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Evaluation of self-compacting recycled concrete robustness by statistical approach

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HIGHLIGHTS

- Robustness of self-compacting recycled concrete (SCRC) was analysed using statistical approach.
- SCRCs with 20%, 50% and 100% recycled aggregate were modified introducing material variations.
- Water control was found to be the key factor that affects SCRC robustness.
- Six key properties of SCRC were identified as those best to measure robustness.

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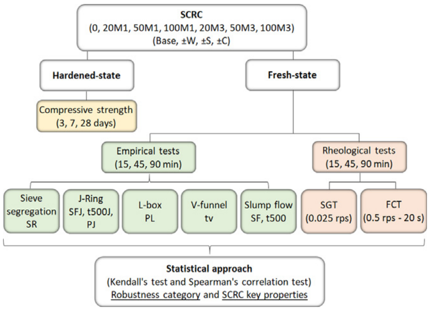
GRAPHICAL ABSTRACT



ABSTRACT

The use of self-compacting recycled concrete appears as to be a very interesting technology for the sustainable construction future. However, one of the major obstacles to a more widespread use of self-compacting concrete is to obtain a robust material. Therefore, the emphasis of this work is placed on analysing both practice and theory to understand the properties that control and assess self-compacting recycled concrete robustness.

Hence, forty-nine different mixes were produced with several replacement percentages of recycled concrete coarse aggregate (0, 20, 50 or 100%) and with two different mixing procedures (all aggregates in dry-state conditions or recycled aggregate with a 3% of natural moisture). The experimental program consisted of making, in the fresh state, rheological tests (a stress growth test and a flow curve test) and empirical characterization tests (slump flow, V-funnel, L-box, J-Ring and sieve segregation) at 15, 45 and 90 min from cement-water contact. In the hardened state, compressive strength was measured at 3, 7 and 28 days.

All results were analysed using a statistical approach based on Kendall's coefficient of concordance and Spearman's rank correlation. This approach allowed us to successfully identify six key properties that can be measured to evaluate SCRC robustness (capacity of the material to tolerate certain variations in material characteristics and mixture parameters). For each mix, a ranking that defines its robustness category was obtained by considering all properties. Also, it showed that water control is the key factor that affects SCRC robustness.

1. Introduction and objectives

In the near future, using recycled materials in conventional and high performance applications should be a priority area [1]. At this

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stage, it is fundamental to analyse the characteristics of recycled materials, recycling procedures and manufacturing processes. The main difference between natural aggregate and the recycled concrete aggregate is the adhered mortar [2,3]. The presence of this material decreases with the number of crushing processes, the size fraction and the original waste quality [4,5].

In general terms, the quality of vibrated recycled concrete is lower than that of conventional concrete with the same mix proportions [6,7]. Many of the current studies in vibrated recycled concrete field deal with short-term analysis related to basic properties and structural performance, and a few of them have studied the long-term behaviour [8,9]. The compressive and splitting tensile strengths and modulus of elasticity decrease when the percentage of recycled aggregate increases, and the shrinkage and creep increase deformations [10,11]. These variations are mostly due to the adhered mortar.

On the other hand, self-compacting concrete is a highly flowable concrete that spreads rapidly into place and fills formwork without vibrating compaction in order to ease casting and to achieve durable concrete structures [12,13]. At the construction site, it has increasingly been used over the past two decades and it is empirically described according to its filling ability, passing ability and segregation resistance [14]. Most of studies state that, if a SCC is well designed, it can provide similar mechanical properties to its equivalent vibrated concrete [15]. However, the SCC flow properties and its fresh rheological behaviour diverge from what is expected from vibrated concrete of normal consistency [16].

One of the major obstacles to a more widespread use of self-compacting concrete is to obtain a robust material [17,18]. Robustness is the capacity of a concrete to maintain its properties when changes in materials, mixing parameters or environmental variables take place [19,20].

Self-compacting concrete has shown to be more sensitive to variations in its design process than vibrated concrete [21,22]. The mix design is a critical step to obtain high quality self-compacting concrete. A large number of variables must be considered in the mix design process and its interactions are difficult to predict [23].

Different studies have been developed to analyse self-compacting concrete robustness. In general, aggregate density and size, paste density, type of mixer, mixing protocol, mixing time and total mixing energy are factors that have to be taken into account to analyse robustness [24]. Some works conclude that robustness can be influenced by the water to powder volume ratio, the superplasticiser to powder weight ratio and the solid volume [25–27]. Others state that errors in weighing water and fines content [19] or those affecting aggregate moisture [28] are of capital importance.

Lastly, a new material, self-compacting recycled concrete (SCRC) appears as a self-compacting concrete made with recycled aggregate, in this work, recycled concrete coarse aggregate. This concrete has to combine successfully the behaviour of a self-compacting concrete and that of a vibrated recycled concrete [29]. The materials used to produce SCRC are the same as in self-compacting concrete, but recycled aggregates are used as replacement of natural aggregates [30,31]. The type and shape of coarse aggregate, combined gradation of sand and coarse aggregate, content of cement and supplementary cementitious materials, paste volume, and water to powder ratio must be considered when designing SCRC as in self-compacting concrete [32–35]. The use of recycled aggregate could improve the environmental aspects of self-compacting concrete without significant impact on workability and strength characteristics when low replacement percentages are used (up to 50%) [36–39]. However, not so much works have studied the rheological properties of SCRC, measuring the static yield stress and plastic viscosity [30,38,40,41], and analysed the specificity of its rheological behaviour [42].

Keeping the above in mind, extensive scientific research has been developed on vibrated recycled concrete over the last decades [7,11]. At the same time, high performance concretes have become a great challenge and one of the most remarkable topics in the field of materials engineering. In this context, the use of self-compacting concrete introducing new variables, as the replacement of natural aggregates with recycled aggregates, appears as to be a very interesting technology for the sustainable construction future.

As a consequence, SCRC has been studied only for a short time and there is a significant gap in the knowledge of its robustness [43]. SCRC involves multi-physics phenomena related to the specific intrinsic characteristics of recycled aggregates and the other components and variables of concrete design. Therefore, the emphasis of this work is placed on analysing both practice and theory to understand the properties that control and assess SCRC robustness.

In order to be successful in this approach, a statistical analysis is made with results from a wide experimental program. Taking into account the work of Naji et al. [21] on conventional self-compacting concrete, Kendall's coefficient of concordance and Spearman's rank correlation can be used to evaluate self-compacting recycled concrete robustness and to select adequate concrete properties that could be measured to determine it. Therefore, in this work, a statistical approach to SCRC robustness is carried out with the aim of determining which tests provide more sensitivity when the robustness of a SCRC mix is evaluated.

2. Methodology

Two research stages were conducted, an experimental stage and an analytical stage. The former consisted of 49 mixes of SCRA in which several replacement percentages of recycled aggregate and relevant parameters (mixing procedure and constituent materials) were varied. In the second stage, a statistical approach was performed to draw general conclusions and to reduce the number of properties that could provide a reliable understanding of SCRC robustness.

2.1. Testing program

In this work, the studied mixes were prepared with a Portland cement (CEM-I 52.5-R), with a density of 3110 kg/m^3 and a specific surface (BET) of 1.02 m^2/g. A limestone filler was also used with a density of 2710 kg/m^3 and a specific surface (BET) of 1.77 m^2/g. The properties of cement and filler are given in Tables 1 and 2. A superplasticiser (a modified polycarboxylate) was used as chemical additive. It showed a solid content of 35% and a density of 1080 kg/m^3. This kind of superplasticiser is used to produce high performance, high strength and flowable concretes.

Table 1
Properties of cement.

CEM-I 52.5-R Physical and mechanical properties	
Initial setting time	190 min
Final setting time	260 min
Soundness	0.3 mm
Initial strength	45.5 MPa
Strength	64 MPa

Table 2
Chemical composition of cement and filler.

Oxide/Element	CEM-I 52.5-R (%)	Filler (%)
CaO	64.1	54.7
SiO_2	15.9	1.6
SO_3	4.3	0.18
Al_2O_3	4.1	0.46
Fe_2O_3	4.0	0.22
K_2O	1.3	0.12
MgO	1.1	0.47
SrO	0.78	0.046
Na_2O	0.27	–
TiO_2	0.25	–
ZnO	0.12	0.009
Cl	0.059	–
P_2O_5	0.050	–
MnO	0.047	–
CuO	0.040	0.010
ZrO_2	0.036	0.003
PbO	0.022	–
Loss on ignition (1000 °C)	3.2	41.8

Table 4
Mix proportions of reference concrete (1 m^3).

SCRC0 – Dosage	
Cement, c (kg)	400
Filler, f (kg)	180
Water, w (kg)	184
Natural sand (kg)	866
Natural coarse aggregate (kg)	768
Effective w/c	0.46
Superplasticiser/(c + f) (%)	0.6

The fine aggregate was a crushed limestone sand with a nominal size of 0–4 mm, a fineness modulus of 4.19, a saturated-surface-dry density of 2720 kg/m^3 and a water absorption capacity of 1%. As coarse aggregates, a crushed granitic natural aggregate and a recycled fraction obtained from real demolition debris of structural concrete were used, both with a nominal size of 4–11 mm. The natural coarse aggregate showed a fineness modulus of 7.14, a saturated-surface-dry density of 2560 kg/m^3 and a water absorption capacity of 1.12%.

The recycled coarse aggregate was made up mainly of concrete and stone. So, it was a recycled concrete coarse aggregate. Its fineness modulus was 6.47 and the main properties are presented in Table 3. It is remarkable that after 10 min it absorbs up to 80% of its total water absorption at 24 h. This percentage was taken into account when all recycled concretes were produced.

The design of mixes consisted of a reference mix and three recycled mixes with 20%, 50% and 100% replacement percentages of recycled coarse aggregate (by volume) (Table 4). Two mixing procedures were also used, one using aggregates in dry-state conditions (M1 method) and another where the recycled aggregate was used with a 3% of natural moisture (M3 method). Therefore, seven baseline mixes were designed (SCRC0, SCRC20M1, SCRC50M1, SCRC100M1, SCRC20M3, SCRC50M3, SCRC100M3).

Moreover, the study of robustness of mixes produced with M1 and M3 method (SCRC0, SCRC20M1, SCRC50M1, SCRC100M1, SCRC20M3, SCRC50M3, SCRC100M3) has been made using water variations (W+, 0, W−, that corresponds to +3%, base, −3%) and superplasticiser variations (S+, 0, S-, that corresponds to +5%, base, −5%). Robustness of mixes produced with M1 method (SCRC0, SCRC20M1, SCRC50M1, SCRC100M1) was also studied using cement variations (C+, 0, C−, that corresponds to +3%, base, −3%).

Recycled concretes were produced by adding an extra quantity of water during mixing. This was calculated to compensate the 80% of recycled aggregate absorption at 24 h. The mixing protocol for both M1 and M3 methods was as follows: firstly, the aggregates (sand and coarse aggregates) were mixed with the extra water for 2 min and then left to rest for another 8 min; secondly, the cement was added along with the filler. After 2.5 min of mixing, water was added (98.5%). This cement–water contact is considered the reference time for performing all fresh concrete tests. After 2 min of mixing, the superplasticiser and the remaining water were introduced. The mixing was continued for another 3 min, the concrete was left to rest for 2 min and finally mixed again for an additional 2 min.

Regarding tests methods, on the one hand, rheology was studied throughout two tests: a stress growth test and a flow curve test. The parameters measured with these tests were the static yield stress (τ_0) and the plastic viscosity (μ_{pl}) respectively.

A rotational portable rheometer with a four-bladed vane was used to conduct the rheological tests. Firstly, the stress growth test was made at a low and constant speed of 0.025 rps as soon as the vane of the rheometer was immersed into the concrete. After that, the vane was removed, the concrete remixed, the vane reinserted and the flow curve test started. After a breakdown period of 20 s at a constant speed of 0.5 rps, the torques at decreasing speeds were measured in seven steps. In this research, according to previous works [29], the Bingham model was applied to the five data points obtained with the lowest rotational speeds in the flow curve test.

On the other hand, workability was studied with several empirical characterization tests: slump flow (EN 12350-8 [44]), V-funnel (EN 12350-9 [45]), L-box (EN 12350-10 [46]), J-Ring (EN 12350-12 [47]) and sieve segregation (EN 12350-11 [48]). The parameters measured with these tests were: slump flow diameter (SF), time of 500 mm slump flow (t500), time of V-funnel (tv), blocking coefficient (PL), J-Ring diameter (SFJ), time of J-Ring (t500J), blocking step (PJ) and sieve segregation percentage (SR).

Rheological and empirical characterization tests were made over time (at 15, 45 and 90 min from cement-water contact) and all obtained results were used for developing the statistical approach.

Also, results of compressive strength (f_c) at different ages (3, 7 and 28 days) were incorporated into the statistical analysis.

2.2. Analytical investigation

Kendall's coefficient of concordance is a measure of the agreement among several *k* "judges" used to assess a characteristic of

Table 3
Main physical properties and composition of recycled aggregate.

Particle size (mm)	Physical properties			Composition (%)			
	ρ_{ssd} (kg/m^3)	Absorption 24 h (%)	Absorption 10 min (%)	Natural aggregate and aggregate with mortar	Ceramic	Asphalt	Rest
4/11	2340	6.96	5.57	96.35	0.79	0.48	3.25

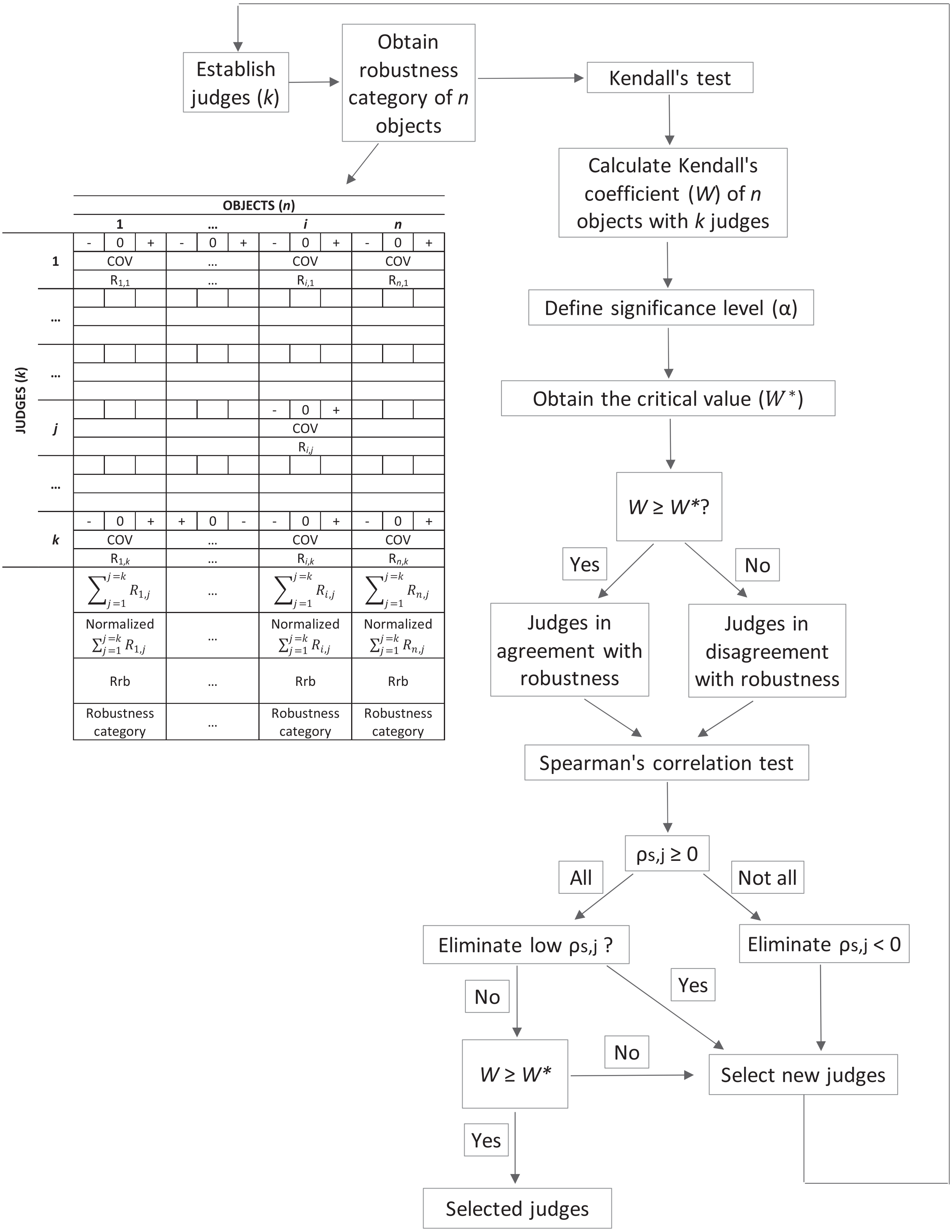

Fig. 1. Flow chart of statistical approach methodology.

a given set of *n* objects. The method is used to evaluate the degree of agreement among several "judges" [49]. The methodology used in this work is summarized in Fig. 1.

In this study, *n* (the objects to be assessed) are the different mixes characterised by their recycled aggregate percentage (0, 20, 50 or 100%) and the mixing method (M1 or M3). Therefore, when water and superplasticiser variations are imposed, M1 and M3 methods are used and then $n = 7$. However, when cement variations are analysed, only M1 method is used, then, in this case, $n = 4$.

Each object (i object, with i from 1 to n) is going to be ranked using different "judges" as assessors or a single judge applying different criteria. Then, a rank $R_{i,j}$, with i from 1 to n and with j from 1 to k, is obtained in each object for each judge based on the coefficients of variation obtained with each judge.

In this work, when water and superplasticiser variations are imposed, 31 properties were considered as the "judges of robustness" ($k = 31$) and the coefficients of variation (COVs) obtained with each judge were used to rank the seven mixes ($n = 7$). In the case of cement variations, 26 properties were considered ($k = 26$) to rank the four mixes ($n = 4$). Each COV is obtained for each object (mix) and for each judge (property) with the results of the baseline mix ("0") and of the same mix with the two material variations (increase, "+", and decrease, "–"). Therefore, these COVs are used to rank each object (mix) within each judge (property), $R_{i,j}$.

The result of the judgment (concrete robustness) can be obtained summing, in each object (mix), the ranks ($R_{i,j}$) gotten with each judge (property) (Eq. (1)).

$$SR_i = \sum_{j=1}^{j=k} R_{i,j} \quad i = 1 \cdots n \tag{1}$$

This result (SR_i) can be normalized and then used to define SCRC robustness. This "normalized sum of ranking" (0–100%) (Eq. (2)) will be used to rank the objects according to their robustness, "Rrb" (from more robust to less robust). Moreover, this can be used to define a category (high, medium, low) that classifies the robustness of each SCRC mix [21].

$$Normalized\ sum\ of\ ranking\ (\%) = \frac{(SR_{max} - SR_i)}{(SR_{max} - SR_{min})} 100 \tag{2}$$

Being:

$$SR_{max} = \max(SR_i) \quad i = 1 \cdots n \tag{3}$$

$$SR_{min} = \min(SR_i) \quad i = 1 \cdots n \tag{4}$$

On the left of the Fig. 1, a flow chart is shown to summarize this part of the methodology.

Once the characteristic (robustness) has been assessed, it is necessary to be sure that there is agreement among the "judges" used. To check this, the significance of Kendall's coefficient has to be evaluated.

For this purpose, the Kendall's coefficient (W) is calculated for the sample. To evaluate its significance, a significance level (α) is chosen and then the critical value of W ($W*$) is calculated for this significance level. If the observed W is greater than or equal to the critical value $W*$, then the null hypothesis (there is no agreement among the "judges") may be rejected at that level of significance, i.e. the "judges" are in agreement (there is concordance among them) in the assessment of the characteristic (robustness).

Therefore, firstly, the Kendall's coefficient is calculated as follows:

$$W = \frac{S}{\frac{1}{12} \cdot k^2 \cdot (n^3 - n)} \tag{5}$$

Being:

$$S = \sum_{i=1}^{n} (SR_i - SR)^2 \tag{6}$$

$$SR = \frac{(n+1) \cdot k}{2} \tag{7}$$

Then, to test whether an observed value of W is significant, it is necessary to consider the distribution of W. The actual distribution of W is irregular for low values of k and n, and likely to be quite irregular for moderate values [49].

Regarding small samples, the distribution of W under H_o (null hypothesis, the assumption that the judges are in disagreement) has been worked out and the critical values of Kendall's coefficient ($W*$) can be obtained taking into account the approximation based on Fisher's degrees of freedom (Eqs. 8–10). The "z" values have been tabled for the following different significance levels, $\alpha = 0.05$ and $\alpha = 0.01$ [50].

$$z = \frac{1}{2} log_e \frac{(k-1)W}{1-W} \tag{8}$$

$$v_1 = n - 1 - \frac{2}{k} \tag{9}$$

$$v_2 = (k-1)v_1 \tag{10}$$

For large samples, Friedman's test can be used to determine the significance of W. The Friedman's test statistic is distributed approximately as chi-square (Σ^2), with ($n - 1$) degrees of freedom (Eq. (11)). In this case, also, for a desired level of significance and a particular value of n, under the null hypothesis (H_o), the critical values ($W*$) can be obtained.

$$\chi^2 = k(n-1)W \tag{11}$$

when W equals or exceeds the critical value $W*$ obtained for a desired level of significance, the null hypothesis (the assumption that the judges are in disagreement) may be rejected. That is, the k "judges" (properties) are in agreement with each other and it can be concluded that there is a good consensus among them concerning the evaluation of the characteristic (robustness) of the n objects (mixes).

On the right of the Fig. 1, the flow chart shows this part of methodology.

Lastly, when the significance of Kendall's coefficient was evaluated, the correlation between the rankings of an individual "judge" ($R_{i,j}$) and the final ranks of the objects, "Rrb", has to be assessed. To do so, Spearman's correlation test can be used.

Spearman's correlation test calculates the Spearman's rank correlation coefficient or Spearman's ρ_s. It is a non-parametric measure of statistical correlation between two ranked variables [51], and it can be expressed as follows:

$$\rho_{s,j} = 1 - \frac{6 \cdot \sum_{i=1}^{n} (R_{i,j} - Rrb_i)^2}{n \cdot (n^2 - 1)} \tag{12}$$

Spearman's $\rho_{s,j}$ ranges between −1 and 1 and measures the correlation between rankings obtained with an individual judge ($R_{i,j}$) and the final ranks of the objects, "Rrb". A positive value of $\rho_{s,j}$ implies a positive correlation among the two series of rankings. On the contrary, a negative $\rho_{s,j}$ value indicates a no correlation between them.

Therefore, the result of this test allows us to eliminate those judges which provide no correlation and/or those which provide a low correlation. In this way, the number of judges may be reduced, simplifying the characteristic assessment. In any case, if the number of judges is changed, it is necessary to check that Kendall's coefficient maintains a value higher than the critical one according to the desired level of significance. Once this has been done, it can be concluded that the selection of judges that provide the best correlation to assess the characteristic is achieved.

Table 5
SCRC robustness classification.

Normalized sum of ranking	Robustness category
>90%	High
6–90%	Medium-High
30–60%	Medium-Low
$\leq$30%	Low

Table 7
Evaluation of SCRC robustness (cement variations).

Mix	Cement variations	
	Normalized sum of ranking (%)	Robustness
SCRC0	100	High
SCRC20M1	96	High
SCRC50M1	56	Medium-Low
SCRC100M1	0	Low

3. Results and discussion

3.1. Robustness category

In the study of robustness of mixes produced with M1 and M3 method using water and superplasticiser variations, thirty-one properties of SCRC were used as “judges”. These properties include six rheological properties, three mechanical ones and twenty-two workability parameters. Therefore, seven mixes ($n = 7$, SCRC0, SCRC20M1, SCRC50M1, SCRC100M1, SCRC20M3, SCRC50M3, SCRC100M3) were analysed with 31 properties ($k = 31$).

In the case of robustness of mixes produced with M1 method using cement variations, twenty-six properties were used as “judges”. These properties include six rheological properties, three mechanical ones and seventeen workability parameters. Therefore, four mixes ($n = 4$, SCRC0, SCRC20M1, SCRC50M1, SCRC100M1) were analysed with 26 properties ($k = 26$).

Tables 16–18 (see Appendix) present the rheological, mechanical and workability properties obtained in mixes where water, superplasticiser and cement variations were imposed, respectively. The COV values obtained with each property and the corresponding ranking assigned to each mix are also presented. If a property value does not appear on the tables, this means that it was not possible to develop the test to measure it due to the loss of self-compactability. Then, this mix was ranked with the highest ranking value.

In the three cases (see Appendix: water variations, Table 16, superplasticiser variations, Table 17, and cement variations, Table 18), the COVs obtained with each property were calculated for each mix. Based on the COV values, the SCRC mixes were ranked. The mix with the lowest COV value is the mix that presents the best level of robustness, so this mix will be ranked with the number “1” and so on.

At this step, all properties are considered to evaluate robustness and then, for each mix, all the individual rankings have been summarized obtaining a “SR_i” value. This has been used to rank the mixes (within each material variation) according to their robustness, “Rrb” (from more robust to less robust). Moreover, the sum of rankings SR_i has been normalized according to Eq. (2). Tables 16–18 (see Appendix) also show all these values for water, superplasticiser and cement variations, respectively.

Finally, according to the normalized sum of ranking, a category (high, medium-high, medium-low, low) that classifies the robustness has been selected (Table 5).

Then, Tables 6 and 7 summarize the robustness category of the investigated mixes obtained with each of the three different material variations (water, superplasticiser and cement).

As seen in Table 6, when water and superplasticiser variations are analysed, the 20% replacement concretes (SCRC20M1 and SCRC20M3) show a medium-high level of robustness and SCRCs with a 50% of recycled aggregate display medium-high and medium-low robustness for M1 and M3 methods, respectively. Regarding the 100% replacement concretes, the M1 method provides a SCRC mix with a medium-low or low robustness whereas the M3 method always provide a concrete with a normalized sum of ranking $\leq$30%, which is considered as a low level of robustness. This mix will be, then, the least robust.

When cement variations are observed (Table 7), these robustness categories are corroborated in general terms. As seen, the 20% replacement concrete shows a high level of robustness, the SCRC50M1 mix displays medium-low robustness and the 100% replacement percentage provides a concrete with a low robustness.

3.2. Selection of SCRC properties to evaluate robustness

According to methodology, once the characteristic (robustness) has been assessed, it is necessary to be sure that there is agreement among the “judges” (properties) used. To check this, the Kendall’s coefficient has to be calculated and its significance measured. Tables 8–10 show the Kendall’s coefficient of concordance among concrete properties that were used as “judges” for water, superplasticiser and cement variations respectively.

To evaluate the significance of Kendall’s coefficient, a significance level (α) is chosen and then the critical value of W is determined (Table 11). When W equals or exceeds the critical value $W*$ obtained for a desired level of significance, it can be concluded that there is a good consensus among the properties used to evaluate robustness of the mixes.

In both water and superplasticiser variations, as W is greater than the critical value $W*$, for any of the considered significance levels, it can be concluded with considerable confidence that there is agreement among the 31 properties ($k = 31$) concerning the evaluation of the robustness of the mixes.

In the case of cement variations, the W value calculated given 26 properties ($k = 26$) is slightly higher than the critical values for the $\alpha = 0.05$ and $\alpha = 0.01$ significance levels. Then, the selected

Table 6
Evaluation of SCRC robustness (water and superplasticiser variations).

Mix	Water variations		Superplasticiser variations	
	Normalized sum of ranking (%)	Robustness	Normalized sum of ranking (%)	Robustness
SCRC0	100	High	100	High
SCRC20M1	70	Medium-High	73	Medium-High
SCRC50M1	63	Medium-High	67	Medium-High
SCRC100M1	28	Low	40	Medium-Low
SCRC20M3	86	Medium-High	87	Medium-High
SCRC50M3	58	Medium-Low	62	Medium-High
SCRC100M3	0	Low	0	Low

Table 8

Kendall's coefficient and Spearman's $\rho_{s,j}$ (water variations).

SCRC	τ_0 (15′)	μ_{pl} (15′)	τ_0 (45′)	μ_{pl} (45′)	τ_0 (90′)	μ_{pl} (90′)	$f_{c,3d}$	$f_{c,7d}$	$f_{c,28d}$	t500 (15′)	SF (15′)	tv (15′)	PL (15′)	t500J (15′)	SFJ (15′)	PJ (15′)	SR	t500 (45′)	SF (45′)	tv (45′)	PL (45′)	t500J (45′)	SFJ (45′)	PJ (45′)	t500 (90′)	SF (90′)	tv (90′)	PL (90′)	t500J (90′)	SFJ (90′)	PJ (90′)	Rrb
	$R_{i,j}$																															
0	1	1	1	1	1	2	5	4	2	1	1	2	1	3	2	2	1	2	1	3	2	4	1	4	1	1	1	2	1	1	2	1
20 M1	2	2	3	2	3	3	6	6	7	2	3	5	2	2	4	6	2	5	4	5	3	3	2	3	5	3	2	4	2	2	1	3
50 M1	3	5	4	4	2	5	2	1	5	4	6	4	4	4	3	3	4	4	2	4	4	5	4	2	4	5	4	3	4	4	4	4
100 M1	6	6	6	6	6	6	4	5	1	5	4	3	6	6	6	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
20 M3	4	4	2	3	5	4	1	3	3	3	2	1	3	1	1	1	3	1	3	1	1	1	3	5	2	4	5	1	3	3	3	2
50 M3	5	3	5	5	4	1	3	2	4	6	5	6	5	5	5	4	5	3	5	2	5	2	5	1	3	2	3	5	5	5	5	5
100 M3	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Kendall's coefficient *W* (Eq. (5)) = 0.6527																																
Spearman's $\rho_{s,j}$ (Eq. (12))																																
$\rho_{s,j}$	0.9	0.8	1.0	1.0	0.8	0.6	0.3	0.3	0.2	0.9	0.9	0.7	1.0	0.9	0.9	0.8	1.0	0.8	0.9	0.7	1.0	0.6	1.0	0.3	0.9	0.8	0.8	0.9	1.0	1.0	0.9	

Table 9

Kendall's coefficient and Spearman's $\rho_{s,j}$ (superplasticiser variations).

SCRC	τ_0 (15′)	μ_{pl} (15′)	τ_0 (45′)	μ_{pl} (45′)	τ_0 (90′)	μ_{pl} (90′)	$f_{c,3d}$	$f_{c,7d}$	$f_{c,28d}$	t500 (15′)	SF (15′)	tv (15′)	PL (15′)	t500J (15′)	SFJ (15′)	PJ (15′)	SR	t500 (45′)	SF (45′)	tv (45′)	PL (45′)	t500J (45′)	SFJ (45′)	PJ (45′)	t500 (90′)	SF (90′)	tv (90′)	PL (90′)	t500J (90′)	SFJ (90′)	PJ (90′)	Rrb
	$\mathbf{R_{i,j}}$																															
0	1	3	5	2	1	2	1	1	2	1	1	6	1	4	2	2	1	6	3	4	1	6	4	6	2	1	1	1	1	1	1	1
20 M1	2	2	2	4	2	5	7	3	6	3	5	7	3	3	5	6	3	4	2	3	2	2	3	5	4	4	2	2	3	2	3	3
50 M1	5	4	3	3	3	3	4	6	5	2	3	3	4	5	4	5	2	3	1	2	3	4	6	3	5	5	3	5	4	5	4	4
100 M1	4	5	4	5	6	6	2	2	3	6	6	2	6	6	6	3	6	5	5	1	6	5	5	4	6	6	6	6	6	6	6	6
20 M3	3	1	1	1	4	4	5	4	4	4	2	4	5	2	1	4	4	1	4	5	4	1	1	1	3	3	4	4	2	3	2	2
50 M3	6	6	6	6	5	1	6	7	7	5	4	1	2	1	3	1	5	2	6	6	5	3	2	2	1	2	5	3	5	4	5	5
100 M3	7	7	7	7	7	7	3	5	1	7	7	5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Kendall's coefficient *W* (Eq. (5)) = 0.4026																																
Spearman's $\rho_{s,j}$ (Eq. (12))																																
$\rho_{s,j}$	0.9	0.9	0.6	0.9	0.9	0.5	0.0	0.4	-0.1	0.9	0.9	-0.5	0.7	0.5	0.8	0.3	0.9	0.3	0.6	0.1	0.9	0.4	0.6	0.2	0.6	0.8	0.9	0.8	1.0	0.9	1.0	

Table 10
Kendall's coefficient and Spearman's $\rho_{s,j}$ (cement variations).

SCRC	τ_0 (15′)	μ_{pl} (15′)	τ_0 (45′)	μ_{pl} (45′)	τ_0 (90′)	μ_{pl} (90′)	$f_{c,3d}$	$f_{c,7d}$	$f_{c,28d}$	t500 (15′)	SF (15′)	tv (15′)	t500J (15′)	SFJ (15′)	PJ (15′)	SR	t500 (45′)	SF (45′)	t500J (45′)	SFJ (45′)	PJ (45′)	t500 (90′)	SF (90′)	t500J (90′)	SFJ (90′)	PJ (90′)	Rrb
	$R_{i,j}$																										
0	2	3	1	4	1	1	2	2	1	1	1	1	4	4	4	1	2	1	4	4	4	1	2	1	2	1	1
20 M1	1	1	3	2	2	2	1	1	2	3	2	4	3	3	3	2	1	2	3	2	3	3	1	3	1	2	2
50 M1	3	2	4	3	3	3	3	4	4	2	3	3	1	2	2	3	3	3	1	1	1	2	3	2	3	3	3
100 M1	4	4	2	1	4	4	4	3	3	4	4	2	2	1	1	4	4	4	2	3	2	4	4	4	4	4	4
Kendall's coefficient W (Eq. (5)) = 0.1402																											
Spearman's $\rho_{s,j}$ (Eq. (12))																											
$\rho_{s,j}$	0.8	0.4	0.4	−0.8	1	1	0.8	0.6	0.8	0.8	1	0.2	−0.8	−1.0	−1.0	1	0.8	1	−0.8	−0.4	−0.8	0.8	0.8	0.8	0.8	1	

Table 11
Critical values of Kendall's coefficient (W^*).

α	W^*	
	$n = 7$; $k = 31$	$n = 4$; $k = 26$
0.05	0.0615	0.0880
0.01	0.0805	0.1229

properties to "judge" robustness will be also in agreement for the considered significance levels.

Once the significance of Kendall's coefficient has been evaluated, the correlation between the rankings of an individual "judge" ($R_{i,j}$) and the final ranks of the objects, "Rrb", has to be assessed. To do so, Spearman's correlation test is used, being it then necessary to obtain Spearman's rank correlation coefficient.

In Tables 8–10, the Spearman's coefficient for each concrete property ($\rho_{s,j}$) is calculated, Eq. (12), for water, superplasticiser and cement variations respectively.

A positive result of this Spearman's $\rho_{s,j}$ implies a good correlation between the evaluation (ranking) obtained with this property and the final evaluation (rank) obtained in the mix when all studied properties are considered. A negative $\rho_{s,j}$ value indicates non correlation between the evaluation made with this property and the final evaluation obtained in the mix.

Therefore, those "judges" (properties) which provide no correlation have to be eliminated and those that provide low correlation can also be removed to simplify the robustness (characteristic) assessment. In this way, the number of properties ("judges") is changed and again, Kendall's coefficient has to be calculated and its significance checked according to the desired level of significance. Once this has been done, it can be concluded that the selection of properties that provide the best correlation to assess the robustness is achieved.

Then, some of the 31 properties that exhibited negative or low $\rho_{s,j}$ values were removed to reduce the number of properties that could be used for the evaluation of SCRC robustness. As a result, a minimum of six properties were selected: two rheological properties, τ_0 (15′) and μ_{pl} (15′), and four workability parameters, t500 (15′), SF (15′), SFJ (15′) and SR. This selection took into account the $\rho_{s,j}$ values obtained in the three material variations (water, superplasticiser and cement) (Tables 8–10). Moreover, these six properties would describe the rheological properties (fundamental physical quantities) and the three key workability characteristics (empirical physical quantities) of a SCRC mix.

The robustness categories determined using the six selected properties can be observed in Tables 12–14 for water, superplasticiser and cement variations, respectively. Both sets of properties, the full 31 and the 6 selected properties, showed the same results regarding robustness evaluation of the seven SCRC mixes (in general terms of high, medium–high, medium- low and low).

Again, to determine the significance of W, a significance level (α) has to be chosen and the critical value of W for this α obtained (Table 15) [50]. If the calculated W (Tables 12–14) is greater than or equal to the critical value of the Kendall's coefficient W∗ for any particular level of significance, Table 15, then there is a good agreement among the properties used to evaluate robustness.

As it can be seen, in both water and superplasticiser variations, W exceeds the critical value W∗ for all the considered significance levels. So, it can be concluded with considerable confidence that there is a high agreement among the selected 6 properties ($k = 6$) when water or superplasticiser vary.

The $\rho_{s,j}$ values were recalculated with the final ranking (Rrb) obtained for each mix (according to the sum of rankings obtained with the six selected properties). They are presented in

Table 12
Kendall's coefficient and Spearman's $\rho_{s,j}$ (6 properties - water variations).

SCRC	τ_0 (15′)	μ_{pl} (15′)	t500 (15′)	SF (15′)	SFJ (15′)	SR	Rrb	Robustness
	$\mathbf{R_{i,j}}$							
0	1	1	1	1	2	1	1	High
20 M1	2	2	2	3	4	2	2	Medium-high
50 M1	3	5	4	6	3	4	4	Medium-low
100 M1	6	6	5	4	6	6	6	Low
20 M3	4	4	3	2	1	3	3	Medium-high
50 M3	5	3	6	5	5	5	5	Medium-low
100 M3	7	7	7	7	7	7	7	Low
Kendall's coefficient (*W*) (Eq. (5)) = 0.8433								
Spearman's $\rho_{s,j}$ (Eq. (12))								
ρ_s	0.96	0.89	0.96	0.82	0.82	1.00		

Table 13
Kendall's coefficient and Spearman's $\rho_{s,j}$ (6 properties – superplasticiser variations).

SCRC	τ_0 (15′)	μ_{pl} (15′)	t500 (15′)	SF (15′)	SFJ (15′)	SR	Rrb	Robustness
	$\mathbf{R_{i,j}}$							
0	1	3	1	1	2	1	1	High
20 M1	2	2	3	5	5	3	3	Medium-high
50 M1	5	4	2	3	4	2	4	Medium-high
100 M1	4	5	6	6	6	6	6	Low
20 M3	3	1	4	2	1	4	2	Medium-high
50 M3	6	6	5	4	3	5	5	Medium-low
100 M3	7	7	7	7	7	7	7	Low
Kendall's coefficient (*W*) (Eq. (5)) = 0.7619								
Spearman's $\rho_{s,j}$ (Eq. (12))								
ρ_s	0.86	0.86	0.86	0.89	0.82	0.86		

Table 14
Kendall's coefficient and Spearman's $\rho_{s,j}$ (6 properties - cement variations).

SCRC	τ_0 (15′)	μ_{pl} (15′)	t500 (15′)	SF (15′)	SFJ (15′)	SR	Rrb	Robustness
	$\mathbf{R_{i,j}}$							
0	2	3	1	1	4	1	1	High
20 M1	1	1	3	2	3	2	2	High
50 M1	3	2	2	3	2	3	3	Medium-high
100 M1	4	4	4	4	1	4	4	Low
Kendall's coefficient (*W*) (Eq. (5)) = 0.3000								
Spearman's $\rho_{s,j}$ (Eq. (12))								
ρ_s	0.80	0.40	0.80	1.00	-1	1		

Tables 12–14. According to these $\rho_{s,j}$, it can be concluded that τ_0 (15 min), μ_{pl} (15 min), t500 (15 min), SF (15 min), SFJ (15 min) and SR can be successfully used to assess the SCRC robustness due to the fact that all of them suitably correlate with the final result obtained.

In the case of cement variations, the *W* value calculated with the six selected properties was lower than the critical value $W*$ for both $\alpha = 0.05$ and $\alpha = 0.01$ significance levels. As seen when 26 properties were considered, cement variations are less sensitive to evaluate robustness than water and superplasticiser ones (it would be necessary to make more tests to evaluate the SCRC robustness).

Table 15
Critical values of Kendall's coefficient (W^*).

α	W^*	
	$n = 7$, $k = 6$	$n = 4$, $k = 6$
0.05	0.2589	0.3276
0.01	0.3351	0.4505

Lastly, it can be seen that when water variations are imposed the values of Kendall's coefficient and Spearman's coefficient are the highest ones. Therefore, according to the results of this statistical approach, introducing water variations in the mix is the most effective procedure to asses SCRC robustness.

Comparing these results with those obtained by Naji et al. [21] for conventional self-compacting concrete, it is observed that also in SCC variations in sand humidity and consequently water variations should be controlled to ensure concrete behaviour. Moreover, in both cases, recycled and conventional self-compacting concrete, static yield stress and plastic viscosity using a rheometer are key properties to control self-compacting robustness. It means that rheology is a robust tool to characterize any type of concrete in its fresh state and as a fluid. In addition, it would be interesting to use a couple of empirical characterization tests to check filling ability, passing ability and segregation resistance. In agreement with Naji et al. [21], the obtained results suggest the use of J-Ring test and in this work, according to the analysis developed, the slump flow test is really recommended. For the segregation resistance, both the surface settlement (proposed by Naji et al. [21]), or the sieve segregation test, used in this work, can be accurately employed. Finally, on the contrary to Naji et al. [21], the results suggest that compressive strength is not a key property to evaluate robustness.

4. Conclusions

The robustness of self-compacting recycled concrete (SCRC) was deeply analysed. Based on the results obtained, the following conclusions can be drawn:

The key materials that have to be controlled when SCRC robustness is taken into account in an industrial production are the recycled aggregate percentage and the water variations (especially those due to aggregate moisture). When low replacement percentages of recycled coarse aggregate are used, SCRC shows a higher level of robustness. Moreover, when aggregates are used with a moisture content, the control of water is more difficult and this affects SCRC robustness negatively. Therefore, in a real production process, previous moisture of recycled aggregate has to be thoroughly controlled.

In general, the 20% replacement concretes show a medium-high level of robustness and SCRCs with a 100% of recycled aggregate display low robustness. Regarding the 50% replacement concretes, the level of robustness depends largely on the mixing procedure in terms of water control and previous moisture of recycled aggregates.

Moreover, the statistical approach based on Kendall's coefficient of concordance and Spearman's rank correlation was successfully used to identify six key properties of SCRC that can be measured to evaluate robustness: τ_0 (15 min), μ_{pl} (15 min), t500 (15 min), SF (15 min), SFJ (15 min) and SR. These parameters are practically the same as those suggested in the literature [21] to evaluate conventional self-compacting concrete.

Finally, according to this statistical approach, and in agreement with other studies developed with conventional self-compacting concrete, water variation is the key factor that affects SCRC robustness. In fact, in this work it has been observed that this type of concrete is more sensitive to water variations than conventional SCC. Therefore, introducing water variations in the mix is the most effective procedure to assess SCRC robustness.

Compliance with ethical standards

This study was funded by two projects entitled: (a) "Industrial Investigation about Concrete for a Sustainable Market (InHorMeS)" funded by the Innovation Galician Agency (Ref: IN852A 2013/57); (b) "Robust self-compacting recycled concretes: rheology in fresh state and mechanical properties (Ref: BIA2014-58063-R)" funded by MINECO.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix

See Tables 16–18.

Table 16
Test results and ranking of SCRCs according to COV of properties at different water levels.

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
τ_0 (15')	W−; 0; W+	93.2	79.0	56.3	114	90.0	65.3	145	114	72.3	245	132	82.0	152	107	61.1	204	147	70.6	712	136	140
	COV (%)	24.5			27.3			32.9			54.4			42.6			47.7			101		
	Rank	1			2			3			6			4			5			7		
μ_{pl} (15')	W−; 0; W+	38.7	30.8	28.7	39.3	31.8	28.7	48.4	33.0	31.0	83.9	57.9	32.4	47.5	34.5	29.1	53.3	45.7	34.8	180	52.4	51.2
	COV (%)	16.2			16.3			25.8			44.3			25.5			20.8			78.4		
	Rank	1			2			5			6			4			3			7		
τ_0 (45')	W−; 0; W+	238	214	179	326	251	228	395	297	237	776	361	238	335	262	246	533	309	266	1607	328	449
	COV (%)	14.0			19.1			25.8			61.4			16.9			38.8			88.8		
	Rank	1			3			4			6			2			5			7		
μ_{pl} (45')	W−; 0; W+	43.7	32.8	31.6	45.6	33.0	32.8	56.9	36.5	33.1	129	63.7	41.4	49.8	38.7	32.4	84.3	50	40.8	225	60.7	77.4
	COV (%)	18.6			19.7			30.6			58.4			21.8			39.3			74.7		
	Rank	1			2			4			6			3			5			7		
τ_0 (90')	W−; 0; W+	742	515	482	898	644	523	917	846	530		1079	804	1397	587	474	2714	1076	1077		1119	3053
	COV (%)	24.4			27.8			26.9						61.5			58.3					
	Rank	1			3			2			6			5			4			7		
μ_{pl} (90')	W−; 0; W+	60.5	35.0	34.4	79.8	43.0	40.6	116	58.3	48.2		139	88.8	109	54.0	47.1	123	92.4	65.7		140	257
	COV (%)	34.4			40.3			49.6						48.4			30.6					
	Rank	2			3			5			6			4			1			7		
$f_{c,3d}$	W−; 0; W+	68.6	68.3	67.2	66.5	64.2	64.8	64.5	64.2	63.8	60.6	59.9	59.5	66.9	66.8	66.3	64.9	64.8	63.9	63.1	60.0	59.1
	COV (%)	1.1			1.8			0.5			1.0			0.4			0.8			3.4		
	Rank	5			6			2			4			1			3			7		

(continued on next page)

Table 16 (*continued*)

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
$f_{c,7d}$	W−; 0; W+	74.9	73.8	73.2	74.4	70.2	70.2	68.1	68.1	67.9	66.6	64.2	64.9	71.4	70.9	70.7	69.2	69.5	69.3	67.5	65.3	61.6
	COV (%)	1.2			3.4			0.2			1.9			0.5			0.3			4.6		
	Rank	4			6			1			5			3			2			7		
$f_{c,28d}$	W−; 0; W+	80.8	80.4	79.6	80.5	76.9	75.5	76.3	75.5	73.6	70.4	70.5	70.0	80.8	79.0	79.0	76.1	75.9	74.2	72.0	69.3	69.3
	COV (%)	0.8			3.3			1.9			0.4			1.3			1.4			2.2		
	Rank	2			7			5			1			3			4			6		
t500 (15‘)	W−; 0; W+	1.59	1.45	1.1	2.26	1.96	1.34	2.57	2.38	1.51	5.45	4.07	2.95	2.4	2.29	1.43	3.81	2.59	1.7		4.41	3.14
	COV (%)	18.3			25.3			26.2			30.1			26.0			39.2					
	Rank	1			2			4			5			3			6			7		
SF (15‘)	W−; 0; W+	770	815	850	745	745	820	700	710	815	630	680	720	710	715	780	640	705	750		660	650
	COV (%)	4.9			5.6			8.6			6.7			5.3			7.9					
	Rank	1			3			6			4			2			5			7		
tv (15‘)	W−; 0; W+	29.5	23.7	18.4	39.0	25.8	25.7	40.6	30.6	24.9	43.1	33.2	26.4	34.0	24.8	23.9	47.3	32.5	27.6		22.0	14.6
	COV (%)	23.3			25.5			24.8			24.5			20.3			28.5					
	Rank	2			5			4			3			1			6			7		
PL (15‘)	W-; 0; W+	0.85	0.90	0.90	0.82	0.87	0.90	0.74	0.88	0.90	0.57	0.83	0.89	0.84	0.86	0.92	0.67	0.82	0.91		0.79	0.76
	COV (%)	3.3			4.7			10.4			22.3			4.8			15.2					
	Rank	1			2			4			6			3			5			7		
t500J (15‘)	W−; 0; W+	3.00	2.5	1.60	3.03	2.96	1.76	4.46	3.73	2.37	9.64	4.25	2.64	3.77	3.22	2.33	5.07	3.91	2.40		4.50	3.96
	COV (%)	29.9			27.6			30.1			66.5			23.4			35.3					
	Rank	3			2			4			6			1			5			7		
SFJ (15‘)	W−; 0; W+	750	820	850	730	750	845	670	700	775	535	675	745	695	725	735	620	690	730		660	665
	COV (%)	6.3			7.9			7.6			16.5			2.9			8.2					
	Rank	2			4			3			6			1			5			7		
PJ (15‘)	W−; 0; W+	12	10	9	18	13	8	23	19	16	31	20	18	16	14	12	23	17	13		20	20
	COV (%)	14.8			38.5			18.2			30.4			14.3			28.5					
	Rank	2			6			3			5			1			4			7		
SR	W−; 0; W+	11.1	13.6	15.3	8.9	13.1	13.5	7.5	11.5	13.4	2.7	3.5	7.6	7.3	10.6	12.9	5.6	9.4	11.8	0.02	4.8	2.0
	COV (%)	15.7			21.4			27.9			57.5			27.9			34.9			105		
	Rank	1			2			4			6			3			5			7		
t500 (45‘)	W−; 0; W+	2.39	1.95	1.9	3.3	2.31	2.21	3.53	2.75	2.57	8.77	5.41	3.53	3	2.58	2.48	4.13	3.46	3.01		5.71	2.95
	COV (%)	12.9			23.1			17.3			44.9			10.3			15.9					
	Rank	2			5			4			6			1			3			7		
SF (45‘)	W−; 0; W+	770	800	800	695	740	785	690	705	755	500	630	675	670	715	750	620	700	725		620	610
	COV (%)	2.2			5.9			4.6			15.1			5.6			8.0					
	Rank	1			4			2			6			3			5			7		
tv (45‘)	W−; 0; W+	33.3	24.7	21.2	45.5	35.2	22.5	59.3	45.3	33.0		42.1	40.2	34.9	28.1	26.6	43.9	34.1	31.5		32.9	21.3
	COV (%)	23.6			33.5			28.7						14.9			17.9					
	Rank	3			5			4			6			1			2			7		
PL (45‘)	W−; 0; W+	0.83	0.90	0.90	0.81	0.82	0.89	0.75	0.82	0.87	0.38	0.84	0.90	0.85	0.86	0.90	0.68	0.83	0.92		0.80	0.73
	COV (%)	4.6			5.2			7.4			40.3			3.0			15.3					
	Rank	2			3			4			6			1			5			7		
t500J (45‘)	W−; 0; W+	3.37	2.47	1.75	4.20	3.17	2.38	5.01	4.59	2.43		6.00	4.21	4.63	3.49	2.82	6.09	5.08	3.50		6.59	9.65
	COV (%)	32.1			28.1			34.5						25.1			26.7					
	Rank	4			3			5			6			1			2			7		
SFJ (45‘)	W−; 0; W+	740	790	795	700	745	760	650	690	750		630	700	660	725	760	600	680	720		620	525
	COV (%)	3.9			4.2			7.2						7.1			9.0					
	Rank	1			2			4			6			3			5			7		
PJ (45‘)	W−; 0; W+	15	10	10	21	15	15	25	23	17		26	25	30	20	15	26	21	20		24	40
	COV (%)	24.7			20.4			19.2						35.3			14.4					

Table 16 (*continued*)

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
	Rank	4			3			2			6			5			1			7		
t500 (90‘)	W−; 0; W+	4.71	2.44	2.13	8.28	2.8	2.58	13.0	5.83	3.53			5.69	8.52	4.44	2.9	12.9	7	3.95			
	COV (%)	45.5			70.9			66.3						54.9			57.4					
	Rank	1			5			4			6			2			3			7		
SF (90‘)	W−; 0; W+	705	715	785	570	690	730	495	640	705		455	565	510	660	700	490	570	620		435	
	COV (%)	5.9			12.5			17.5						16.1			11.7					
	Rank	1			3			5			6			4			2			7		
tv (90‘)	W−; 0; W+	47.2	34.5	28.5	73.0	48.8	29.1		61.8	54.7			60		65	36.2		70.3	64.2			
	COV (%)	26.0			43.7																	
	Rank	1			2			4			6			5			3			7		
PL (90‘)	W−; 0; W+	0.54	0.75	0.82	0.38	0.60	0.91	0.38	0.62	0.77		0.56	0.51	0.51	0.73	0.74	0.21	0.60	0.89		0.17	
	COV (%)	20.7			42.8			33.3						19.7			60.2					
	Rank	2			4			3			6			1			5			7		
t500J (90‘)	W−; 0; W+	5.42	3.12	2.96	7.82	4.83	3.50	22.7	7.44	6.22			13.1	11.6	7.69	4.12		12.4	8.12			
	COV (%)	35.9			41.1			75.8						48.1								
	Rank	1			2			4			6			3			5			7		
SFJ (90‘)	W−; 0; W+	690	720	750	610	660	700	475	590	650			525	510	600	690		530	570			
	COV (%)	4.2			6.9			15.6						15.0								
	Rank	1			2			4			6			3			5			7		
PJ (90‘)	W−; 0; W+	25	17	16	35	26	25	59	35	32			50	49	35	25		44	35			
	COV (%)	26.2			19.7			35.2						33.2								
	Rank	2			1			4			6			3			5			7		
SR_i		57			104			116			171			80			124			216		
Rrb		1			3			4			6			2			5			7		

Table 17
Test results and ranking of SCRCs according to COV of properties at different superplasticiser levels.

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
τ_0 (15‘)	S−; 0; S+	87.6	79.0	80.2	105	90.0	83.0	136	114	90.7	155	132	105	128	107	88.3	181	147	98.9	524	136	163
	COV (%)	5.7			12.0			20.0			19.2			18.5			28.9			79.0		
	Rank	1			2			5			4			3			6			7		
μ_{pl} (15‘)	S−; 0; S+	34.5	30.8	29.1	36.1	31.8	31.0	38.3	33.0	32.5	61.4	57.9	42.1	35.7	34.5	33.6	65.8	45.7	40.9	125	52.4	57.9
	COV (%)	8.7			8.3			9.3			19.1			3.1			26.0			51.8		
	Rank	3			2			4			5			1			6			7		
τ_0 (45‘)	S−; 0; S+	264	214	201	265	251	244	316	297	263	392	361	308	265	262	264	522	309	287	1365	328	465
	COV (%)	14.6			4.3			9.3			12.0			0.7			34.8			78.3		
	Rank	5			2			3			4			1			6			7		
μ_{pl} (45‘)	S−; 0; S+	40.0	32.8	32.1	43.5	33.0	32.3	47.9	36.5	36.2	79.1	63.7	54.2	46.0	38.7	38.1	93.8	50.0	48.3	185	60.7	82.5
	COV (%)	12.5			17.3			16.6			19.1			10.8			40.3			60.7		
	Rank	2			4			3			5			1			6			7		
τ_0 (90‘)	S−; 0; S+	556	515	463	816	644	508	1131	846	650	1787	1079	934	825	587	456	1600	1076	908		1119	3541
	COV (%)	9.1			23.5			27.6			36.0			30.1			30.2					
	Rank	1			2			3			6			4			5			7		
μ_{pl} (90‘)	S−; 0; S+	45.3	35.0	38.7	67.8	43.0	41.9	86.1	58.3	56.2	213	139	107	78.4	54.0	49.4	115	92.4	91.7		140	258
	COV (%)	13.1			28.8			25.0			35.7			25.7			13.1					
	Rank	2			5			3			6			4			1			7		
$f_{c,3d}$	S−; 0; S+	66.6	68.3	67.0	64.9	64.2	68.5	63.7	64.2	66.5	59.5	59.9	58.3	67.0	66.8	69.7	62.9	64.8	66.1	60.2	60.0	58.5
	COV (%)	1.3			3.4			2.3			1.4			2.3			2.5			1.6		
	Rank	1			7			4			2			5			6			3		
$f_{c,7d}$	S−; 0; S+	73.7	73.8	73.9	70.1	70.2	72.3	67.6	68.1	70.2	63.7	64.2	62.2	72.4	70.9	73.5	68.6	69.5	71.4	65.6	65.3	63.3
	COV (%)	0.2			1.7			2.0			1.6			1.8			2.03			1.9		
	Rank	1			3			6			2			4			7			5		
$f_{c,28d}$	S−; 0; S+	80.8	80.4	81.5	76.9	76.9	79.3	73.6	75.5	76.2	70.4	70.5	69.4	78.6	79.0	81.0	72.2	75.9	76.1	69.9	69.3	69.0
	COV (%)	0.73			1.8			1.75			0.9			1.6			2.9			0.7		
	Rank	2			6			5			3			4			7			1		
t500 (15‘)	S−; 0; S+	1.47	1.45	1.41	2.27	1.96	1.51	2.77	2.38	2.07	6.47	4.07	2.9	2.53	2.29	1.59	2.68	2.59	1.7		4.41	4
	COV (%)	2.1			20.0			14.6			40.6			22.9			23.3					
	Rank	1			3			2			6			4			5			7		
SF (15‘)	S−; 0; S+	790	815	820	720	745	780	695	710	730	568	680	700	695	715	725	670	705	700		660	620
	COV (%)	2.0			4.0			2.5			10.9			2.1			2.7					
	Rank	1			5			3			6			2			4			7		
tv (15‘)	S−; 0; S+	39.1	23.7	21.2	38.4	25.8	16.2	34.8	30.6	19.7	27.8	33.2	21.1	32.8	24.8	18.7	24.5	32.5	23.2	37.0	22.0	21.0
	COV (%)	34.6			41.5			27.4			22.1			27.7			18.9			33.7		
	Rank	6			7			3			2			4			1			5		
PL (15‘)	S−; 0; S+	0.89	0.90	0.91	0.84	0.87	0.89	0.81	0.88	0.84	0.69	0.83	0.83	0.82	0.86	0.90	0.79	0.82	0.83	0.24	0.79	0.82
	COV (%)	1.1			2.9			4.2			10.3			4.7			2.6			53.0		
	Rank	1			3			4			6			5			2			7		
t500J (15‘)	S−; 0; S+	3.44	2.5	1.90	3.84	2.96	2.15	4.88	3.73	2.32	10.4	4.25	4.00	3.38	3.22	2.90	4.18	3.91	3.62		4.50	5.07
	COV (%)	29.7			28.3			35.2			58.3			7.8			7.2					
	Rank	4			3			5			6			2			1			7		
SFJ (15‘)	S−; 0; S+	780	820	820	710	750	815	680	700	770	550	675	705	720	725	755	665	690	715		660	620
	COV (%)	2.9			7.0			6.6			12.8			2.6			3.6					
	Rank	2			5			4			6			1			3			7		
PJ (15‘)	S−; 0; S+	12	10	7	25	13	9	30	19	13	33	20	19	24	14	12	23	17	15		20	23
	COV (%)	26.0			53.1			41.7			31.6			37.5			23.4					
	Rank	2			6			5			3			4			1			7		
SR	S−; 0; S+	12.8	13.6	15.1	11.0	13.1	13.3	11.1	11.5	13.1	2.4	3.5	8.3	9.9	10.6	12.7	7.9	9.4	11.1	0.0	4.8	2.9

Table 17 (*continued*)

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
	COV (%)	8.5			9.8			9.2			66.6			13.2			16.5			94.5		
	Rank	1			3			2			6			4			5			7		
t500 (45‘)	S−; 0; S+	3.09	1.95	1.58	3.15	2.31	1.81	3.78	2.75	2.59	5.72	5.41	3.22	3.32	2.58	2.43	3.65	3.46	2.6		5.71	4.5
	COV (%)	35.7			27.9			21.2			28.5			17.2			17.3					
	Rank	6			4			3			5			1			2			7		
SF (45‘)	S−; 0; S+	745	800	810	715	740	765	690	705	725	585	630	680	690	715	795	660	700	790		620	610
	COV (%)	4.5			3.2			2.5			7.5			7.4			9.3					
	Rank	3			2			1			5			4			6			7		
tv (45‘)	S−; 0; S+	34.5	24.7	22.6	40.0	35.2	31.9	47.4	45.3	42.2	42.1	42.1	40.5	35.0	28.1	21.7	32.9	34.1	18.1		32.9	23.9
	COV (%)	23.2			11.4			5.8			2.1			23.6			31.3					
	Rank	4			3			2			1			5			6			7		
PL (45‘)	S−; 0; S+	0.89	0.90	0.91	0.80	0.82	0.83	0.80	0.82	0.85	0.69	0.84	0.85	0.81	0.86	0.86	0.78	0.83	0.87		0.80	0.69
	COV (%)	1.1			1.9			3.1			11.3			3.4			5.5					
	Rank	1			2			3			6			4			5			7		
t500J (45‘)	S−; 0; S+	3.46	2.47	1.94	3.63	3.17	2.76	5.51	4.59	3.26	8.27	6.00	5.03	3.71	3.49	3.13	6.00	5.08	4.01		6.59	6.21
	COV (%)	29.4			13.7			25.4			25.8			8.5			19.8					
	Rank	6			2			4			5			1			3			7		
SFJ (45‘)	S−; 0; S+	715	790	795	700	745	765	640	690	740	600	630	680	695	725	750	655	680	710		620	610
	COV (%)	5.8			4.5			7.2			6.3			3.8			4.2					
	Rank	4			3			6			5			1			2			7		
PJ (45‘)	S−; 0; S+	27	10	10	28	15	10	30	23	20	34	26	22	24	20	17	25	21	17		24	30
	COV (%)	62.6			52.6			21.1			22.4			17.6			19.0					
	Rank	6			5			3			4			1			2			7		
t500 (90‘)	S−; 0; S+	3.71	2.44	1.93	5.12	2.8	2.36		5.83	4.13			9.05	6.42	4.44	2.78	8.93	7	4.44			
	COV (%)	34.0			43.3									40.1			33.2					
	Rank	2			4			5			6			3			1			7		
SF (90‘)	S−; 0; S+	695	715	760	560	690	700		640	645		455	485	550	660	695	515	570	585		435	
	COV (%)	4.4			12.0									11.9			6.9					
	Rank	1			4			5			6			3			2			7		
tv (90‘)	S−; 0; S+	41.5	34.5	34.1	66.6	48.8	42.0		61.8	52.0					65	36.1		70.3				
	COV (%)	11.3			24.2																	
	Rank	1			2			3			6			4			5			7		
PL (90‘)	S−; 0; S+	0.71	0.75	0.80	0.51	0.60	0.79		0.62	0.56		0.56	0.34	0.40	0.73	0.78	0.33	0.60	0.55		0.17	
	COV (%)	6.0			22.6									32.4			29.1					
	Rank	1			2			5			6			4			3			7		
t500J (90‘)	S−; 0; S+	4.66	3.12	2.88	8.00	4.83	3.76		7.44	5.57			18.8	10.9	7.69	5.76		12.4	5.87			
	COV (%)	27.2			39.9									32.3								
	Rank	1			3			4			6			2			5			7		
SFJ (90‘)	S−; 0; S+	670	720	730	575	660	680		590	675			510	510	600	690		530	605			
	COV (%)	4.5			8.7									15.0								
	Rank	1			2			5			6			3			4			7		
PJ (90‘)	S−; 0; S+	28	17	15	55	26	18		35	30			42	53	35	25		44	27			
	COV (%)	34.8			59.4									38.1								
	Rank	1			3			4			6			2			5			7		
SR$_i$		74			109			117			151			91			123			203		
Rrb		1			3			4			6			2			5			7		

Table 18

Test results and ranking of SCRCs according to COV of properties at different cement levels.

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1		
τ_0 (15‘)	C−; 0; C+	70.6	79.0	83.2	88.6	90.0	96.7	92.6	114	130	97.4	132	150
	COV (%)	8.3			4.7			16.7			20.8		
	Rank	2			1			3			4		
μ_{pl} (15‘)	C−; 0; C+	25.5	30.8	31.2	30.7	31.8	33.0	31.9	33.0	35.5	36.2	57.9	59.0
	COV (%)	10.9			3.6			5.5			25.2		
	Rank	3			1			2			4		
τ_0 (45‘)	C−; 0; C+	214	214	244	228	251	310	240	297	347	293	361	386
	COV (%)	7.7			16.2			18.2			13.8		
	Rank	1			3			4			2		
μ_{pl} (45‘)	C−; 0; C+	28.8	32.8	38.1	33.0	33.0	41.5	34.3	36.5	44.4	52.2	63.7	67.3
	COV (%)	14.0			13.7			13.8			12.9		
	Rank	4			2			3			1		
τ_0 (90‘)	C−; 0; C+	504	515	608	596	644	744	659	846	1164	879	1079	3967
	COV (%)	10.6			11.4			28.7			87.5		
	Rank	1			2			3			4		
μ_{pl} (90‘)	C−; 0; C+	34.5	35.0	45.0	40.8	43.0	68.8	56.8	58.3	104	87.7	139	198
	COV (%)	15.7			30.6			36.6			39.0		
	Rank	1			2			3			4		
$f_{c,3d}$	C−; 0; C+	66.2	68.3	69.8	63.7	64.2	65.1	60.5	64.2	60.8	55.1	59.9	56.8
	COV (%)	2.7			1.1			3.3			4.3		
	Rank	2			1			3			4		
$f_{c,7d}$	C−; 0; C+	71.4	73.8	75.7	70.9	70.2	71.1	62.2	68.1	67.6	59.3	64.2	62.0
	COV (%)	2.9			0.7			5.0			3.9		
	Rank	2			1			4			3		
$f_{c,28d}$	C−; 0; C+	79.8	80.4	80.6	76.7	76.9	78.5	69.5	75.5	73.8	63.9	70.5	67.0
	COV (%)	0.5			1.3			4.3			4.9		
	Rank	1			2			4			3		
t500 (15‘)	C−; 0; C+	1.39	1.45	1.78	1.57	1.96	2.93	1.97	2.38	3.35	2.21	4.07	4.21
	COV (%)	13.6			32.5			27.6			31.9		
	Rank	1			3			2			4		
SF (15‘)	C−; 0; C+	820	815	760	800	745	705	790	710	685	760	680	660
	COV (%)	4.2			6.4			7.5			7.6		
	Rank	1			2			3			4		
tv (15‘)	C−; 0; C+	22.9	23.7	25.8	23.9	25.8	38.8	25.1	30.6	37.7	27.7	33.2	22.6
	COV (%)	6.2			27.6			20.4			19.0		
	Rank	1			4			3			2		
t500J (15‘)	C−; 0; C+	1.71	2.5	2.88	2.19	2.96	3.38	3.15	3.73	3.87	3.31	4.25	4.70
	COV (%)	25.3			21.2			10.7			17.3		
	Rank	4			3			1			2		
SFJ (15‘)	C−; 0; C+	820	820	740	775	750	720	740	700	695	715	675	680
	COV (%)	5.8			3.5			3.5			3.2		
	Rank	4			3			2			1		
PJ (15‘)	C−; 0; C+	9	10	19	12	13	20	15	19	21	16	20	22
	COV (%)	42.7			29.1			16.7			15.8		
	Rank	4			3			2			1		
SR	C−; 0; C+	16.0	13.6	12.1	16.4	13.1	11.3	13.1	11.5	8.8	8.2	3.5	3.9
	COV (%)	14.2			18.9			19.8			50.4		
	Rank	1			2			3			4		
t500 (45‘)	C−; 0; C+	1.71	1.95	2.23	2.33	2.31	2.52	2.47	2.75	3.77	2.62	5.41	5.75
	COV (%)	13.3			4.9			22.8			37.4		

Table 18 (*continued*)

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1		
	Rank	2			1			3			4		
SF (45‘)	C−; 0; C+	780	800	750	740	740	695	735	705	665	723	630	600
	COV (%)	3.2			3.6			5.0			9.9		
	Rank	1			2			3			4		
t500J (45‘)	C−; 0; C+	2.11	2.47	2.92	2.70	3.17	3.70	4.50	4.59	4.61	4.90	6.00	6.13
	COV (%)	16.2			15.7			1.3			11.9		
	Rank	4			3			1			2		
SFJ (45‘)	C−; 0; C+	800	790	730	755	745	715	695	690	685	675	630	640
	COV (%)	4.9			2.7			0.7			3.6		
	Rank	4			2			1			3		
PJ (45‘)	C−; 0; C+	10	10	20	13	15	21	19	23	24	20	26	27
	COV (%)	42.5			24.8			12.7			14.9		
	Rank	4			3			1			2		
t500 (90‘)	C−; 0; C+	2.32	2.44	2.99	2.64	2.8	4.95	3.18	5.83	6.03	5		
	COV (%)	13.8			37.2			31.7					
	Rank	1			3			2			4		
SF (90‘)	C−; 0; C+	730	715	680	690	690	650	680	640	570	580	455	
	COV (%)	3.6			3.4			8.8					
	Rank	2			1			3			4		
t500J (90‘)	C−; 0; C+	2.91	3.12	3.57	3.82	4.83	5.75	6.08	7.44	8.50	14.9		
	COV (%)	10.5			20.1			16.5					
	Rank	1			3			2			4		
SFJ (90‘)	C−; 0; C+	750	720	705	660	660	650	640	590	555	525		
	COV (%)	3.0			0.9			7.2					
	Rank	2			1			3			4		
PJ (90‘)	C−; 0; C+	16	17	20	20	26	28	33	35	46	38		
	COV (%)	12.3			17.2			18.4					
	Rank	1			2			3			4		
SR_i		55			56			67			82		
Rrb		1			2			3			4		

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