ROBUSTNESS OF SELF-COMPACTING RECYCLED CONCRETE. ANALYSIS OF SENSITIVITY PARAMETERS

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Abstract

This work is focused on understanding the origin of the lower robustness detected in self-compacting recycled concretes and on identifying the parameters affecting this property to a greater extent.

A reference concrete (0%) and three recycled concretes were studied. The replacement percentages of natural with recycled coarse aggregate were 20%, 50% and 100% (by volume). Each baseline mix was modified using two levels of water (±W: -3%, +3%), two levels of superplasticiser (±S: -5%, +5%) and two levels of cement (±C: -3%, +3%). The analysis is focused on the sensitivity parameters calculated with the variations of the results of different tests obtained with the modified mixes. Four industrial tests and two rheological tests were made at a mix age of 15 and 45 min.

It could be concluded that self-compacting recycled concretes present the "Rheological parameter – Ø/Ø$_{max}$" curves with higher slope than the ones of conventional self-compacting concrete. Then, when high percentages of recycled coarse aggregate are used, and when long term self-compacting behaviour is required, there is a greater possibility to reach the high slope region of high slope curves causing high rheological changes and low robustness.

Keywords: self-compacting concrete; recycled coarse aggregate; robustness; yield stress; plastic viscosity; sensitivity parameters.

1 INTRODUCTION

Self-compacting concrete (SCC) is renownedly more sensitive to small changes in raw material characteristics, mix parameters and mixing conditions than conventional vibrated concrete [1, 2], i.e. it is less robust. Robustness is defined as the capacity of concrete to maintain its performance requirements (in a fresh or hardened state) when faced with some variations in component proportions, mixing procedures, transport or casting [1, 3]. It should be noted that it also refers to the ability of a SCC mixture to maintain its filling ability, passing ability and segregation resistance during processing and placement [4].

The increase of concrete robustness can be achieved in two different ways [2]. One possible way is to reduce variations in the constituent materials through more quality control or by increasing the accuracy of existing equipment. Another way to increase robustness is to look for a mix that enables larger deviations while maintaining the properties inside an acceptance interval. This can be achieved by a well-balanced selection and proportioning of constituent materials or by changing the constituent materials.

Nunes et al. [5] proposed to assess the robustness of SCC in terms of the frequency of satisfying the acceptance criteria despite daily fluctuations of the ingredients. These authors observed that the water to powder volume ratio exhibited the greatest effect on SCC properties, and the superplasticiser to powder weight ratio and solid volume also influenced them significantly.

Higher paste volume may improve robustness by reducing the required yield stress and viscosity of cement paste to maintain the same concrete slump flow [4]. Kwan and Ng [6] concluded that the robustness of SCC can be improved by increasing the powder content. The incorporation of cementitious materials of high specific gravity, such as slag, dolomite, or limestone, increases robustness [7].

Higher robustness is also achieved by increasing the viscosity of the mixture by means of material selection and incorporation of a viscosity modifying admixture [8]. The use of a viscosity-enhancing admixture can increase SCC stability when changes in sand humidity occur [3]. Higher fine aggregate to coarse aggregate ratio also improves robustness [4]. Although smaller aggregate size, better gradation, and higher aggregate packing density can all improve robustness of SCC mixes, smaller aggregate size and better gradation seem to have a more significant impact on robustness than higher aggregate packing density.

In recent decades, extensive scientific research has tried to clarify the potential use of recycled aggregates in concrete [9, 10]. This contributes to the protection of natural resources and sustainable development, reducing CO_2 emissions associated with aggregate transportation, concrete waste from landfills and the demand for natural aggregates [11, 12]. Recycled aggregate produced by crushing concrete from demolished concrete structures is named as recycled concrete aggregate. It is known that this aggregate is made up by two different materials, natural aggregate and adhered mortar [13]. The latter is the origin of its lower density and higher absorption, affecting concrete behaviour, especially fresh properties. In this context, some recent works [14-18] have studied the use of recycled concrete coarse aggregate in SCC, developing a new environmentally friendly concrete.

2 RESEARCH SIGNIFICANCE

One of the main obstacles to a wider use of self-compacting concrete is its sensitivity to small variations of the constituent materials, mix proportions, and other external factors, which may lead to variability of performance [19, 20]. According to "The European Guidelines for Self-Compacting Concrete", robustness is an important step in the SCC design process [21].

The total quantity of mixing water is a key factor affecting the robustness of SCC [3]. It is well-known that the use of recycled aggregate (with a high water absorption capacity) leads to define specific mixing methods to produce recycled concrete. These mixing methods try to compensate the water absorption in different ways [22]. The wide experience obtained throughout the analysis of the literature and developed in previous works [23] enables to state that water control is a difficult issue in vibrated recycled concrete. In this context, the use of recycled aggregate is expected to significantly affect SCC robustness.

In this work, different tests are developed to analyse self-compacting recycled concrete (SCRC) robustness. All these tests indicate that mixes with low aggregates substitutions ratios are more robust than the ones produced with high substitution ratios. Therefore, this paper is focused on understanding the origin of this measured trend and, then, on identifying the main parameters affecting SCRC robustness.

3 MATERIALS AND PROTOCOLS

3.1 Materials and concretes

Regarding materials, a Portland cement without admixtures labelled CEM-I 52.5 R and a limestone filler were used as powder fraction. A modified polycarboxylate was used as superplasticiser. As fine aggregate, a limestone sand was used, and two types of coarse aggregates, natural and recycled, were used. The recycled aggregate was obtained from real demolition debris of structural concrete. Table 1 summarizes the main aggregate properties. Regarding recycled aggregate, in addition to the standard absorption test, in this work, continuous measurement of water absorption over time was carried out. This work belongs to a wide research project and part of the material properties have already been published [24].

Table 1. Basic properties of aggregates

Property	NFA	NCA	RCA
Fineness modulus	4.19	7.14	6.47
Fines percentage (%)	8.40	0.84	3.00
Saturated-surface-dry density (t/m^3)	2.72	2.56	2.34
Water absorption (%)	1.00	1.12	6.96
Flakiness index (%)	-	5.41	5.33
Shape	Crushed	Crushed	Crushed

Note: NFA = natural fine aggregate; NCA = natural coarse aggregate; RCA = recycled coarse aggregate

A reference concrete (0%) and three recycled concretes were studied (baseline mixes) (Table 2). The replacement percentages of natural with recycled coarse aggregate were 20%, 50% and 100% (by volume). Aggregates were used in dry-state conditions and an extra quantity of water was added during mixing. The amount of added water was chosen in order to compensate the recycled aggregate absorption at 10 min (i.e. 80% of that at 24 h).

Table 2. Mix proportions of baseline mixes (1 m³)

Concrete SCRC	% RCA			
Dosage	0%	20%	50%	100%
Cement, c (kg)	400.00	400.00	400.00	400.00

Concrete SCRC	% RCA			
Dosage	**0%**	**20%**	**50%**	**100%**
Filler, f (kg)	180.00	180.00	180.00	180.00
Water, w (kg)	184.00	184.00	184.00	184.00
Extra water (kg)	10.25	16.71	26.40	42.56
Natural sand (kg)	865.59	865.59	865.59	865.59
Natural coarse aggregate (kg)	768.00	614.40	384.00	0.00
Recycled coarse aggregate (kg)	0.00	140.40	351.00	702.00
Maximum packing fraction of granular skeleton	0.70	0.71	0.72	0.73
Effective w/c	0.46	0.46	0.46	0.46
Superplasticiser/(c+f) (%)	0.60	0.60	0.60	0.60
w/(c+f)	0.32	0.32	0.32	0.32

Each baseline mix (0%, 20%, 50% and 100%) was modified using two levels of water (±W: -3%, +3%), two levels of superplasticiser (±S: -5%, +5%) and two levels of cement (±C: -3%, +3%). These percentages were selected to be representative of possible deviations in industrial production and taking into account tolerances for materials weighing established by Eurocode standard.

3.2 Test methods

Four industrial tests were selected to study the key properties of the self-compacting behaviour (filling ability, passing ability and resistance to segregation). These were: the slump flow test (EN 12350-8), the L-box test (EN 12350-10), the J-Ring test (EN 12350-12) and the sieve segregation test (EN 12350-11). In parallel, two different tests were carried out with the ICAR rheometer: a stress growth test and a flow curve test. All mixes (baseline and modified) were tested using both industrial and rheological tests developed at 15 and 45 min after the initial contact between water and cement. The sieve segregation test was developed at the end of the mixing period placing concrete into a bucket and allowing it to settle over 15 min.

3.3 Calculation of sensitivity parameters

The sensitivity parameters of each concrete are calculated as the amplitude of variation of each tested property regarding the baseline value (in percentage) (Figure 1). The amplitude of variation is calculated as the distance between both the increase and the decrease of different parameters, (yield stress, plastic viscosity and industrial parameters) obtained with the modified mixes (±W, ±S and ±C).

The analysis is focused on the sensitivity parameters obtained with the static yield stress, plastic viscosity and industrial results at a mix age of 15 and 45 min.

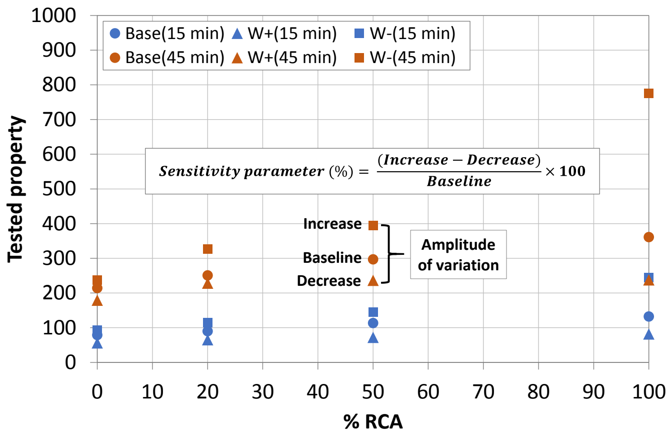

Figure 1. Calculation of sensitivity parameters (example with water changes)

Regarding sensitivity parameters of static yield stress and plastic viscosity, they were calculated as the average of those at 15 and 45 min. Concerning the ones determined with the industrial tests, the average of those obtained with SF, t500, PL, t500J, SFJ and SR values at 15 and 45 min was determined.

4 EXPERIMENTAL RESULTS

4.1 Baseline mixes. Baseline values

Figure 2 to Figure 5 show the results of the baseline values for each rheological and industrial parameter of each SCRC mix at 15 and 45 min. In general terms, as the replacement percentage increases, all parameters are negatively affected, but for the sieve segregation index.

The static yield stress increases as a function of the replacement percentage, being this increase of 67% in the case of 100% SCRC. This increase seems to follow a linear trend (Figure 2). The plastic viscosity also slightly increases up to 50% replacement ratio (increase of 7%). From 50% to 100% replacement ratios, this increase is more noticeable (88%) (Figure 2).

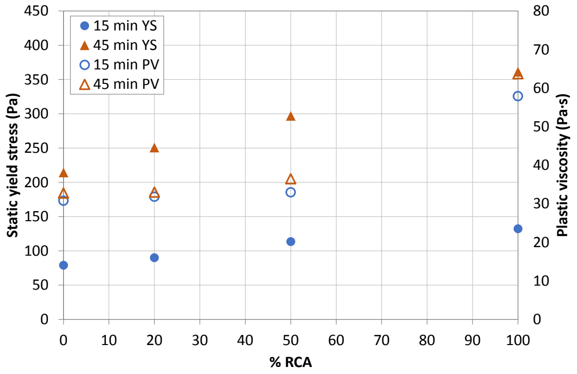

Figure 2. Results of static yield stress (YS) and plastic viscosity (PV)

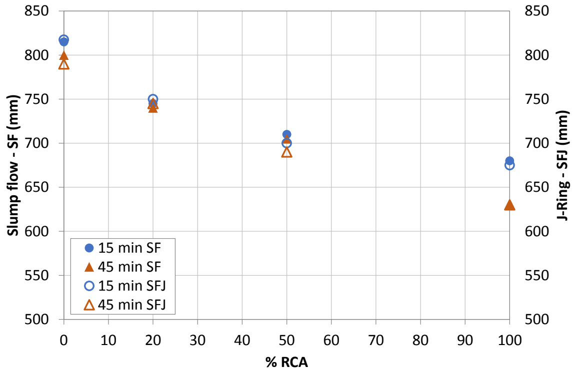

Figure 3. Results of slump flow and J-Ring diameters

Regarding the industrial tests, results of diameter (SF) and time (t500) in the slump flow test show a decrease or increase, respectively, as a function of the replacement percentage (Figure 3 and Figure 4). The passing ability measured with the L-box test (Figure 5) shows quite similar values among all studied concretes, between 0.8 and 0.9.

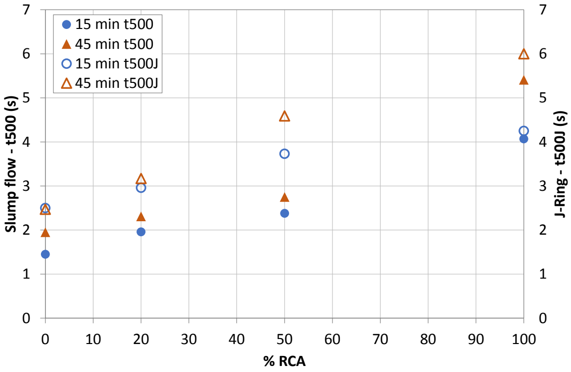

Figure 4. Results of slump flow and J-Ring times

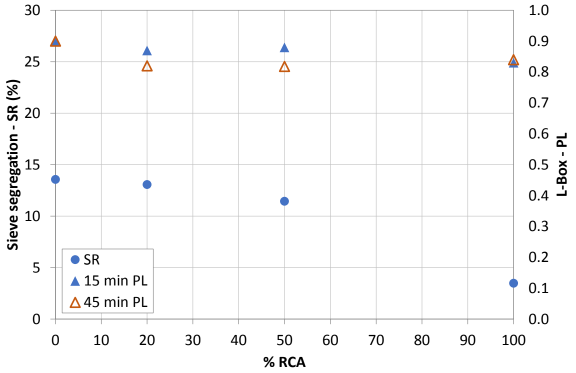

Figure 5. Results of sieve segregation and L-box tests

In the case of J-Ring test, the time and the diameter (Figure 3 and Figure 4) show a similar trend to that described with the parameters of slump flow test. Lastly, Figure 5 shows the results of sieve segregation test. This industrial parameter decreases when the replacement percentage increases. This means that self-compacting recycled concretes present lower tendency to segregation than conventional ones.

4.2 Values of sensitivity parameters

In Figure 6, Figure 7 and Figure 8, the sensitivity parameters for each concrete when water, superplasticiser and cement were modified are shown. In all cases, the values of sensitivity parameters increase as the replacement percentage increases. Therefore, mixes with low replacement ratios are more robust (they present lower sensitivity parameters) than those produced with high substitution percentages.

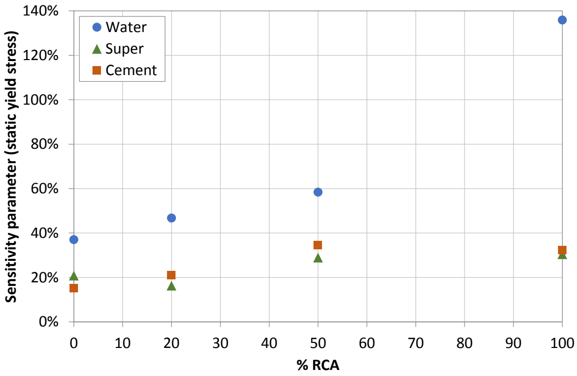

Figure 6. Sensitivity parameters of static yield stress

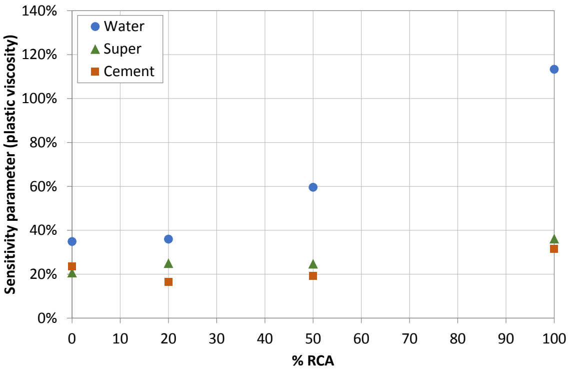

Figure 7. Sensitivity parameters of plastic viscosity

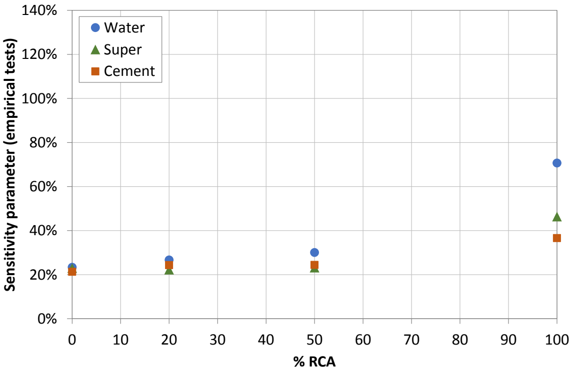

Figure 8. Sensitivity parameters of industrial tests

Up to 20% recycled aggregate, the sensitivity parameters are similar to those obtained with the reference concrete (0% recycled aggregate), independently of the tested property and the material variation. In general, this trend is maintained up to 50% replacement percentage when variations in cement or superplasticiser are considered.

In any case, the 100% replacement percentage shows higher sensitivity parameters than those of the reference concrete, also independently of the tested property and the material change.

The rheological tests provide the greatest sensitivity parameters, indicating that these tests are more adequate than the industrial tests to measure concrete robustness. Moreover, in agreement with the literature, changes in water provide the highest sensitivity parameters, higher than those obtained with superplasticiser or cement changes.

5 ANALYSIS AND DISCUSSION

5.1. Factors affecting SCRC rheology and robustness

Authors state that rheology of fluid concrete can be seen as resulting from the rheology of the cement matrix amplified by the presence of rigid aggregates [25, 26]. The factors at the origin of the specific SCRC rheology and robustness can therefore be divided into two categories: factors affecting the solid phase (aggregates) and factors affecting the fluid phase (cement matrix).

5.1.1 Factors affecting cement matrix

The cement particles represent the solid phase in cement matrix [27]. In this case, the quantity and the characteristics of these particles are the factors that affect cement matrix rheology. The cement quantity is considered with the solid volume fraction (Ø). The cement particles characteristics are considered with the maximum packing fraction ($Ø_{max}$), which depends on their fineness and morphology (shape and texture). To study rheology, it is usual to analyse the relationship between the rheological parameters and the $Ø/Ø_{max}$ ratio (Figure 9).

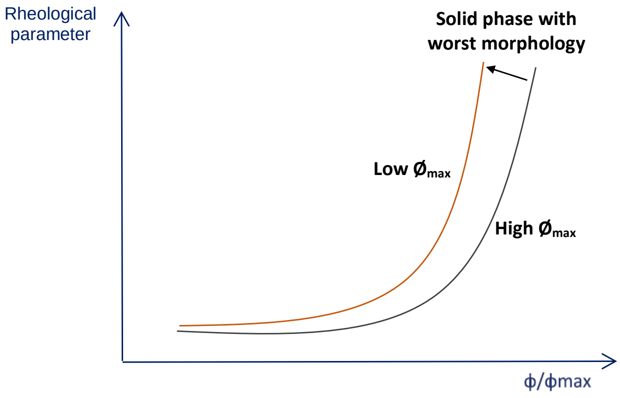

Figure 9. Rheological parameter – $Ø/Ø_{max}$

An irregular shape decrease the $Ø_{max}$ value and change the “Rheological parameter - $Ø/Ø_{max}$” curve at a constant value of Ø, increasing its slope (Figure 9). However, in this work, the same type of cement was used to produce all concrete mixes, so cement nature and particle size distribution is not a factor that explains the differences in the rheological behaviour of recycled and conventional concretes.

5.1.2 Factors affecting solid phase

The solid phase in concrete is represented by aggregates. The main factor affecting concrete rheology related to the solid phase is the aggregate morphology (measured throughout the maximum packing fraction) [28, 29].

Aggregates with irregular shape and rough texture lead to a lower maximum packing fraction changing the "Rheological parameter - $\emptyset/\emptyset_{max}$" curve in a similar way as it is changed in the cement matrix (Figure 9).

The recycled aggregates overall shape is very similar to that of the natural aggregate used in this study. Moreover, the recycled aggregate has different texture, it is rougher than the natural one. In this work, despite the above potential differences, they present a quite similar maximum packing fraction (Table 2). In fact, the maximum packing fraction is even slightly higher in the recycled aggregate than in the natural aggregate. So, in this work, the differences in SCRC rheology are not coming from this parameter.

However, the fines content of recycled aggregate is higher than the one of the natural aggregates used in this study (Table 1). These fines increase the water demand mainly due to their high absorption capacity. Moreover, their irregular shape and their rough texture are affecting the "Rheological parameter - $\emptyset/\emptyset_{max}$" curve (Figure 9). In addition, the adhered mortar on the RCA could potentially be ripped off during mixing, providing fines that can react with water and be hydrated, changing the cement matrix composition of the studied concretes [30-32].

Hence, these factors will influence on the SCRC rheological behaviour and, then, self-compacting recycled concrete will show curves with higher slope than the ones of conventional self-compacting concrete and this slope will increase with the increase in the replacement percentage (Figure 10).

Due to the high slope of the curves, material changes in recycled concretes lead to higher changes in rheology (Figure 10). When these changes significantly move the recycled mixes through the high slope region of their high slope curves, they produce significant increases in the rheological parameters and then, significant growth in the sensitivity parameters. This effect is clear when high replacement percentages are used and it is the cause of the low robustness of self-compacting recycled concrete with high content of recycled aggregate.

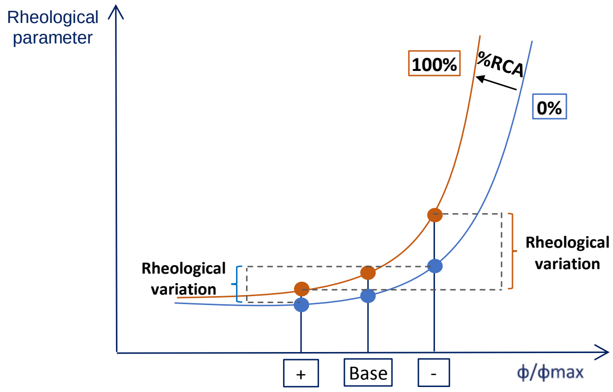

Figure 10. Rheological parameter – $\emptyset/\emptyset_{max}$

5.2 Sensitivity parameters

5.2.1 Water dosage variations

As seen, variations in water provide the highest values of the sensitivity parameters (higher than those obtained with superplasticiser or cement changes).

More water involves an increase in the w/c ratio and also a decrease in the solid volume fraction, Ø. On the contrary, less water involves a decrease in the first parameter and an increase in the second one. It can be seen that an increase in water will not affect the fresh parameter to the same extent as a decrease. In the first case, changes will move the mix towards the slight slope region of the curves, while, in the second one, they will move it towards the high slope region of them (Figure 11 and Figure 12).

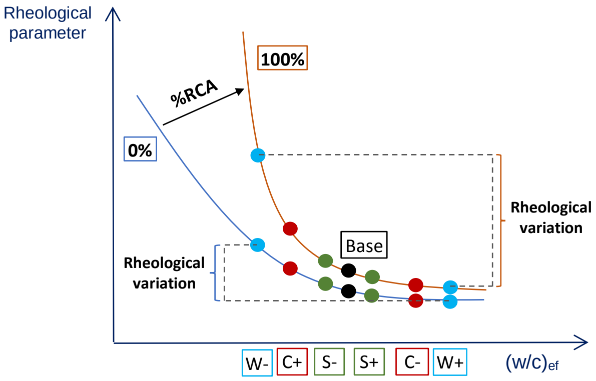

Figure 11. Rheological parameter vs. (w/c)$_{ef}$. Influence of materials changes

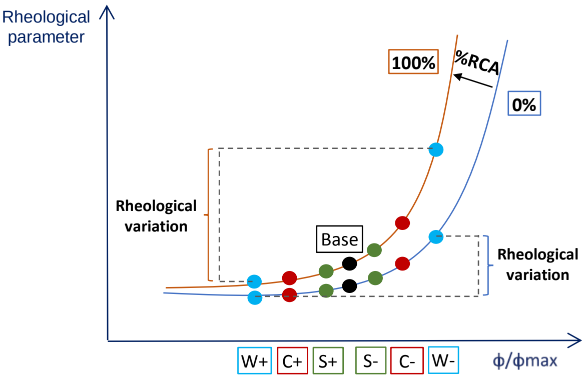

Figure 12. Rheological parameter vs. $\emptyset/\emptyset_{max}$. Influence of materials changes

Moreover, in recycled concrete, the water content decreases because of the evolution of the water absorption of recycled aggregate. The evolution of the non-compensated water absorption in the mixing protocol implies that the effective water content is higher in conventional than in recycled concrete. This is significant when the testing time is far from that used to compensate the recycled aggregate absorption. In this case, the baseline value in recycled concretes will be moved towards the high slope of the rheological curves. So, this effect implies that the material changes will lead to high rheological variations.

5.2.2 Cement dosage variations

Figure 6, Figure 7 and Figure 8 also show the results of the cement amount variations, which follow the same trend as those obtained with the water variations. However, water changes influence the SCRC behaviour to a greater extent than cement changes. This is due to the different effect in (w/c)$_{ef}$ and in $\emptyset/\emptyset_{max}$ that water and cement variations produce. In the first case (water), both effects are additive and in the second one (cement), they counteract leading to influence rheological values to a less extent (Figure 11 and Figure 12).

When water decreases, $(w/c)_{ef}$ decreases and $\text{Ø}/\text{Ø}_{max}$ increases (there is less paste volume and the solid volume fraction increases). Both effects lead rheological values to increase. However, when cement increases, $(w/c)_{ef}$ decreases and $\text{Ø}/\text{Ø}_{max}$ decreases (there is more paste volume and the solid volume fraction decreases). Both effects counteract and finally rheological values increase although to a lesser extent. In the same way, when water increases, the effects in both $(w/c)_{ef}$ and $\text{Ø}/\text{Ø}_{max}$ lead rheological values to increase. However, when cement decreases, the effects in $(w/c)_{ef}$ and $\text{Ø}/\text{Ø}_{max}$ counteract and, again, rheological values decrease although to a lesser extent.

Therefore, the sensitivity parameters obtained with cement variations are lower than those obtained with water changes.

5.2.3 Superplasticiser dosage variations

Regarding the changes in superplasticiser dosage, in Figure 6, Figure 7 and Figure 8, it can be seen that these modify fresh behaviour parameters to a lesser extent than water changes. In fact, the variations in superplasticiser imply very little volumetric quantities (5% superplasticiser variation approximately implies 0.05% $\text{Ø}/\text{Ø}_{max}$ variation) and, therefore, these barely involve changes in the effective w/c ratio and they hardly alter the $\text{Ø}/\text{Ø}_{max}$ ratio (Figure 11 and Figure 12).

Moreover, the quantity of superplasticiser has been designed (in conventional self-compacting concrete) very close to the saturation point, where its changes lead to very low rheological parameter variations (Figure 13). However, in recycled concrete (due to the different water content because of the evolution of the water absorption), the percentage of superplasticiser will be further from the saturation point. That is why self-compacting recycled concretes with high replacement percentages show higher sensitivity parameters, evaluated with superplasticiser changes, than those obtained with conventional SCC.

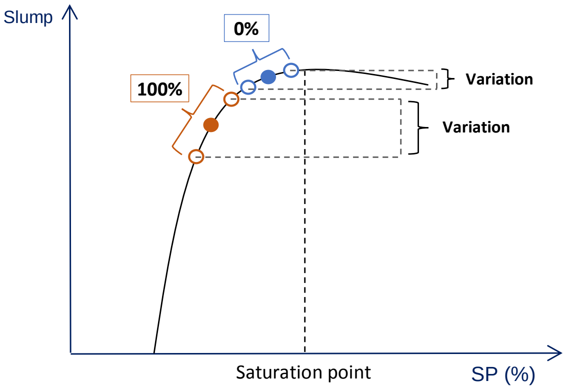

Figure 13. Slump vs. Superplasticiser (%) (0-100% RCA)

6. CONCLUSIONS

This work is focused on understanding the origin of the lower robustness detected in self-compacting recycled concretes and on identifying the parameters affecting this property to a greater extent. Based on the obtained results, the following conclusions can be drawn:

- Self-compacting recycled concrete is less robust than conventional self-compacting concrete. The factors at the origin of the specific SCRC rheology and robustness are:
  - The aggregate morphology (measured throughout the maximum packing fraction) and the fines content are the two main factors affecting SCRC rheology related to the solid phase. Aggregates with irregular shape and rough texture lead to a high maximum packing fraction changing the “Rheological parameter - $\emptyset/\emptyset_{max}$” curve.
  - The evolution of the non-compensated water absorption in the mixing protocol implies that the effective water content is lower in recycled concrete than in conventional one. The baseline value in recycled concretes will be moved (at longer times) towards the high slope of the rheological curves and then, this effect implies that the material changes will lead to high rheological variations.
- Changes in water provide the highest values of the sensitivity parameters (higher than those obtained with superplasticiser or cement changes), especially as the percentage of RCA

increases. This is due to the greater movement towards the high and the slight slope of the rheological curves that water changes imply.

Finally, it can be concluded that SCRC presents the "Rheological parameter – $\emptyset/\emptyset_{max}$" curves with higher slope than the ones of conventional SCC. Then, when high percentages of recycled coarse aggregate are used, and when long term self-compacting behaviour is required, there is a greater possibility to reach the high slope region of high slope curves causing high rheological changes.

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