and combo. C125 were selected because of high performance among samples containing CCP (section 3.4). Cost estimation was performed on the basis of production of one cubic meter of concrete. In this research, the ratio of increase in strength to increase in cost relative to control sample 2 is referred as economic index for each mix design. This economic index is recognized as a factor for selection of the suitable economic condition among the mixtures. In calculating economic index, 28 days compressive strength was considered as a reference, since this is the most important property of concrete. The data in Figure 21 indicate that C125 sample with the value of 9.2, is more economical in comparison to other mixtures, because CCP is inexpensive and available in Iranian market.

TABLE 9. Comprehensive evaluation and prioritization of samples

Step	Mixture code	Properties										
		Fresh								Hardened		
		Slump flow	T_{50cm} Slump	J-ring	J-ring (h)	V-funnel	V-5min	L-box	U-box	Compressive strength	Water absorption	Electrical resistivity
1	Control1	out*	out*	out*	out*	out*	out*	out*	out*	increase***	Moderate	High
	Control2	within**	within**	within**	out*	out*	out*	within**	out*	Reference	Moderate	Very high
	C50	within**	within**	within**	within**	out*	within**	within**	out*	increase***	Moderate	Low to moderate
	C100	within**	within**	within**	within**	out*	within**	within**	out*	increase***	Good	Low to moderate
	C125	within**	within**	out*	within**	within**	within**	within**	within**	increase***	Good	Low
	C150	within**	within**	out*	out*	within**	within**	out*	out*	increase***	Moderate	Low to moderate
	C175	out*	within**	out*	out*	within**	within**	out*	out*	increase***	Moderate	Low to moderate
	C200	out*	out*	out*	out*	out*	out*	out*	out*	increase***	Moderate	Low to moderate
	M28	within**	within**	within**	within**	out*	within**	within**	out*	increase***	Moderate	Low to moderate
	Combo	within**	within**	within**	within**	within**	within**	within**	within**	increase***	Moderate	Low to moderate
2	Initial selection	Control2 C50 C100 C125 C150 M28 Combo	Control2 C50 C100 C125 C150 C175 M28 Combo	Control2 C50 C100 M28 Combo	C50 C100 C125 M28 Combo	C125 C150 C175 Combo	C50 C100 C125 C150 C175 M28 Combo	Control2 C50 C100 C125 M28 Combo	C125 Combo	Control1 C50 C100 C125 C150 C175 C200 M28 Combo	C100 C125	C125
3	Mixture code		Control1	Control2	C50	C100	C125	C150	C175	C200	M28	Combo
	Frequency		1	4	7	8	9	5	4	1	7	9
4	Prioritization	1. C125 and Combo C100 C50 and M28 C150 Control2 and C175 2. Control1 and C200										

* out of acceptance limits
** within acceptance limits
*** increase in compressive strength

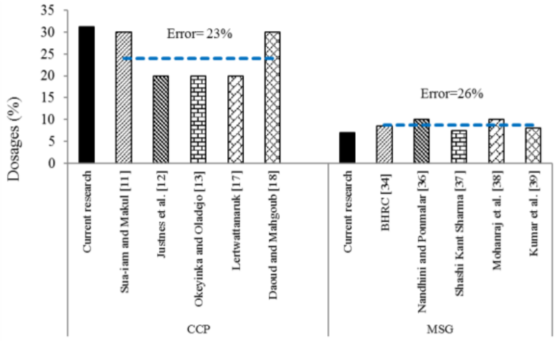

Figure 20. Verification of dosage of CCP and consumption of MSG via comparison with the litreture values

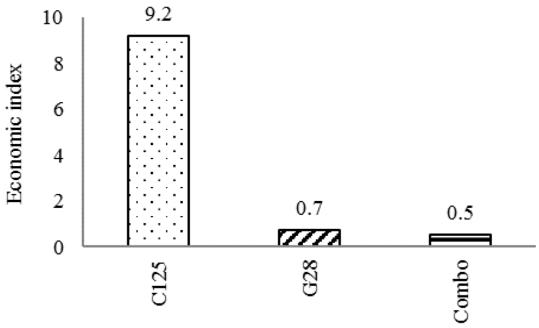

Figure 21. Estimated economic index based on compressive strength test

TABLE 10. Economic analysis for four mix designs

Mix design	Total Cost ($)	Increase in cost relative to control sample 2 (%)	Compressive strength (MPa)	Increase in strength relative to control sample 2 (%)	Economic index
Control2	13.8	0.0	36.4	0.0	-
C125	14.5	5.1	53.4	46.7	9.2
M28	20.0	44.9	48.0	31.9	0.7
Combo	20.7	50.0	46.1	26.6	0.5

4. CONCLUSION

The followings are the most significant conclusions from the experimental work on fresh and hardened concrete samples:

1. The results show that, MSG has positive impacts on increasing of strength and durability of concrete. Also, it causes more flowability than CCP for the admixture. But, it cannot provide a sustainable concrete admixture and this is a kind of deficiency.
2. CCP can compensate the deficiency caused by MSG. CCP samples have higher mechanical property and durability in comparison to MSG sample. This is due to the denser molecular structure and stronger bond between aggregate and cement paste.
3. In a rational foresight, simultaneous application of admixtures, Combo, should be expected to have a proper mix design which benefits from MSG advantage, flowability and CCP advantages, sustainability, durability, and mechanical strength.
4. The variations in the CCP dosage often lead to higher coefficient of variations on fresh concrete rather than hardened concrete experiments. The V-funnel T5minutes test shows the maximum sensitivity to the amount of CCP, whereas the minimum sensitivity belongs to the water absorption test.
5. In an overall approach through the decision making method, the results show that Combo and C125 samples stand in the first priority among the entire samples. In this study, Code C125, refers to the sample containing the optimal dosage of CCP, 31.25%.
6. Regarding the economic analysis and practical engineering, the usage of CCP is more cost effective, because CCP is inexpensive and available in Iranian market.

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Persian Abstract

چکیده

اثرات دو افزودنی، پودر کربنات کلسیم (CCP) و ژل میکروسیلیکا (MSG) روی خواص بتن خود متراکم (SCC) مانند کارآیی، مقاومت فشاری و دوام بررسی می‌شود. نتایج نشان می‌دهد که در برخی موارد، بتن با MSG قادر به ایجاد شرایط پایدار نیست، اگرچه روانی بالاتر است. نتایج آزمایشگاهی نشان می‌دهد که اثر CCP بر پایداری، مقاومت و دوام مخلوط قابل توجه است. طرح اختلاط Combo برای بهره‌مندی از ویژگی‌های مثبت دو افزودنی معرفی می‌شود. نتایج روش تصمیم‌گیری نشان می‌دهد که این مخلوط می‌تواند به عنوان یک نمونه مناسب همراه با نمونه حاوی دوز بهینه CCP در نظر گرفته شود. علاوه بر این، این روش نشان می‌دهد که دوز بهینه CCP، ٪31/25 است که منجر به بهترین بهبود در خصوصیات بتن تازه و سخت شده می‌شود. در مهندسی کاربردی، تحلیل اقتصادی نشان می‌دهد که استفاده از CCP مقرون به صرفه‌تر است زیرا در بازار ایران در دسترس بوده و ارزان است.