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Research article

Prediction and multi-objective optimization of workability and compressive strength of recycled self-consolidating mortar using Taguchi design method

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A R T I C L E I N F O

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A B S T R A C T

Concrete is the most consumed material in the construction industry. Using recycled aggregates (RA) and silica fume (SF) in concrete and mortar could preserve natural aggregates (NA) and reduce CO_2 emissions and construction and demolition waste (C&DW) generation. Optimizing the mixture design based on both fresh and hardened properties of recycled self-consolidating mortar (RSCM) has not been performed. In this study, multi-objective optimization of mechanical properties and workability of RSCM containing SF was performed via Taguchi Design Method (TDM) with four main variables including cement content, W/C ratio, SF content and superplasticizer content at three different levels. SF was used to decrease the environmental pollution caused by cement production as well as compensating the negative effect of RA on the mechanical properties of RSCM. The results revealed that TDM could appropriately predict the workability and compressive strength of RSCM. Also, mixture design containing W/C = 0.39, SF = 6%, cement = 750 kg/m^3 and SP = 0.33% was found as the optimum mixture having the highest compressive strength and acceptable workability as well as low cost and environmental concerns.

1. Introduction

High workability and durability of self compacting concrete (SCC) makes it desirable in structures. Because of the strong relation between durability and compaction of concrete, ordinary concrete structures have inadequate durability; therefore, several studies have been carried out to improve its rheological and mechanical properties [1–3]. Appropriate compaction of concrete depends on the quality of workers; as a result, the use of SCC which does not need external compaction is important to create high durable concrete [4, 5].

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Using supplementary cementitious materials (SCMs) such as fly ash and nano particles in cement mortars has gained considerable attention in recent years, with the aim of improving its properties [6]. Several researchers have studied the effect of using these materials on the properties of concrete. Mahdikhani and Ramezanianpour [7] found the relation between different rheological properties of concrete using mini column segregation, mini J-ring and mini Orimet tests. Mehrinejad Khotbehsara et al. [8] experimentally investigated the effect of SnO_2, ZrO_2 and $CaCO_3$ nano particles on the durability, mechanical and rheological properties of concrete containing fly ash, and observed that the compressive strength and durability of concrete specimens improved.

Resources of natural aggregates (NAs) are not renewable, and ecological concerns regarding the mining of NAs that cause water pollution, erosion in the river bank, etc. have been raised [9]. Recycled aggregate concrete (RAC) has been utilized as a suitable substitution to natural aggregate concrete, addressing the concerns about global sustainability issues including deterioration of natural resources and the extreme generation of construction waste [10]. In other words, recycling of waste concrete is an important method for applying sustainable development strategies [11]. The addition of recycled aggregates (RA) has a negative effect on the durability and mechanical properties of RAC in most cases [12,13]. Therefore, several studies have been performed to enhance the properties of RAC, including the use of nanoparticles.

The mechanical properties of RAC modified by nanoparticles was evaluated by Gao et al. [14] and it was observed that the nanoparticles significantly improved the mechanical properties of RAC. Bai et al. [15] enhanced the workability of RAC by adjusting the W/C ratio, controlling the moisture content of aggregate, and using different mixing processes. Muduli and Mukharjee [16] found that the properties of RAC could improve by adding metakaolin. Besides RA, other parameters such as cement content, W/C ratio, addition of SCMs such as SF and superplasticizer influence the compressive strength of RAC. Thus, it is important to know the influence of these parameters to obtain optimum mixture design with desired properties of fresh and hardened concrete. This could help in minimizing the time and cost of the experiments related to the production of concrete specimens [17,18].

In recent years, Taguchi design method (TDM) has been widely used to determine the optimum mixture design and behavior of cement mortar and concrete containing different additives [19,20]. Ozbay et al. optimized the mixture design of high strength SCC (HSSCC) using TDM [21]. Joshaghani et al. evaluated different concrete properties such as permeability, density, porosity and strength using the TDM [22]. Tanyildizi [23] investigated the post-fire compressive strength and crack properties of structural lightweight concrete containing fly ash using TDM. Olivia and Nikraz [24] optimized the durability and mechanical properties of geopolymer mixtures containing fly ash using TDM. Tanyildizi and Sahin [25] statistically investigated the ultrasonic pulse velocity and compressive strength of concrete strengthened with polymer after exposure to high temperature. Teimortashlu et al. [26] optimized the compressive strength of concrete specimens containing fly ash, slag and nano silica using TDM and illustrated that the highest compressive strength was achieved with 64% cement replacement.

Most notably, the workability and mechanical properties of RSCMs are in relation with SCM and their properties; and obtaining the optimum mixture design is a time consuming and costly process. According to the abovementioned, several investigations have been performed to evaluate workability of fresh mortar. However, simple and small-scale tests are required to appropriately determine the workability of fresh mortar containing RA on the construction site. Therefore, an efficient mixture design method is useful to manage all different ingredients and find the optimum mix design for each of the desired properties of RSCMs. Moreover, the addition of supplementary materials such as SF in RSCM not only compensates for the negative effect of RA on its mechanical properties, but also reduces the environmental effects related to the production of CO_2. The available literature on RAC is currently limited to investigation of the effects of RA on concrete's mechanical and/or workability properties. In addition, several studies have been conducted on the effect of using SF and superplasticizer on the properties of natural aggregate concrete. However, optimizing the mix design of RAC containing SF and superplasticizer based on both mechanical and workability properties has not been performed yet.

In this study, the Taguchi Design Method (TDM) with 4 variables (including cement, W/C ratio, SF and superplasticizer) at 3 different levels was applied aiming at multi-objective optimization of workability and compressive strength of RSCM. For this purpose, the mixture designs suggested by TDM were prepared. Subsequently, the results of workability and compressive strength tests of RSCMs with various mixture designs were obtained and compared with all the predictions resulting from TDM. Finally, multi-objective optimization of workability and compressive strength of RSCM was performed and contribution of each factor was determined by the ANOVA technique.

2. Orthogonal array and S/N ratio

The mixture designs were obtained using the "orthogonal array" technique which is a fractional factorial design with pair wise balancing property. The orthogonal array technique can predict the influences of various factors on the desired performance or quality properties of a process or product at the same time. The proposed standard orthogonal array with nine levels (L_9) prepares the least degrees of freedom for experimental investigation [27]. In other words, orthogonal array is used to decrease the time and cost of tests. For instance, if an experiment has four control factors and three levels, all the possible mixture designs are $n = 3^4 = 81$. By means of orthogonal array L_9, the optimum mixture design can be estimated by only 16 mixtures [28]. This L_9 array has four columns and 9 rows. Each row demonstrates a trail mixture design and the number in each element represents the level of related factors (see section 3.2).

In TDM, the signal to noise ratio (S/N) is used to examine the variation of the response. In fact, the S/N ratio is applied instead of the standard deviation, because the standard deviation has a reverse relation with the mean; while the mean increases, the standard deviation decreases and vice versa. The S/N ratio is defined as the ratio of the mean to the standard deviation [29]. In total, Taguchi defines three conditions of S/N ratio for categorizing the objective function including "the larger the better", "the smaller the better" and "On-target, minimum-variation" conditions which are used when the objective is to minimize, maximize and target the response, respectively. In this study, the S/N ratio of workability and compressive strength of RSCMs were considered as "larger the better" and was calculated according to Eq. (1) [30].

$$(S/N)_{ij} = -10 \log \left[\frac{1}{n} \sum_{k=1}^{n} \frac{1}{Y_{ijk}^2} \right] \tag{1}$$

where Y_{ijk}^2 represents the experimental value of the *i*th performance characteristics (in this study, compressive strength and workability of RSCMs) in the *j*th experiment at the *k*th test, and n is the number of tests.

3. Experimental program

3.1. Materials

For all RSCM specimens, a commercial Type II Portland cement was used according to the ASTM C150-07 standard [31]. Furthermore, SF was added to the mixture to increase the strength of the RSCM specimens. The chemical composition and physical properties of the Type II Portland cement and SF are summarized in Table 1. Also, potable water was used for mixture production and curing of specimens. Based on the ASTM C 494 [32], a poly-carboxylate ether-base type superplasticizer with a specific weight of 1.25 kg/lit was utilized to enhance the consistency of RSCM.

Some mortar and concrete wastes were crushed into RA (≤10 mm) by a jaw crusher and dried subsequently. The grading operation was performed according to ASTM C136-01 [33]. The particle size distribution of RA is shown in Fig. 1. Based on ASTM C 128-01, the fineness modulus, specific gravity and water absorption of RA were obtained to be 3.35, 2.11 gr/cm^3 and 4.88%, respectively [34].

The chemical composition of the RA which was obtained by XRF is presented in Table 2. As presented, the main constituents were SiO_2, Al_2O_3, CaO, Fe_2O_3 and MgO. Studies have shown that the SiO_2 content in RA increases the compressive strength of concrete. Also, $CaCO_3$ content in RA decreases the induction period of C_3S and helps hydration of C_3S [35,36].

Scanning electron microscope (SEM) images of RA (≤75 μm) and cement are respectively shown in Fig. 2(a) and (b). As shown, cement particles are more uniform and its surface is much smoother. Moreover, RA carries some amount of C-S-H gels. Previous observations found that the non-uniform structure of RA increased its water consumption and reduced the rheological properties of mixture [37].

3.2. Methodology and mixture designs

TDM is widely implemented for simple, efficient, and systematic optimization of the desired performance or quality properties of a process or product. The purpose of this study was to evaluate the effect of different variables on the compressive strength and workability of RSCM and finally, obtain the optimum mixture design. The procedure's steps are summarized in Fig. 3. In order to consider the nonlinear effects of different variables on the compressive strength and workability of RSCMs, three levels with four control factors including cement content (650, 700 and 750 kg/m^3), W/C ratio (0.38, 0.41 and 0.44), amount of SF (0, 3 and 6% of cement weight) and superplasticizer dosage (0.3, 0.33 and 0.36% of cement weight) were considered (see Table 3).

The specific weight of all RSCM specimens were kept constant (= 2300 kg/m^3). Hence, the amount of RA was not considered as a factor. Also, due to different amounts of cement and W/C ratio, the amount of fine aggregate was inconstant. The proposed standard orthogonal array with nine levels (L_9) is provided in Table 4. Based on Table 4, the mixture designs were calculated as presented in

Table 1
Chemical components and physical properties of type II Portland cement and SF.

Chemical components	Cement	SF
SiO_2 (%)	21.24	93.55
Al_2O_3 (%)	5.21	1.31
Fe_2O_3 (%)	4.31	0.94
CaO (%)	62.93	0.52
MgO (%)	1.64	0.96
SO_3 (%)	2.12	0.06
Na_2O (%)	0.28	0.55
K_2O (%)	0.63	0.91
LOI (%)	1.33	–
C_3S	68.79	–
C_2S	9.02	–
C_3A	6.51	–
C_4AF	13.10	–
Physical properties		
Density (gr/cm^3)	3.298	2.250
Specific surface (m^2/kg)	3250	>20,000
Autoclave expansion (%)	0.21	–
Initial setting time (min)	115	–
Final setting time (min)	185	–

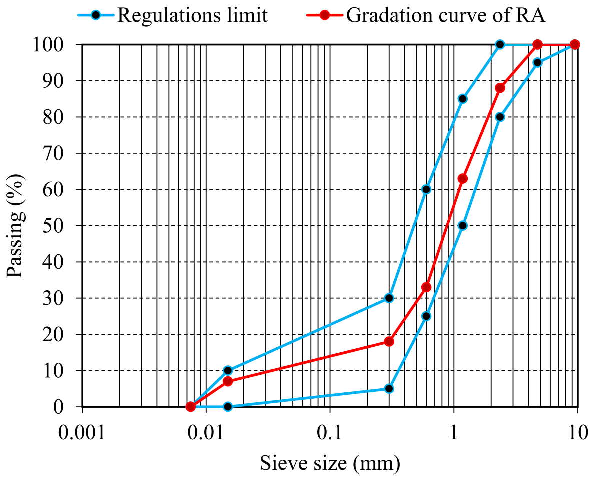


Fig. 1. The grading curve of RA.

Table 2
Chemical components of RA.

Chemical components	Percentage (%)
SiO_2 (%)	50
Al_2O_3 (%)	5
Fe_2O_3 (%)	2
CaO (%)	40
MgO (%)	3

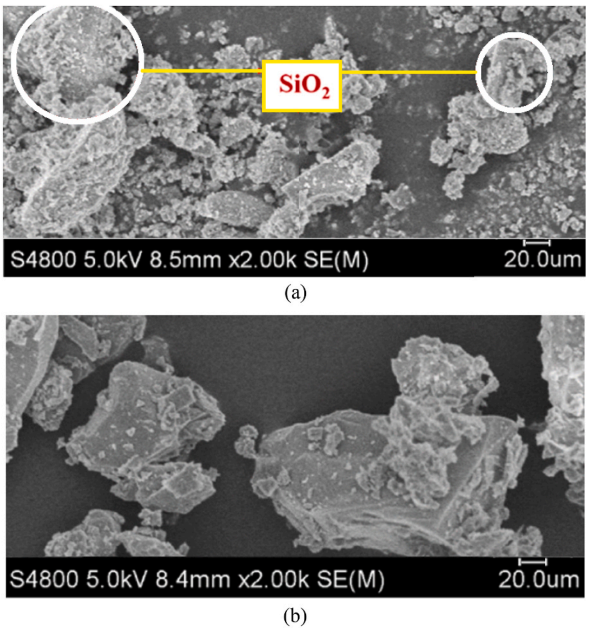


Fig. 2. SEM image of (a) RA (b) cement.

Table 5.

To prepare RSCM specimens, the subsequent steps were followed:

(I) Dry components (RA, cement and SF) were appropriately mixed for 1 min in a mixer;
(II) Water and superplasticizer were gradually added to the dry mixture and were appropriately mixed for 4 min;

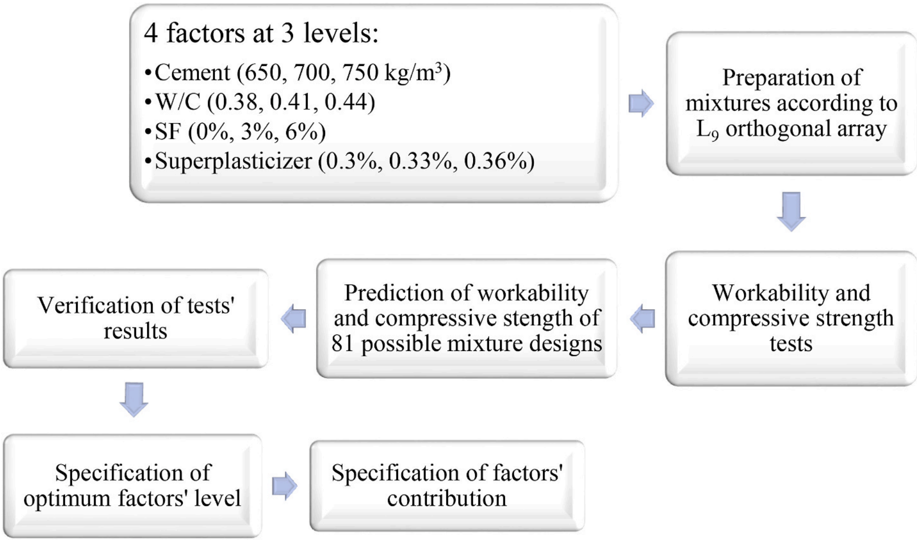


Fig. 3. The schematic of total procedure.

Table 3
Factors and levels used in TDM.

Level	W/C	SF (%)	Cement (kg/m^3)	Superplasticizer (%)
1	0.38	0	650	0.3
2	0.41	3	700	0.33
3	0.44	6	750	0.36

Table 4
L_9 standard orthogonal array.

No.	W/C	SF	Cement	Superplasticizer
M1	1	1	1	1
M2	1	2	2	2
M3	1	3	3	3
M4	2	1	2	3
M5	2	2	3	1
M6	2	3	1	2
M7	3	1	3	2
M8	3	2	1	3
M9	3	3	2	1

Table 5
The mixture designs based on L_9 array.

No.	W/C	SF (%)	Cement (kg/m^3)	Superplasticizer (%)	Fine aggregate (kg/m^3)
M1	0.38	0	650	0.3	1403
M2	0.38	3	700	0.33	1334
M3	0.38	6	750	0.36	1265
M4	0.41	0	700	0.36	1313
M5	0.41	3	750	0.3	1242.5
M6	0.41	6	650	0.33	1383.5
M7	0.44	0	750	0.33	1220
M8	0.44	3	650	0.36	1364
M9	0.44	6	700	0.3	1292

(III) A portion of fresh mortar was used for workability tests and the remaining mortar was casted into 5 cm cubic molds for compressive strength tests;

(IV) The casted RSCM were covered with wet towel for 24 h. Then, they were demolded and cured in limewater in a water tank at a temperature of 20 ± 2 °C until the age of compressive strength test.

3.3. Testing procedure

EFNARC has proposed empirical tests to evaluate the properties of fresh SCC [38]. Different tests including the mini slump flow, mini J-ring, mini V-funnel flow, T20 and mini segregation column tests were carried out to assess the workability of fresh RSCM based on the EFNARC standard [38]. Workability tests' equipment used in this paper is shown in Fig. 4. The purpose of mini slump flow test is measuring the flowability of RSCMs. The mini slump flow test on M4 is shown in Fig. 5(a). The time interval for diameter of mortar to reach 20 cm was recorded as T20 time to evaluate the viscosity of RSCMs. The mini J-ring test was carried out to evaluate the passing ability of RSCMs throughout the rebars. The mini J-ring test on M4 is shown in Fig. 5(b). The mini V-funnel flow test was performed to determine the viscosity of RSCMs.

The mini segregation column test was conducted to assess the segregation resistance and consistency of the RSCMs. Similar to Mehdipour et al. [39] and Libre et al. [40] and based on the ASTM C 1610/C 1610M-06a [41] recommendations, a small apparatus was implemented as shown in Fig. 5(d). The segregation index (SI) was calculated using Eq. (2) [41].

$$SI = 2\left[\frac{(CA_B - CA_T)}{(CA_B + CA_T)}\right] \times 100 \tag{2}$$

where CA_B and CA_T are the mass of remained material on the #50 sieve for the bottom and the top part of the segregation column, respectively. According to previous studies, segregation limits could be expressed as [7,39,40]:

(I) SI ≤ 30%: No segregation
(II) 30% ≤ SI ≤ 130%: Tendency to segregation
(III) SI ≥ 130%: Severe segregation

In addition to workability tests, compressive strength tests were also carried out on 7 and 28 days cubic specimens according to ASTM C109/C109M-20b standard [42]. In each age, three specimens were used for the compressive strength test, and the average was calculated.

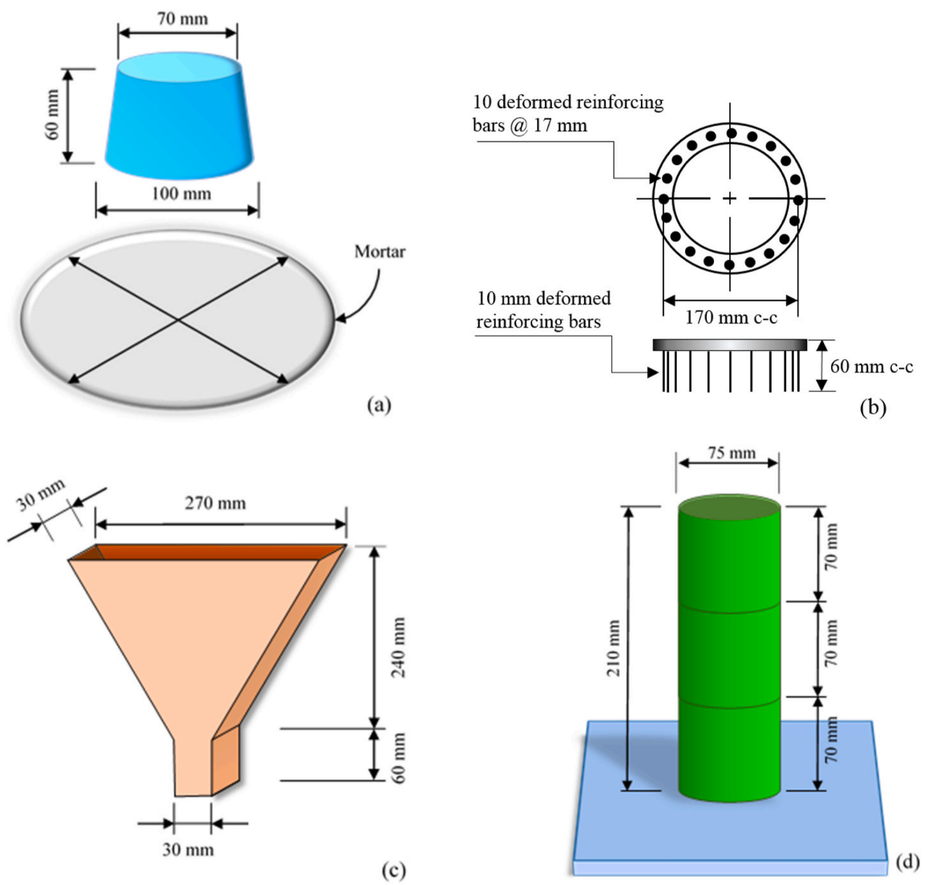
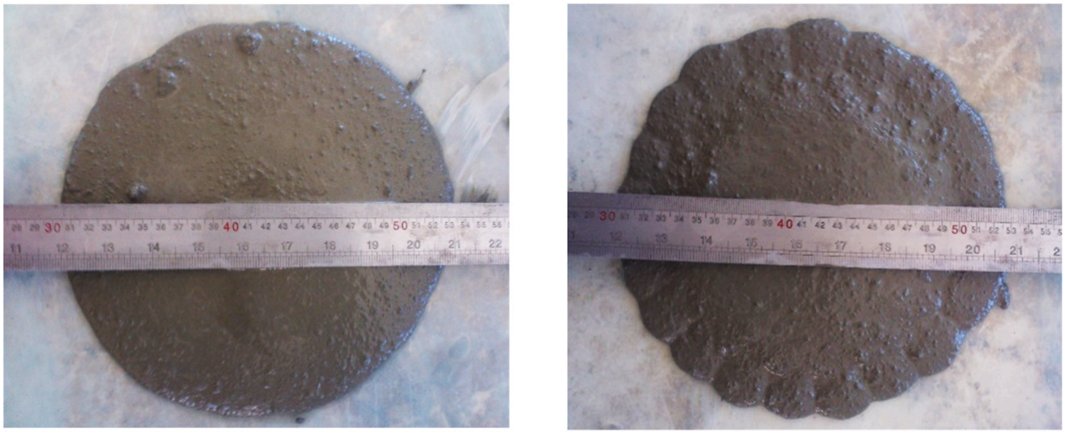


Fig. 4. The workability tests equipment (a) truncated cone (b) mini J-ring (c) mini V-funnel (d) segregation column [38].



(a) (b)

Fig. 5. (a) Mini slump flow test (b) Mini J-ring test on M4.

4. Analysis, results and discussion

Design and analysis of TDM was performed using Minitab software. The results of workability and compressive strength tests are presented in Table 6. As illustrated, the workability of all 9 mixture designs met the requirements of EFNARC [38]. The effect of each factor at different levels on the compressive strength and workability of RSCM are presented in Fig. 6.

4.1. Mini slump flow, mini J-ring and T20

As could be found from the results of the mini J-ring and mini slump flow tests, by increasing the W/C ratio, superplasticizer dosage and the cement content, the flowability and passing ability of the mortars increased almost linearly. Moreover, the overall trend of T20 time was the opposite of the mini slump flow test results. Similar results were observed in previous studies [7,18,43]. The difference between the results of mini J-ring and mini slump flow tests indicate the passing ability of the RSCM. According to the results, the difference between the two mentioned tests was less than 4.5%, which indicated the acceptable passing ability of RSCM. Unlike the effect of W/C ratio, superplasticizer dosage, and the cement content, once the amount of SF was increased, the consistency of RSCM was enhanced and its flow diameter was reduced. Small particle size and high specific surface of SF reduced the available water around particles and led to higher relative water demand. The distribution of fine particles could have a significant effect on the fresh and hardened properties of RSCM, as reported in previous studies [44–46].

4.2. Mini V-funnel and mini segregation column

According to the results, by increasing the W/C ratio, superplasticizer dosage and the cement content, the viscosity of RSCM decreased and the risk of segregation RSCM increased; thus, the discharge time was reduced and the SI increased. It could be found that the effect of W/C ratio on SI was relatively less significant than the superplasticizer dosage and the cement content. In addition, SF increased the cohesion of the mortar that led to reduction in the discharge time and increase in SI. Based on the results reported in 4.1, it is concluded that the factors which increased the flowability of RSCM, increased the risk of segregation.

Table 6
The results of workability and compressive strength tests of RSCMs.

No.	Mini slump (cm)	Mini V-funnel (sec)	Mini J-ring (cm)	**SI (%)**	**T20 (sec)**	Compressive strength (MPa)	
						7 day	28 day
M1	20.0	12.00	18.25	4.50	5.05	34.7	51.7
M2	23.0	5.08	21.75	9.60	2.38	42.1	62.2
M3	27.5	4.44	26.75	15.10	1.90	36.8	51.7
M4	32.0	3.91	32.00	35.00	1.40	35.4	52.0
M5	26.5	3.40	25.80	4.60	1.50	36.8	57.0
M6	20.8	3.98	18.25	3.10	4.02	35.7	56.8
M7	32.5	3.50	32.25	31.00	1.50	31.0	47.4
M8	27.5	3.28	28.25	3.10	0.67	38.6	48.2
M9	23.5	2.38	22.70	3.70	1.08	36.0	50.1

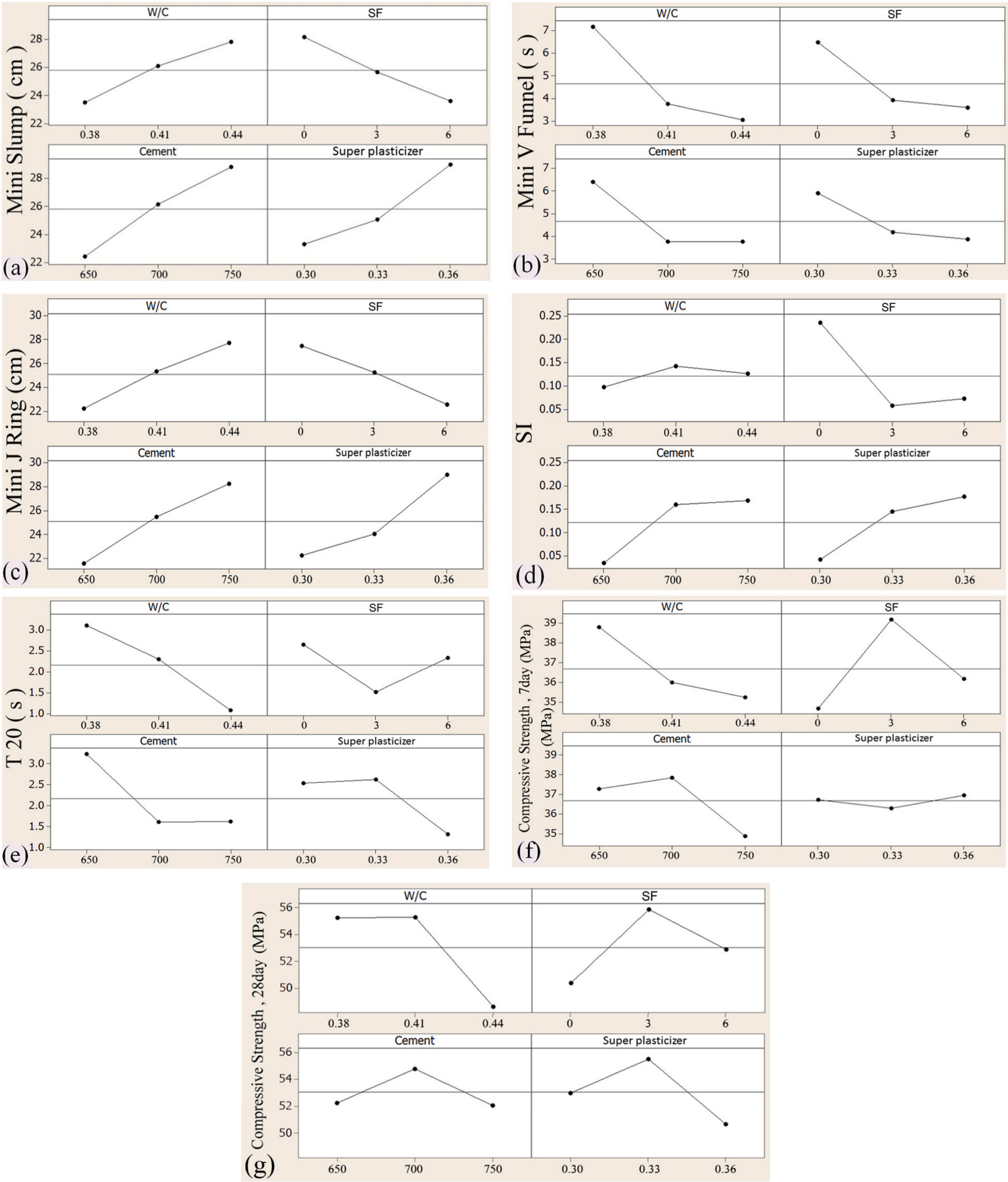


Fig. 6. The influence of factors on the results of workability and compressive strength tests.

4.3. Compressive strength

The compressive strength of RSCM mainly depends on its water-cement ratio. As the water-cement ratio increases, segregation potential is increased and a higher amount of water is available for the creation of air bubbles, so air content increases [47]. Hence, based on the results, by increasing the W/C ratio, the air content of mortar is increased and the 7 and 28-day compressive strength declines. On the other hand, increasing the amount of SF and cement increased the compactness and cohesion of the mortar. However, due to their high water demand, excessive amount of these materials causes an incomplete hydration reaction. Therefore, the second and third levels of SF and cement yield the maximum and minimum 7 and 28-day compressive strength among all mixes, respectively. Superplasticizer reduces the water demand and increases the viscosity of mortar which led to decreasing segregation potential. Therefore, an optimum amount of superplasticizer (second level) increases the 28-day compressive strength of RSCM. However, it was observed that the 7-day compressive strength was not affected significantly by varying the superplasticizer dosage.

5. Verification of properties prediction

In this section, verification of the results as predicted by the Taguchi method is presented. For this purpose, 9 of the 81 possible mixture designs were prepared and their workability and compressive strength were compared with the Taguchi predictions. The selected 9 mixture designs are presented in Table 7.

The comparison of Taguchi predictions and experimental results of workability and compressive strength of RSCMs are illustrated in Fig. 7. The highest difference between the Taguchi predictions and mini slump flow, mini J-ring, and mini segregation column tests were 7.7%, 8.3% and 9.09%, respectively. These differences revealed that TDM could predict the workability and compressive strength of RSCMs with good accuracy. Also, the highest difference between the Taguchi prediction and experimental results of the mini V-funnel flow test and the T20 time was 1.96 s and 0.85 s, respectively. In addition to workability predictions, as shown in Fig. 7, TDM could accurately predict RSCM's compressive strength, such that the highest difference between the Taguchi predictions and experimental results of 7 and 28-day compressive strength were 10.4% and 9.7%, respectively.

The workability and compressive strength of all 81 mixture designs using the TDM are listed in Table 8. As presented, the range of mini slump flow diameters was 15.4 cm–36.4 cm. The main effect of SF on mini slump flow and mini J-ring diameter in high W/C ratio (0.44) mixes were 22.7% and 24.2%, respectively. In addition, the discharge time of RSCM in the mini V-funnel test started from values less than 0.5 s and increased up to 10.76 s.

6. Analysis of variance (ANOVA)

The Analysis of Variance (ANOVA) technique is mostly used to analyze the contribution of different factors on the results of experiments. Sums of Squares (SS) is used in ANOVA technique to divide the total response variance into variances due to errors and processing parameters [48]. Therefore, in order to statistically determine the importance and contribution of the factors on RSCMs' workability and compressive strength, *F*-tests and ANOVA technique were used via SPSS software.

The contribution of factors (W/C ratio, cement content, SF content and superplasticizer content) on RSCMs' workability and compressive strength are presented in Table 9. The *F*-test was carried out with a confidence level of 95%. The *p*-value for all of the factors were less than 0.05 in workability and compressive strength tests, which indicates that influence of the factors were significant. W/C ratio was the most effective factor in mini V-funnel flow, T20, and 7 and 28-day compressive strength tests. Furthermore, SF content had a key effect in the results of mini segregation column test and the contribution of the cement content was more than other factors in the results of the mini slump flow diameter test. Additionally, the superplasticizer played an important role in the mini J-ring test, with a contribution of 33.76%.

The contribution of factors on RSCMs' workability and compressive strength are depicted in Fig. 8. As shown, the error was negligible for mini slump flow, mini V-funnel flow, mini J-ring, mini segregation column, and T20 tests; but it slightly increased for 7 and 28-day compressive strength tests (8.59% and 4.91%, respectively). On the other hand, the superplasticizer content had a negligible effect on the 7-day RSCM's compressive strength.

7. Multi-objective optimization

The acceptable ranges for RSCM's workability tests as recommended by EFNARC are presented in Table 10 [38].

The mixture which had the maximum 7- and 28-day compressive strength while having acceptable workability was selected as the optimum mixture. Based on the results provided in Table 8, M39 specimen with W/C = 0.39, SF = 6%, cement = 750 kg/m^3 and SP = 0.33% was selected as the optimum mixture, which had 7- and 28-day compressive strength of 43.1 MPa and 66.5 MPa, respectively

Table 7
The selected mixture designs for verification.

No.	W/C	SF (%)	Cement (kg/m^3)	Superplasticizer (%)	Fine aggregate (kg/m^3)
M10	0.38	3	750	0.3	1073.57
M11	0.38	0	650	0.36	1457.12
M12	0.38	6	700	0.36	986.00
M13	0.41	6	700	0.33	931.22
M14	0.41	3	700	0.36	1121.22
M15	0.41	0	650	0.3	1406.66
M16	0.44	6	750	0.33	750.70
M17	0.44	3	650	0.33	1178.12
M18	0.44	0	700	0.3	1257.32

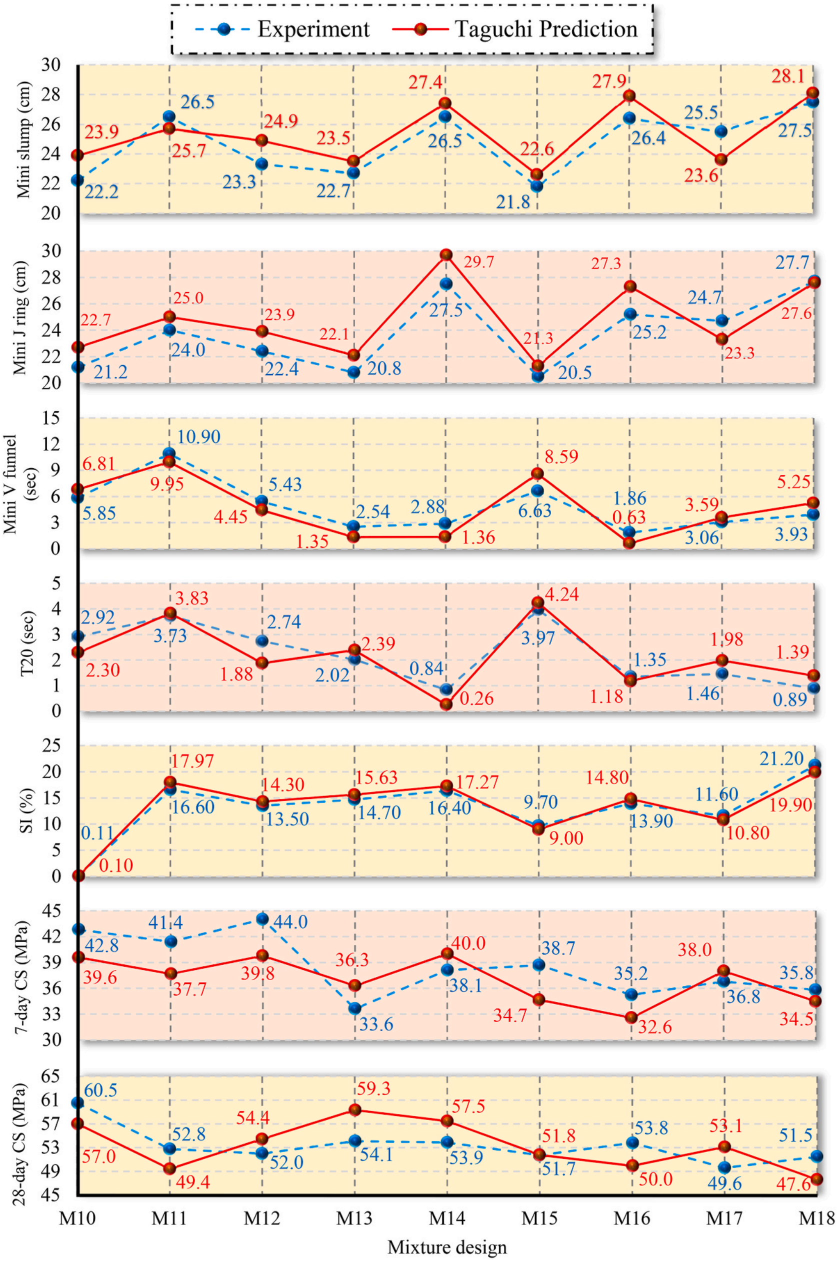


Fig. 7. Comparison of Taguchi prediction and experiment results of workability and compressive strength of SCMs.

[38]. Also according to Fig. 8, it is obvious that W/C ratio was the most effective factor in 7- and 28-day compressive strength of RSCM, with a contribution of 46.20% and 46.46%, respectively. It shows that a cost-effective mixture with high mechanical properties and acceptable workability could be obtained by adjusting the W/C ratio. Similar result was found by Taheri and Ramezanianpour [49], who reported that the W/C ratio was the most substantial parameter in mechanical properties of pervious concrete [49].

In the second order, the SP content significantly affected the 7- and 28-day compressive strength of RSCM with a contribution of 29.78% and 22.32%, respectively. Generally, it could be found that by decreasing the W/C ratio while meeting the standard workability criteria using SP, the optimum mixture design in terms of cost and strength could be obtained. Also, as a result of decreasing the cement demand for enhancing the mechanical properties, several environmental issues related to CO_2 emission from cement companies could be resolved [1]. This fact could be found by comparing the 7- and 28-day compressive strength of M34 and M58 mixes. As presented, with a constant SF content, by decreasing the W/C ratio from 0.41 to 0.38 and cement content from 750 kg/m^3 to 650 kg/m^3, and increasing the SP content from 0.3% to 0.33%, the 7- and 28-day compressive strength of RSCM was enhanced by 14.09% and 4.93%, respectively. Similar result could be found by comparing the 7- and 28-day compressive strength of M35 and M59 mixes.

Table 8
Properties of remaining mixture designs of all 81 possible mixture designs.

No.	W/C	SF (%)	C[1] (kg/m^3)	SP[2] (%)	Mini slump (cm)	Mini V-funnel (sec)	Mini J-ring (cm)	SI (%)	T20 (sec)	CS[3] (MPa)	
										7 day	28 day
M19	0.38	0	650	0.33	21.8	10.26	20.1	0.14	5.14	37.01	54.26
M20	0.38	0	700	0.3	23.7	9.37	22.1	0.17	3.42	38.03	54.26
M21	0.38	0	700	0.33	25.5	8.63	23.9	0.27	3.51	37.59	56.8
M22	0.38	0	700	0.36	29.4	8.32	28.9	0.30	2.20	38.26	51.95
M23	0.38	0	750	0.3	26.4	9.36	24.9	0.17	3.43	35.06	51.55
M24	0.38	0	750	0.33	28.2	7.82	26.8	0.28	3.52	34.61	54.08
M25	0.38	0	750	0.36	32.1	7.91	31.7	0.31	2.21	35.28	49.24
M26	0.38	3	650	0.3	17.5	9.45	16.0	0.01	ND	41.99	57.2
M27	0.38	3	650	0.33	19.3	7.91	17.8	0.01	ND	41.55	59.73
M28	0.38	3	650	0.36	25.0	9.49	25.0	0.01	2.69	42.21	54.88
M29	0.38	3	700	0.3	21.2	6.82	19.9	0.01	2.29	42.57	59.73
M30	0.38	3	700	0.36	26.9	4.77	26.7	0.13	1.07	42.8	57.42
M31	0.38	3	750	0.33	25.7	5.07	24.5	0.10	2.39	39.15	59.55
M32	0.38	3	750	0.36	29.6	4.76	29.4	0.13	1.08	39.82	54.71
M33	0.38	6	650	0.3	15.4	9.13	13.3	0.01	ND	38.97	54.22
M34	0.38	6	650	0.33	17.2	7.99	15.1	0.01	ND	38.53	56.75
M35	0.38	6	650	0.36	21.1	7.98	20.1	0.02	3.51	39.19	59.91
M36	0.38	6	700	0.3	19.2	6.50	17.2	0.01	ND	39.55	56.75
M37	0.38	6	700	0.33	20.9	4.76	19.0	0.11	3.19	39.11	59.28
M38	0.38	6	750	0.3	21.8	6.49	20.0	0.00	3.12	36.57	54.04
M39	0.38	6	750	0.33	27.6	7.75	27.3	0.02	0.51	43.13	66.57
M40	0.41	0	650	0.33	24.4	6.85	23.2	0.19	4.33	34.21	54.31
M41	0.41	0	650	0.36	28.3	6.54	28.1	0.22	3.02	34.88	49.46
M42	0.41	0	700	0.3	26.3	5.96	25.2	0.21	2.62	35.24	54.31
M43	0.41	0	700	0.33	28.1	4.22	27.1	0.32	2.71	34.8	56.84
M44	0.41	0	750	0.3	29.0	5.95	28.0	0.22	2.63	32.26	51.6
M45	0.41	0	750	0.33	30.8	4.21	29.9	0.33	2.72	31.82	54.13
M46	0.41	0	750	0.36	34.7	3.90	34.8	0.36	1.41	32.48	49.28
M47	0.41	3	650	0.3	20.1	6.04	19.1	0.02	3.11	39.19	57.24
M48	0.41	3	650	0.33	21.9	4.30	20.9	0.01	3.20	38.75	59.77
M49	0.41	3	650	0.36	25.8	3.99	25.9	0.05	1.89	39.42	54.93
M50	0.41	3	700	0.3	23.8	3.41	23.0	0.04	1.48	39.77	59.77
M51	0.41	3	700	0.33	25.6	1.67	24.8	0.14	1.57	39.33	62.31
M52	0.41	3	750	0.33	28.3	1.66	26.6	0.15	1.59	36.35	59.6
M53	0.41	3	750	0.36	32.2	1.35	32.5	0.18	0.68	37.02	54.75
M54	0.41	6	650	0.3	18.0	5.72	16.4	0.01	ND	36.17	54.26
M55	0.41	6	650	0.36	23.7	3.67	23.2	0.06	2.71	36.4	51.95
M56	0.41	6	700	0.3	21.8	3.09	20.3	0.05	2.30	36.75	56.8
M57	0.41	6	700	0.36	27.4	1.04	26.1	0.19	1.08	36.98	54.48
M58	0.41	6	750	0.3	24.4	3.08	23.1	0.06	2.31	33.77	54.08
M59	0.41	6	750	0.33	26.2	1.34	24.9	0.16	2.40	33.33	56.62
M60	0.41	6	750	0.36	30.1	1.03	29.8	0.19	1.09	34	51.77
M61	0.44	0	650	0.3	24.3	7.88	23.7	0.07	3.02	33.9	45.11
M62	0.44	0	650	0.33	26.1	6.14	25.6	0.18	3.11	33.46	47.64
M63	0.44	0	650	0.36	30.0	5.83	30.5	0.21	1.80	34.13	42.8
M64	0.44	0	700	0.33	29.8	3.51	29.5	0.30	1.48	34.04	50.17
M65	0.44	0	700	0.36	33.7	3.20	34.4	0.33	0.80	34.71	45.33
M66	0.44	0	750	0.3	30.7	5.24	30.4	0.21	1.41	31.5	44.93
M67	0.44	0	750	0.36	36.4	3.19	37.5	0.34	0.89	31.73	42.62
M68	0.44	3	650	0.3	21.8	5.33	21.5	0.01	1.89	38.44	50.57
M69	0.44	3	700	0.3	25.6	2.70	25.4	0.02	0.26	39.02	53.11
M70	0.44	3	700	0.33	27.3	0.96	27.2	0.12	0.95	38.58	55.64
M71	0.44	3	700	0.36	31.2	0.65	32.1	0.16	0.82	39.24	50.8
M72	0.44	3	750	0.3	28.2	2.69	28.2	0.03	0.87	36.04	50.4
M73	0.44	3	750	0.33	30.0	0.95	30.0	0.13	0.96	35.6	52.93
M74	0.44	3	750	0.36	33.9	0.64	34.9	0.16	0.91	39.26	48.08
M75	0.44	6	650	0.3	19.8	5.01	18.8	0.02	ND	35.41	47.6
M76	0.44	6	650	0.33	21.5	3.27	20.6	0.01	2.79	34.97	50.13
M77	0.44	6	650	0.36	25.4	2.96	25.5	0.05	1.48	35.64	45.28
M78	0.44	6	700	0.33	25.3	0.64	24.5	0.14	1.17	35.58	52.66
M79	0.44	6	700	0.36	29.2	0.33	29.4	0.17	0.81	36.22	47.82
M80	0.44	6	750	0.3	26.1	2.37	25.5	0.04	1.09	33.02	47.42
M81	0.44	6	750	0.36	31.8	0.32	32.2	0.18	0.71	33.24	45.11

[1] C: Cement,
[2] SP: Superplasticizer,
[3] CS: Compressive strength

Table 9
The results of ANOVA.

			W/C	SF	Cement	Superplasticizer	Error	Total
		Degrees of freedom	2	2	2	2	72	81
Mini slump		Sum of square	245.565	283.796	543.992	454.690	7.213	55483.060
		F	1225.556	1416.355	2714.932	2269.246	–	–
		Contribution of factors (%)	16.00	18.49	35.43	29.62	0.47	–
		P-value	0.0012	0.0001	<0.0001	<0.0001	–	–
Mini V-funnel		Sum of square	272.559	130.577	132.430	62.755	3.883	2383.232
		F	2527.104	1210.679	1227.861	581.853	–	–
		Contribution of factors (%)	45.26	21.68	21.99	10.42	0.64	–
		P-value	<0.0001	<0.0001	<0.0001	0.0018	–	–
Mini J-ring		Sum of square	398.388	333.187	594.889	678.476	4.685	53150.935
		F	3061.375	2560.342	4571.366	521.685	–	–
		Contribution of factors (%)	19.82	16.58	29.60	33.76	0.23	–
		P-value	<0.0001	0.0012	<0.0001	<0.0001	–	–
SI		Sum of square	13.367	113.359	94.592	80.419	9.423	4465.013
		F	884.139	1201.176	1120.982	925.834	–	–
		Contribution of factors (%)	4.30	36.43	30.40	25.84	3.03	–
		P-value	0.023	<0.0001	<0.0001	<0.0001	–	–
Compressive strength	7-day	Sum of square	30865.308	19898.523	9893.639	419.215	5737.276	11016662.63
		F	193.672	124.858	62.080	2.630	–	–
		Contribution of factors (%)	46.20	29.78	14.81	0.63	8.59	–
		P-value	<0.0001	<0.0001	0.0013	0.047	–	–
	28-day	Sum of square	84083.459	40382.810	10741.976	36869.532	8884.527	23081653.52
		F	340.705	163.631	43.526	149.395	–	–
		Contribution of factors (%)	46.46	22.32	5.94	20.37	4.91	–
		P-value	<0.0001	<0.0001	0.035	<0.0001	–	–
		Degrees of freedom	2	2	2	2	66	75
T20		Sum of square	51.637	16.151	44.916	25.354	1.454	528.084
		F	1278.544	399.903	1112.129	627.761	–	–
		Contribution of factors (%)	37.01	11.58	32.20	18.17	1.04	–
		P-value	<0.0001	0.0018	<0.0001	0.0001	–	–

On the other hand, comparing the unit cubic meter materials' cost of M34 and M58 (based on IRR currency), it could be found that M34 specimen is about 1′400′000 IRR/m^3 cheaper (89%) than M58 specimen.

8. Conclusions

In this study, the TDM was applied to perform multi-objective optimization of workability and compressive strength of RSCM. For this purpose, based on L_9 orthogonal array, 4 control factors including cement content (650 kg/m^3, 700 kg/m^3 and 750 kg/m^3), W/C ratio (0.38, 0.41 and 0.44), silica fume content (0%, 3% and 6%), and superplasticizer dosage (0.3%, 0.33% and 0.36%) with 3 levels were considered for the experimental program. Then, Taguchi predictions of workability and compressive strength of 9 mixture designs were compared with experimental results. Finally, multi-objective optimization of workability and compressive strength of RSCM was performed, and the contribution of each factor was determined by the ANOVA technique. The following conclusions can be drawn:

1. Based on the results, TDM was able to predict the RSCM's workability and compressive strength with acceptable accuracy. Moreover, the accuracy of Taguchi predictions was more significant in workability properties compared to compressive strength of RSCM.
2. According to the Taguchi predictions and ANOVA results, W/C ratio and SF content had respectively the greatest impact on the compressive strength of RSCM.
3. Based on the TDM and ANOVA results, W/C ratio and cement content had the greatest effect on viscosity of RSCM in mini V-funnel flow and T20 tests.
4. The SF and cement content had the highest effect on segregation resistance and consistency of RSCM. As a result, high segregation resistance and consistency were found in M38 with 6% SF content.
5. The SP content had a negligible impact on the 7-day compressive strength. However, the impact of SP on its 28-day compressive strength was significant. Also, a reverse trend was found in the effect of cement content on the compressive strength of RSCM. So that the cement content had a significant impact on the 7-day compressive strength and a negligible impact on the 28-day compressive strength. Moreover, the contribution of W/C ratio and SF on the compressive strength of RSCM did not change significantly at later ages.
6. Multi-objective optimization revealed that M34 specimen containing W/C = 0.39, SF = 6%, cement = 750 kg/m^3 and SP = 0.33% was the optimum mixture which had highest 7- and 28-day compressive strength and acceptable workability as well as low cost and environmental concerns.

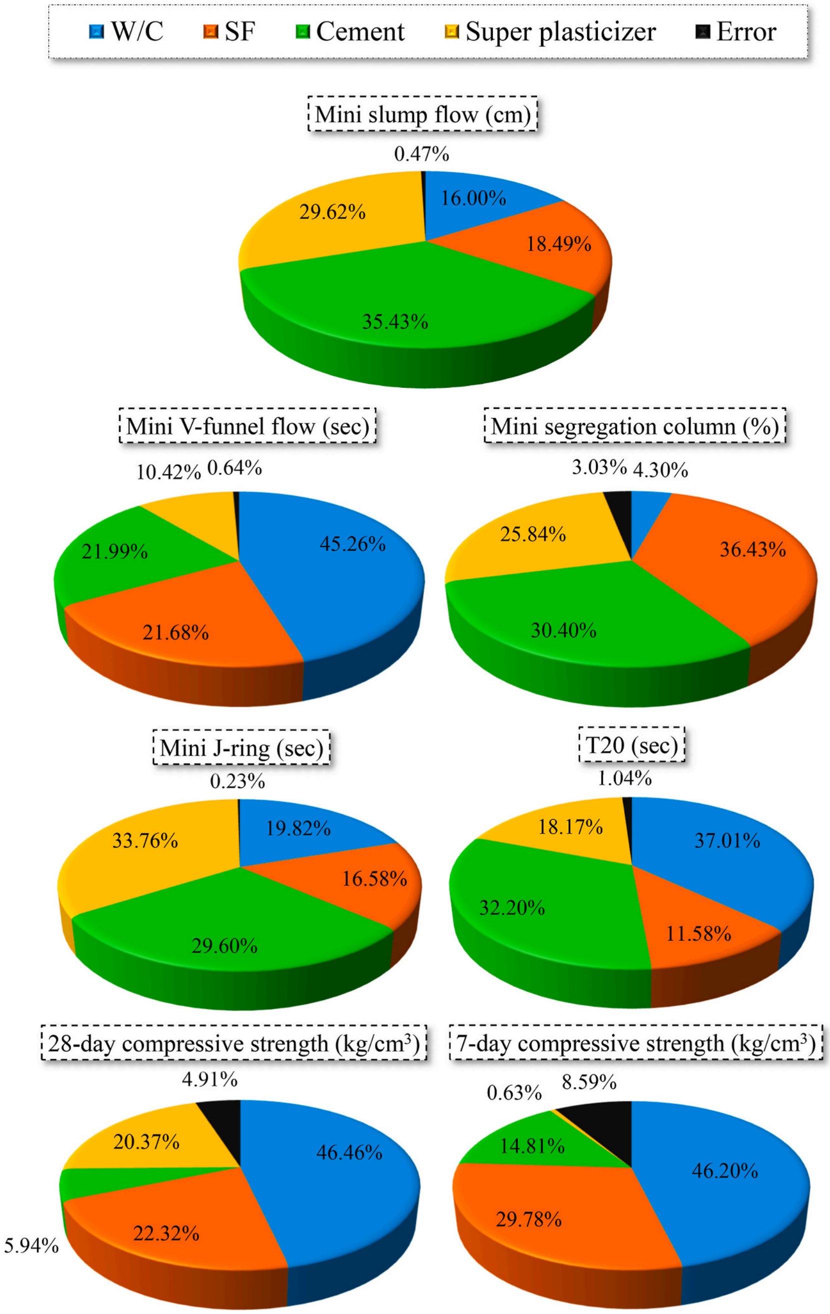


Fig. 8. The factors contribution on workability and compressive strength of RSCM.

Table 10
The EFNARC recommendations for workability tests.

Rheological test	EFNARC recommended limit	
	Lower bound	Upper bound
Mini slump flow test	22 cm	28 cm
Mini V-funnel test	7 s	12 s
Mini J-ring test	22 cm	28 cm
SI test	0%	30%
T20 test	0 s	2 s

Author contribution statement

Omid Bamshad: Performed the experiments; Wrote the paper.
Mahdi Mahdikhani: Conceived and designed the experiments; Wrote the paper.
Amir Mohammad Ramezanianpour, Alireza Habibi: Contributed reagents, materials, analysis tools or data.
Zahra Maleki: Performed the experiments; Analyzed and interpreted the data.
Arsalan Majlesi: Contributed reagents, materials, analysis tools or data; Wrote the paper.
Mohammad Aghajani Delavar: Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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