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RESEARCH ARTICLE-CIVIL ENGINEERING

Predictive Modeling and Multi-response Optimization of Physical and Mechanical Properties of SCC Based on Sand's Particle Size Distribution

Zied Benghazi[1,2] · **Leila Zeghichi**[1,3] · **Adel Djellali**[2] · **Abdelhak Hafdallah**[4]

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Abstract
This paper focuses on the modeling and optimization of the physical and mechanical properties of self-compacting concrete (SCC), prepared using the modified packing model design, taking into consideration sand's particle size distribution (PSD) and fineness modulus (FM). The optimization is predicated using the response surface methodology. The analysis of variance is exploited to determine the statistical significance of the PSD on the studied properties of SCC. For that, we studied twenty-four SCC mixtures, using three kinds of sands with different FM and particle shapes: dune sand, river sand, and crushed sand. The results show that PSD properties of used sand, despite its shape, are good predictors for SCC fresh properties, but less predictive for compressive strength. The multi-response optimization allowed the estimation of sand's PSD parameters that give the optimal physical and mechanical properties of SCC, with an overall desirability of 0.923.

Keywords SCC properties · Particle size distribution · Fineness modulus · Statistical modeling · Multi-response optimization

1 Introduction

Sand assures the continuity between powder and coarse aggregates (gravel) in concrete, and it is important to obtain a well-packed concrete. Therefore, its nature and shape present a key role in concrete's rheology. The effect of sand on the water need, the aggregates packing, and the workability of self-compacting concrete (SCC), depends not only on sand's particle shape but also on its gradation [1].

Round sand gives better rheology for fresh SCC, while angular sand is more beneficial for mechanical strength, due to the difference of frictional forces between the two kinds of sand [2–4]. Therefore, we cannot favor the use of round or angular sand in SCC [2], but we may associate both of them to improve its physical and mechanical properties [5, 6].

These crucial effects of sand give the possibility of modeling and predicting SCC behavior basing on sand particle properties. This would make SCC design easier, faster, and economical compared to most of the existing methods. Several studies were recently made to better understand sand's effects on concrete in general and on SCC, and to develop mathematic models based on sand's properties [5, 7–12].

Bouziani and Sahraoui [7, 11] studied the effect of substitution of crushed sand (CS) by round sand in SCC and made models for the deferent properties of fresh and hardened SCC as a function of the proportion of round sand. They substituted CS with both dune sand (DS) and river sand (RS), and they found that DS has a negative effect on the flowability and workability of fresh SCC, and that river

✉ Zied Benghazi
zied.benghazi@univ-msila.dz;
zied.benghazi@univ-tebessa.dz

Leila Zeghichi
leila.zeghichi@univ-biskra.dz

Adel Djellali
adel.djellali@univ-tebessa.dz

Abdelhak Hafdallah
abdelhak.hafdallah@univ-tebessa.dz

1 Department of Civil Engineering, Faculty of Technology, Mohamed Boudiaf University, M'sila, Algeria

2 Environment Laboratory, Mining Institute, Larbi Tebessi University, Tebessa, Algeria

3 Department of Civil Engineering and Hydraulics, Faculty of Technology, Mohamed Khider University, Biskra, Algeria

4 Department of Mathematics and Computer Sciences, Faculty of Exact Sciences and Sciences of Nature and Life, Larbi Tebessi University, Tebessa, Algeria

sand's effect is positive on these properties, while Zeghichi et al. [5] results show the opposite. These works lead to the hypothesis that the obtained results in both works were not due to sand particle shape alone. It is rather supposed to be the effect of the particle size distribution (PSD) of sand and the percentage of fine particles [8, 13, 14].

Three parameters are mainly used to characterize the PSD of sand to determine its quality as an aggregate for concrete. These parameters are the Hazen's coefficient of uniformity C_u, the coefficient of curvature C_c, and the fineness modulus FM.

C_u and C_c are calculated as follows:

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} \tag{2}$$

with D_{10}, D_{30} and D_{60} are the particle sizes that correspond to 10, 30, and 60% of cumulative passing particles weight, respectively.

A sand PSD curve is considered as well graded if:

$C_u \geq 6$ and $1 < C_c < 3$ [15].

FM represents the mean size of the particles in sand. It is the sum of the cumulative retained R_i on the sieves of standard sieve analysis, divided by 100. Its expression is as follows:

$$\mathrm{FM} = \frac{\sum R_i}{100} \tag{3}$$

Sand is considered as preferential for concrete if:

$2.2 \leq \mathrm{FM} \leq 2.8$ [16].

The conditions mentioned above lead to well-packed solid particles of the mixture materials with an optimal PSD, and then to good physical and mechanical properties of concrete.

The most used design methods, based on the PSD of the solid component of the SCC, are the Chinese method [17] and the Japanese method [18, 19]. These two methods aim to obtain the best fresh and hard SCC properties by ensuring the best packing of particles, considering the variation of solid particles from zero to the maximum diameter (D_{max}).

The modified Andreasen and Andersen model proposes a design method taking into consideration the real case for granular materials, which is the existence of a minimum particle size D_{min} [20, 21]. The model proposed is as follows:

$$P(D) = \frac{D^\alpha - D^\alpha_{\min}}{D_{\max} - D_{\min}} \tag{4}$$

where P stands for the fraction that can pass the sieve with opening D, and D_{max} stands for the maximum particle size of the mixtures. The parameter α takes values from 0 to 1 as a function of the void fraction; the more powders in a mixture, the smaller is α that best characterizes the PSD [22].

The packing density of a concrete mixture depends essentially on the PSD of grains, as well as the packing method [20, 23, 24].

Our work aims to contribute to making the SCC design process easier and at a lower cost, by studying the possibility to predict its rheological and mechanical properties based on sand's PSD, especially in case of limited choices of other SCC's constituent materials. This prediction approach was not treated before in research works.

The present paper correlates the PSD parameters (C_c, C_u, and FM) of sand, using the RSM methodology. This method is very useful in case of irregular experimental design and for a small number of experimental runs. The development of a third-order model was adopted to predict the three fresh properties that differentiate SCC from ordinary concrete: passing ability (PA), segregation resistance (SR), and slump flow (SF), as well as normal compressive strength (R_{c28}) [25, 26]. These properties were then optimized using the desirability function, to obtain the best fresh and hardened properties of SCC based on the considered parameters.

2 Materials and Methods

2.1 Used Materials

The physical and chemical properties of the materials used in the mixtures are presented in Tables 1 and 2, respectively.

We used as admixture MEDAFLOW 30, manufactured by GRANITEX (Algeria). MEDAFLOW 30 is a third-generation superplasticizer (SP) high-range reducing water, consisted of carboxylic ether polymer, which enhances considerably the properties of concrete and allows the obtention of a normal compressive strength > 60 MPa, for a superplasticizer/powder ratio SP/P ≥ 1.4% [27].

The PSD of used materials is shown in Fig. 1. The natural rolled sands used in this work are fine (with a fineness modulus FM < 2.2), which is not entirely suitable for use in concrete if we were looking for good strength. For the CS: FM = 2.85 > 2.8, which may give concretes with good mechanical strength, but with low workability.

Table 1 Physical properties of used materials

Material	Type	ρ (kg/m^3)	Visual sand equivalent (%)	Blaine (cm^2/g)
Cement	CEM II/A 42.5	3100	–	3500
Filler	Limestone powder	2940	–	3200
Dune sand 1 (DS1)	Boussaada sand 0–3	2540	76.8	–
Dune sand (DS2)	Elma Labiod sand 0–3	2500	87.3	–
River sand (RS)	Elkouif sand 0–3	2610	95.7	–
Crushed sand (CS)	ENG quarry 0–3	2530	97.6	–
Crushed gravel 1 (CG1)	ENG quarry sand 3–8	2530	–	–
Crushed gravel 2 (CG2)	ENG quarry gravel 8–16	2530	–	–
Superplasticizer (liquid)	MEDAFLOW 30 (GRANITEX)	1070	–	–

Table 2 Chemical composition of used materials

Material	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	Na_2O	Cl^-
Cement (%)	27.57	5.75	54.82	4.75	1.86	2.48	1.39	0.005
Filler (%)	39.80	8.30	42.21	1.57	4.40	0.75	0.10	0.004

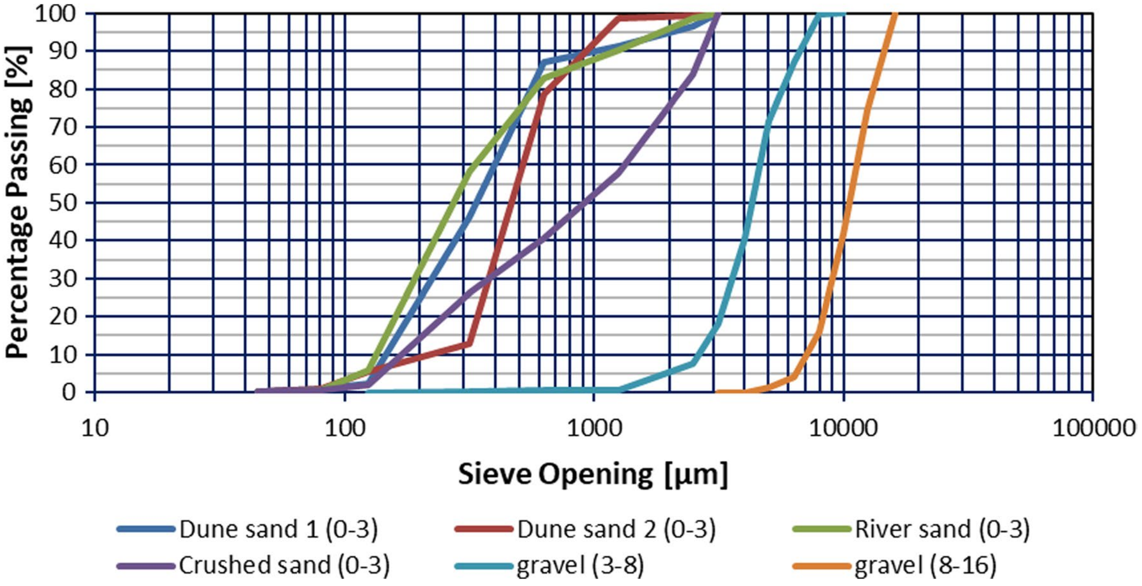

Fig. 1 Particles size distribution of used aggregates

2.2 Experimental Design

In the experimental part of this work, we prepared thirteen SCC mixtures, by gradually substituting the CS with DS1, DS2, and RS, respectively (100/0, 75/25, 50/50, and 0/100). The FM, Cc, and Cu were calculated for each sand mixture.

Mass proportions of the different SCC prepared mixtures are given in Table 3. We used equal proportions of sand and gravel. And in the mortar, powder proportion corresponds to about 37% of its packed density, which is 13% less than the Japanese method's recommendations [21]. For liquid proportions, we used a powder/water ratio of 0.40 and 1.2% for the SP/*P* ratio.

The prepared SCC mixtures were used to study the different considered fresh properties (PA, SR, and SF) and the compressive strength R_{c28} (Table 4). The principle of these tests is described as follows [25]:

Table 3 SCC Mixture mass proportions

Mix. no.	CS (kg)	DS1 (kg)	DS2 (kg)	RS (kg)	CG1 (kg)	CG2 (kg)	Cement (kg)	Filler (kg)	Water (kg)	SP (kg)
1	850	–	–	–	425	425	400	100	200	6
5	–	850	–	–	425	425	400	100	200	6
3	–	–	850	–	425	425	400	100	200	6
4	–	–	–	850	425	425	400	100	200	6
5	637.5	212.5	–	–	425	425	400	100	200	6
6	425	425	–	–	425	425	400	100	200	6
7	212.5	637.5	–	–	425	425	400	100	200	6
8	637.5	–	212.5	–	425	425	400	100	200	6
9	425	–	425	–	425	425	400	100	200	6
10	212.5	–	637.5	–	425	425	400	100	200	6
11	637.5	–	–	212.5	425	425	400	100	200	6
12	425	–	–	425	425	425	400	100	200	6
13	212.5	–	–	637.5	425	425	400	100	200	6

Table 4 SCC experimental design for PA, SR, SF, and R_{c28}

Mix. no.	Sand mixtures' proportions				PSD properties of sand (factors)			Response			
	CS (%)	DS1 (%)	DS2 (%)	RS (%)	FM (factor A)	C_c (factor B)	C_u (factor C)	PA	SR (%)	SF (mm)	R_{c28} (MPa)
1	100	0	0	0	2.85	0.61	8.84	0.33	00.0	450	38.4
2	0	100	0	0	1.70	0.89	2.58	0.85	10.0	790	42.7
3	0	0	100	0	2.03	0.42	1.53	0.90	12.0	760	41.5
4	0	0	0	100	1.18	1.34	2.34	0.00	01.0	530	39.3
5	75	25	0	0	2.74	0.62	6.74	0.6	03.0	720	47.4
6	50	50	0	0	2.26	0.68	5.31	0.82	07.0	790	54.1
7	25	75	0	0	1.97	1.04	4.79	0.85	08.0	780	45.1
8	75	0	25	0	2.64	0.66	6.38	0.61	09.0	780	45.7
9	50	0	50	0	2.43	0.75	4.8	0.85	08.0	750	46.6
10	25	0	75	0	2.23	0.91	3.44	0.84	11.0	750	41.4
11	75	0	0	25	2.50	0.59	6.93	0.78	04.0	610	45.6
12	50	0	0	50	2.17	0.58	5.52	0.81	06.0	660	44.2
13	25	0	0	75	1.84	0.60	4.00	0.62	02.0	570	40.5

2.2.1 Passing Ability (PA)

The L-box test assesses the passing ability of SCC to flow through tight openings between reinforcing bars without segregation or blocking. There are two variations: the two-bar test and the three-bar test. The fresh concrete is first poured into the filling hopper of the L-box and allowed to stand for (60 ± 10) s. Any segregation should be recorded, and then, the gate is raised so that the concrete flows into the horizontal section of the box (Fig. 2). We used the three-bar test in this work, to simulate more congested reinforcement.

The PA is calculated from the following equation:

$$\mathrm{PA} = \frac{H2}{H1} \tag{5}$$

With H1 is the depth of concrete behind the gate, and H2 is its mean depth in the horizontal section.

2.2.2 Segregation Resistance (SR)

The sieve segregation resistance test is used to assess the resistance of self-compacting concrete to segregation. After sampling, the fresh concrete is allowed to stand for 15 min, and any separation of bleed water is noted. The top part of the sample is then poured into a sieve with 5-mm square apertures. After 2 min, the weight of the material which has passed through the sieve is recorded. The segregation ratio is the proportion of the sample passing through the sieve.

The SR is calculated from the following equation:

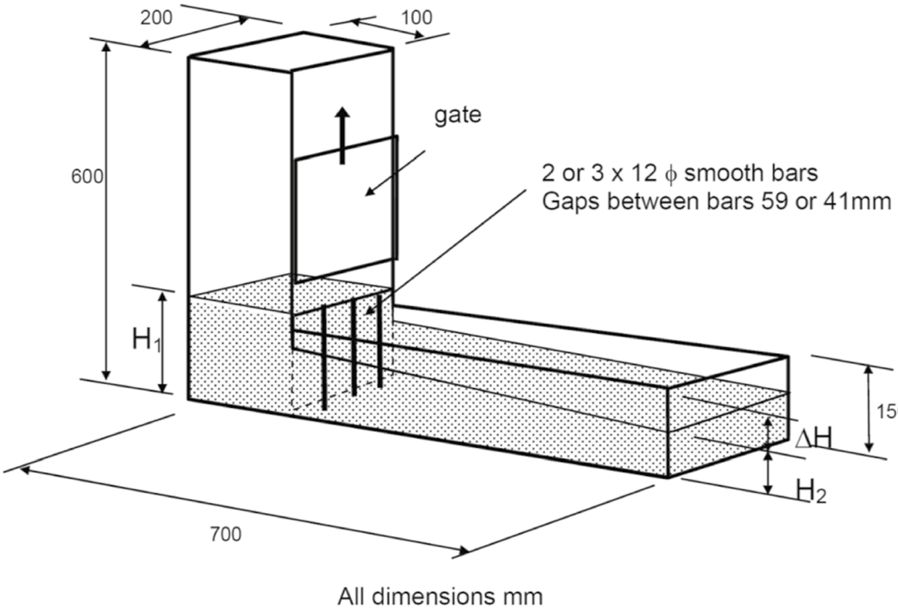

Fig. 2 General assembly of L-box [25]

$$SR = \frac{(W_{ps} - W_p)}{W_c} \times 100\% \quad (6)$$

With Wps is the mass of the receiver and concrete that has passed into it from the sieve, Wp is the mass of the receiver, and W_c is the initial mass of concrete on the sieve.

2.2.3 Slump flow (SF)

The slump flow is a test to assess the flowability and the flow rate of self-compacting concrete in the absence of obstructions. The fresh concrete is poured into a cone as used for the standard slump test. When the cone is withdrawn upwards, the largest diameter of the flow spread of the concrete and the diameter of the spread at right angles to it are then measured, and the mean is the slump flow.

2.2.4 Compressive Strength (R_{c28})

We used cylindrical molds to cast specimens for normal compressive strength at 28 days. These specimens were conserved in water, with a temperature of 20 ± 2 °C, until the time of the test.

2.3 Response Surface Methodology (RSM)

The technique of RSM is an empirical modeling approach dictated to the determination of a relationship between various process parameters and responses. The objective is to explore the effect of these parameters on responses and consequently optimize these responses [28, 29]. The RSM typically follows three steps: the experimental design, the regression models, and the optimization [30].

In this work, we applied the RSM to build regression models, and then, we used the desirability function approach for multi-response optimization. The experimental design was set by combining Tables 4 and 5, to obtain enough data for which we can apply the RSM. We used Design-Expert software (version 9) to analyze these data and for the statistical modeling. The software shows that second- and third-order models are more suitable, while quartic model are higher order are aliased. It is recommended to select the highest order model maximizing the adjusted R^2, where the additional terms are significant, and the model is not aliased. These criteria are fulfilled better with third-order models.

The third-order mathematical models were developed in this work, to understand the effects of (C_u, C_c, and FM) of sand, on the standard physical and mechanical properties of fresh and hardened SCC (PA, SR, SF, and R_{c28}) as recommended by The European Guidelines for Self-Compacting Concrete [25]. The general expression of this third-order mathematical model, for n factors, is as follows:

Table 5 Bouziani's experimental design for PA, SR, SF, and R_{c28} [7]

Mix. no.	Sand mixtures' proportions			PSD properties of sand (factors)			Response			
	RS (%)	DS (%)	CS (%)	FM (factor A)	C_c (factor B)	C_u (factor C)	PA	SR (%)	SF (mm)	R_{c28} (MPa)
1	100	0	0	3.03	0.75	5.45	0.83	06.5	740	43.4
2	0	100	0	1.34	0.99	1.76	0.00	00.0	420	37.6
3	0	0	100	2.16	0.98	2.64	0.89	04.7	665	48.7
4	0	20	80	2.00	0.98	2.47	0.81	03.3	590	46.8
5	0	40	60	1.83	0.98	2.30	0.80	01.6	540	45.0
6	0	60	40	1.67	0.98	2.13	0.65	01.3	520	41.8
7	0	80	20	1.51	0.98	1.95	0.45	00.6	480	39.8
8	20	0	80	2.33	0.88	3.30	0.81	12.6	770	47.3
9	40	0	60	2.43	0.94	3.82	0.87	07.6	750	42.8
10	60	0	40	2.23	0.74	4.23	0.85	01.0	710	40.6
11	80	0	20	2.50	0.64	6.44	0.82	10.4	770	42.4

Table 6 ANOVA results for RSM third-order models of the studied properties

ANOVA results	*F* value	*P* value	Adequate precision
PA model	42.87	<0.0001	22.398
SR model	6.67	0.0045	8.608
SF model	12.90	<0.0001	13.450
R_{c28} model	3.06	0.0298	5.545

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \frac{1}{2} \sum_{\substack{i,j=1 \\ i \neq j}}^{n} \beta_{ij} X_i X_j + \sum_{i=1}^{n} \beta_{iii} X_i^3 + \frac{1}{3} \sum_{\substack{i,k=1 \\ i \neq k}}^{n} \beta_{iik} X_i^2 X_k + \frac{1}{6} \sum_{\substack{i,j,k=1 \\ i \neq j \neq k}}^{n} \beta_{ijk} X_i X_j X_k + \varepsilon \qquad (7)$$

With Y is the response, β_0 is the free term of the regression equation, the coefficients β_i, β_{ii}, and β_{iii} are the linear, quadratic, and cubic terms, respectively, while β_{ij}, β_{iik}, and β_{ijk} are the interacting terms (in which, i, j, and k should not be equal to each other).

3 Results and Discussion

Table 4 shows all the experimental results (responses) of the considered factors: C_c, C_u, and FM. The mixtures in which we combined CS with DS or RS gave better properties in both fresh and hardened states. The presence of round shape sand (DS and RS) helps with frictional efforts decrease in the solid fraction of SCC [2, 5], while the SCC mixture with 100% RS gave less flowability, probably due to its small FM.

Experimental results from Bouziani's work [7] show that SSC mixtures with close PSD sand properties give a similar behavior in both fresh and hardened states (Table 5). This similarity is also valid when comparing Tables 4 and 5 results.

3.1 Analysis of Variance (ANOVA)

The regression equations were generated by Design-Expert software, after eliminating the insignificant terms with P values ≥ 0.05. Table 6 and Fig. 4 illustrate the ANOVA results for passing ability (PA), segregation resistance (SR), slump flow (SF), and normal compressive strength (R_{c28}).

The F values imply that the built models are significant. The greater the F value is, the more significant is the model. The chance that F values this large could occur due to noise is too small: 0.01%, 0.54%, 0.01%, and 2.98% for PA, SR, SF, and R_{c28}, respectively. The models' P values <0.05 indicate that model terms are significant.

The adequate precision parameter measures the signal-to-noise ratio, which should be greater than 4. All the built models meet this criterion, indicating an adequate signal.

The plots in Fig. 3 show a high level of similarity between measured and predicted SCC properties, except for some values. These gaps are generally within an acceptable range.

3.2 Regression Analysis

The relationship between the factors and the performance measures is modeled by cubic regression (Eq. 7). The regression equations obtained are given below by Eqs. (8)–(11) with coefficients of determination R^2 of 91.03%, 92.60%, 82.00%, and 66.30%, respectively (Fig. 4).

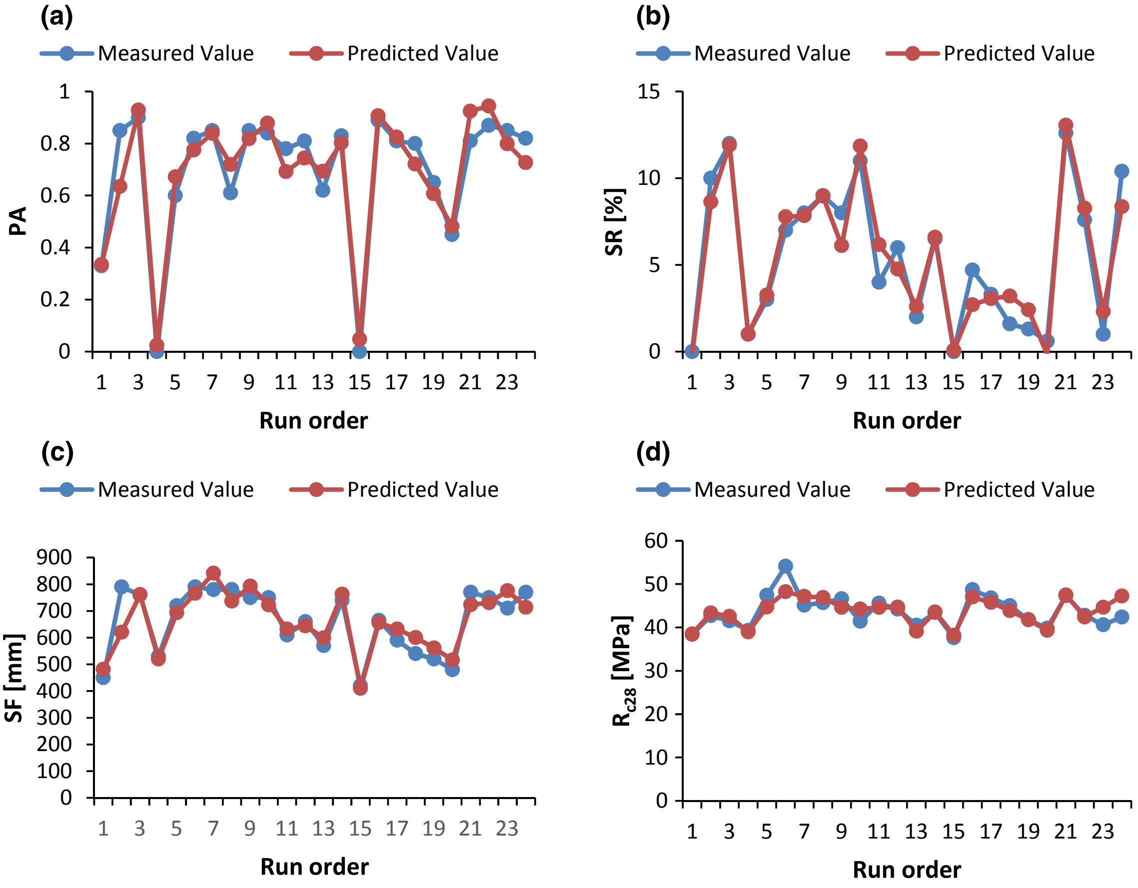

Fig. 3 Measured versus predicted values of SCC properties: **a** passing ability, **b** segregation resistance, **c** slump flow, and **d** normal compressive strength

$$\mathrm{PA} = 1.7098 - 1.4628 \times C_{\mathrm{c}} - 0.1131 \times MF \times C_{\mathrm{u}} + 0.1918 \times MF \times C_{\mathrm{c}} \times C_{\mathrm{u}} - 8.0852 \times 10^{-4} \times C_{\mathrm{u}}^{3} \tag{8}$$

$$\begin{aligned}\mathrm{SR} = {} & 859.0766 - 662.7185 \times MF - 1478.9156 \times C_{\mathrm{c}} - 34.6173 \times C_{\mathrm{u}} + 869.5016 \times MF \times C_{\mathrm{c}} + 13.7724 \times MF \times C_{\mathrm{u}} + 145.7258 \\ & \times MF^{2} + 807.0984 \times C_{\mathrm{c}}^{2} + 5.7111 \times C_{\mathrm{u}}^{2} + 28.1962 \times MF \times C_{\mathrm{c}} \times C_{\mathrm{u}} - 137.6558 \times MF^{2} \times C_{\mathrm{c}} - 9.0571 \\ & \times MF^{2} \times C_{\mathrm{u}} - 257.9810 \times MF \times C_{\mathrm{c}}^{2} - 0.03137 \times MF \times C_{\mathrm{u}}^{2} - 7.1200 \times C_{\mathrm{c}} \times C_{\mathrm{u}}^{2} - 136.6216 \times C_{\mathrm{c}}^{3}\end{aligned} \tag{9}$$

$$\begin{aligned}\mathrm{SF} = {} & -132.8361 + 529.6814 \times MF + 67.3337 \times C_{\mathrm{u}} - 66.1846 \times MF \times C_{\mathrm{u}} - 242.0920 \times MF \times C_{\mathrm{c}}^{2} \\ & + 145.4222 \times C_{\mathrm{c}}^{2} \times C_{\mathrm{u}} - 16.9492 \times C_{\mathrm{c}}^{3}\end{aligned} \tag{10}$$

$$\begin{aligned}R_{\mathrm{c28}} = {} & -24.9727 + 21.8448 \times MF + 83.2815 \times C_{\mathrm{c}} - 9.1428 \times C_{\mathrm{u}} + 3.7257 \times MF^{2} - 30.4171 \times C_{\mathrm{c}}^{2} \\ & + 2.8184 \times C_{\mathrm{u}}^{2} - 7.0894 \times MF^{2} \times C_{\mathrm{c}} - 0.5658 \times MF \times C_{\mathrm{u}}^{2} - 0.0682 \times C_{\mathrm{c}}^{3}\end{aligned} \tag{11}$$

These results give a better prediction for PA and SR, compared to the models built by Bouziani [7], using sand's nature (dune, river, and crushed sand) as factors, in which the values of R^2 were: 78.00%, 66.00%, 87.00%, and 84.00%, respectively, for the same response parameters.

The R^2 values for SF and R_{c28} indicate that these properties cannot be predicted only by taking into consideration the PSD properties. These regression models are useful in predicting the response parameters for the considered input control parameters.

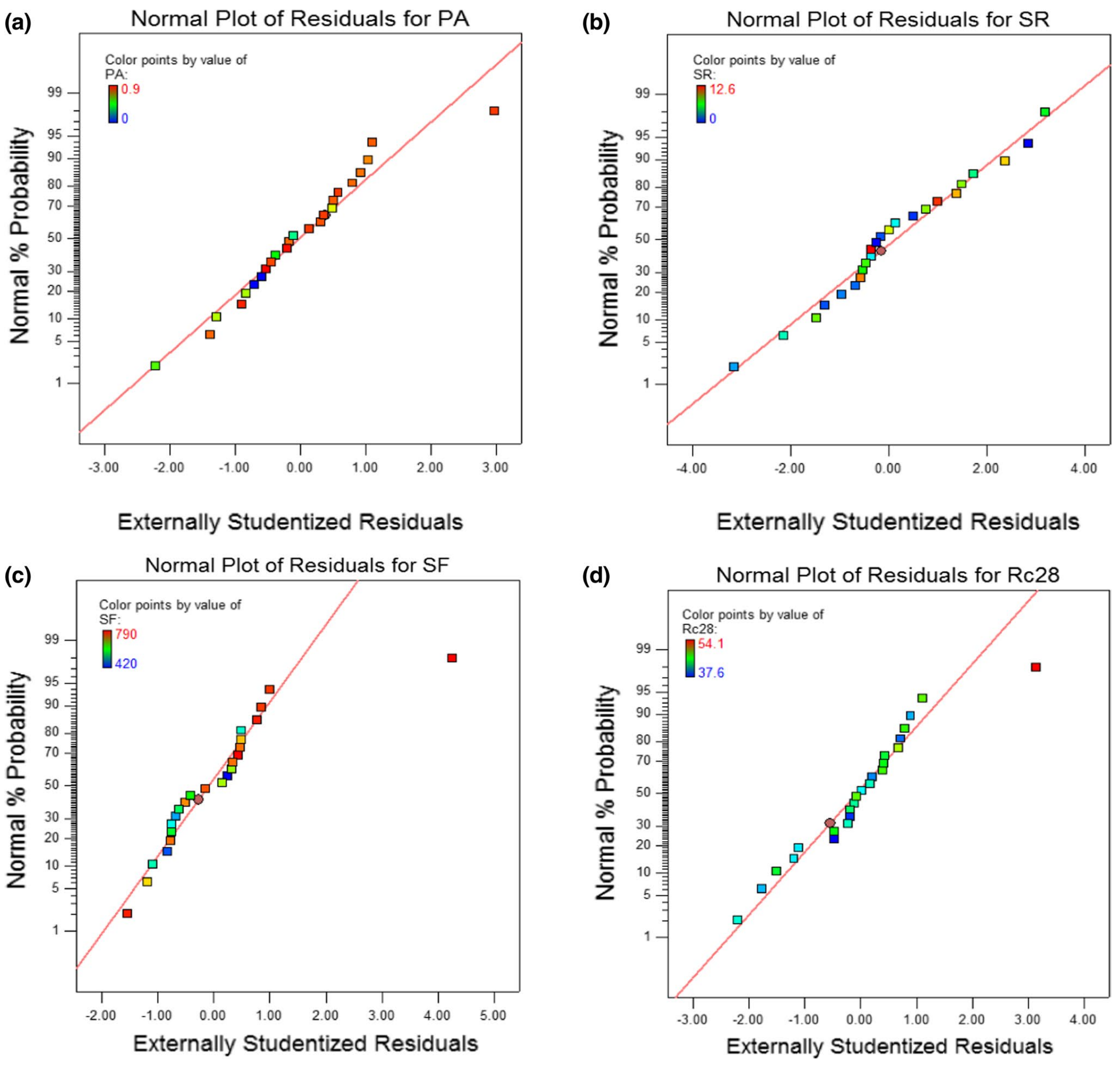

Fig. 4 Normal plot of residuals for: **a** passing ability, **b** segregation resistance, **c** slump flow, and **d** normal compressive strength

Table 7 Conformity criteria for fresh SCC properties values [25]

Property	Criteria
Slump-flow class SF1	≥ 520 mm, ≤ 700 mm
Slump-flow class SF2	≥ 640 mm, ≤ 800 mm
Slump-flow class SF3	≥ 740 mm, ≤ 900 mm
Slump-flow class specified as target value	± 80 mm of target value
L-box class PA1 (two rebars)	≥ 0.75
L-box class PA2 (three rebars)	≥ 0.75
L-box class specified as target value	Not more than 0.05 below the target value
Sieve segregation resistance class SR1	≤ 20%
Sieve segregation resistance class SR2	≤ 15%
Sieve segregation resistance class specified as target value	Not more than 3% above the target value

Table 8 Goals and factors ranges, for quality optimization of SCC

Name	Goal	Lower limit	Upper limit	Upper weight	Importance
Constraints					
FM	In range	1	3.5	1.0	3
Cc	In range	1	2	1.0	3
Cu	In range	6	10	1.0	3
PA	In range	0.8	0.9	1.0	3
SR (%)	In range	0	15	1.0	3
SF (mm)	Maximize	660	900	1.0	5
R_{c28} (MPa)	Maximize	37.6	54.1	1.0	5

Table 9 Solutions for the combined optimization

Number	FM	Cc	Cu	PA	SR	SF	R_{c28}	Desirability	
Solutions									
1	2.173	1.000	6.170	0.884	15.000	906.558	51.649	0.923	Selected
2	2.166	1.000	6.092	0.884	15.000	903.250	51.631	0.922	
3	2.183	1.000	6.272	0.883	15.000	910.741	51.618	0.922	
4	2.194	1.000	6.403	0.881	15.000	951.965	51.478	0.917	
5	2.200	1.000	6.374	0.879	09.392	909.525	51.176	0.907	
6	2.207	1.000	6.550	0.878	15.000	921.594	51.173	0.907	
7	2.149	1.000	6.159	0.892	14.999	913.090	51.153	0.906	
8	2.224	1.000	6.335	0.875	02.859	901.627	50.797	0.894	
9	2.236	1.000	6.384	0.873	00.419	901.107	50.643	0.889	
10	2.221	1.000	6.721	0.873	14.999	927.960	50.590	0.887	
11	2.244	1.000	6.480	0.870	00.003	904.432	50.561	0.886	
12	2.232	1.007	6.490	6.490	00.000	908.933	50.263	0.876	
13	2.154	1.022	6.000	6.000	03.424	900.001	49.983	0.866	
14	2.263	1.000	6.759	6.759	00.015	914.846	49.960	0.866	
15	2.254	1.005	6.733	6.733	00.000	916.809	49.796	0.860	
16	2.277	1.002	7.031	7.031	00.000	925.777	48.512	0.813	
17	2.252	1.000	7.143	7.143	14.999	942.625	47.923	0.791	
18	2.292	1.000	7.216	7.216	00.000	930.780	47.272	0.766	
19	2.174	1.045	6.896	6.896	15.000	955.078	46.817	0.747	
20	2.272	1.000	7.430	7.430	15.000	951.930	44.902	0.665	
21	2.299	1.004	7.461	7.461	00.000	941.496	44.401	0.642	
22	2.187	1.063	7.019	7.019	00.000	956.899	44.104	0.628	
23	2.235	1.025	7.348	7.348	15.000	961.932	43.860	0.616	
24	2.310	1.000	7.552	0.804	00.000	941.710	43.626	0.604	
25	2.187	1.069	7.123	0.900	00.000	962.902	42.583	0.550	
26	2.284	1.000	7.622	0.812	15.000	957.934	42.223	0.529	
27	2.304	1.002	7.656	0.800	04.773	950.586	41.839	0.507	
28	2.291	1.000	7.727	0.800	14.491	960.567	40.544	0.422	
29	2.283	1.012	7.824	0.800	15.000	969.922	37.692	0.075	

4 Optimization of Responses Using the Desirability Function Approach

The multi-response optimization is used to determine conditions on the considered variables that give the most desirable response values. For each response Y_i, a desirability function $d_i(Y_i)$ takes values that range from 0 to 1 [31]. The ideal case is when desirability takes values closer to 1. The overall desirability Δ is the combination of individual disabilities, using the geometric mean [29, 32]:

$$\Delta = (d_1 \times d_2 \times \cdots \times d_n)^{1/n} = \left(\prod_{i=1}^{n} d_i\right)^{1/n} \tag{12}$$

With n is the number of responses. For overall desirability, each desired response must have a lower and upper value.

In this study, we considered a quality optimization approach, which means, getting the optimal combination of sand's PSD properties, to obtain the best rheological properties of fresh SCC and maximum compressive strength. Table 7 gives the limits of fresh SCC properties values, according to the European Guidelines of SCC. The optimization of fresh SCC properties means to maximize its slump flow of least SF2 class, and passing ability with minimum segregation (PA2 and SR2 classes, respectively).

The factor ranges defined for each optimization are summarized in Table 8, according to the criteria mentioned in Table 7. The calculated solutions for the combined optimization of SCC are presented in Table 9. The overall desirability goals apply to both factors and responses. We set our goals to keep the FM, Cc, Cu, PA, and SR in the acceptable ranges defined above in this paper, and to maximize the SF and R_{c28} (the lower limit is the lowest acceptable outcome and the upper limit is desired best result).

The values' weight means that it can range from 0.10 to 10. It fine-tunes how the optimization process searches for the best solution. A low weight (near 0.10) will allow more solutions that do not quite meet the optimal goal. A high weight (close to 10) will cause the optimization to seek a solution close to or beyond the stated goal. From a practical standpoint, it is recommended to leave the weights at 1.0.

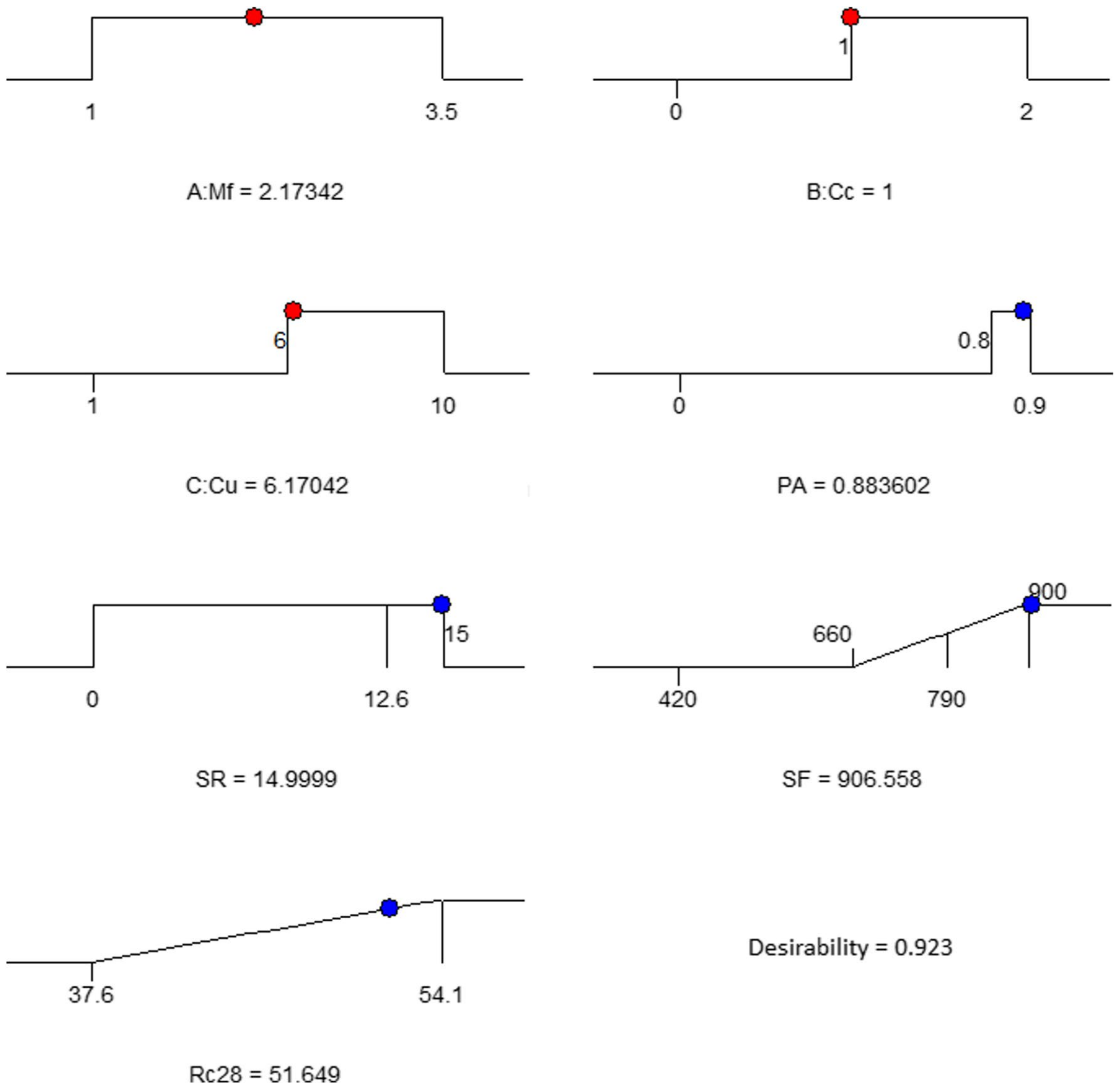

Fig. 5 Ramp function graph for PA, SR, SF, and R_{c28} combined optimization

The importance parameter specifies the relative importance of one goal versus another. Some goals may be critical, while some may be of medium importance, and some are of the lowest importance. Values of goals' importance parameter range from 1 to 5 in Design-Expert software (default is to have all goals set to 3). We kept the value set to 3, and we assigned 5 for SF and R_{c28}, as critical parameters of SCC.

The ramp function graph in Fig. 5 shows the selected optimization results.

Values of optimal PSD properties of sand for optimal quality, in both fresh and hardened SCC, for a combined desirability $\Delta = 0.923$, are found to be: $\mathrm{FM} = 2.173$, $C_c = 1.000$, and $C_u = 6.170$. The optimized SCC quality parameters are as follows: $\mathrm{PA} = 0.883$, $\mathrm{SR} = 14.99\%$, $\mathrm{SF} = 906.558$ mm, and $R_{c28} = 51.64$ MPa.

5 Conclusion

This study focuses on the modeling and determination of optimum PSD properties that lead to best fresh and hardened SCC qualities, under the European Guidelines for Self-Compacting Concrete requirements, by getting a maximum flowability, passing ability, and compressive strength, while kipping a low segregation rate. From the results discussed above, the following conclusions can be drawn:

- PSD properties have a high effect on the physical and mechanical properties of SCC;
- The correlation coefficients of the predictive models of PA, SR, and SF are 91.03%, 92.60%, and 82.00%, respectively. Therefore, the developed models are reliable and have an important industrial interest, since they help to predict fresh SCC properties based only on sand's PSD;
- The SR predictive equation shows a high correlation coefficient, but with many interaction terms, which means that the segregation phenomenon is a complicated one;
- The correlation coefficient of the predictive model of R_{c28} was found equal to 66.30%. This shows that normal compressive strength is not depending only on FM, C_c, and C_u of used sand. Better models of mechanical properties could be found, by introducing other properties such as sand's shape;
- The optimal sand's PSD factors to get the best fresh and hardened properties of SCC within the ranges of the actual experimentation were obtained with overall desirability of 92.30%.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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