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Analysis of rheological behaviour of self-compacting concrete made with recycled aggregates

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HIGHLIGHTS

- Rheological behaviour of self-compacting recycled concrete (SCRC) was analysed.
- A rheograph relating static yield stress and plastic viscosity was obtained.
- Different "rheological variations – $(w/c)_{ef}$" curves in a SCRC compared to a SCC were obtained.
- The intrinsic characteristics of recycled coarse aggregate and the effective water to cement ratio affect SCRC rheology.
- The singular parameters are the rough texture and the fines content and generated during mixing.

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ABSTRACT

This research focuses on studying the fresh state behaviour of self-compacting recycled concrete (SCRC) using rheology as a fundamental tool. For said purpose, a reference self-compacting concrete (SCC) was designed and it was modified to obtain other two SCCs with different water to cement ratios. Lastly, the natural coarse aggregate of each SCC was replaced with recycled aggregate using three different replacement percentages, 20%, 50% and 100% (by volume). At 15 min from the contact time of water with cement (reference time), two different tests were carried out with a rheometer: a stress growth test and a flow curve test.

The results show that the specificity of SCRC design lies in the quantity of extra water necessary to compensate the recycled aggregate absorption during the mixing protocol and in the intrinsic characteristics of this particular aggregate. Mainly the rough texture when both natural and recycled coarse aggregates are crushed-shaped and the fines content in the recycled aggregate and generated during mixing by the wear of old adhered mortar change the baseline mortar.

All these singularities lead to different "rheological variations – $(w/c)_{ef}$" curves in a SCRC compared to a SCC. The SCRC curves present higher slope than the SCC ones, so they predict higher rheological variations, especially when the w/c ratio is low.

1. Introduction

It is well known that one of the main differences between conventional concrete and recycled concrete (RC) is the high water absorption of the recycled aggregate (especially due to the adhered mortar) [1–3]. To control the high absorption of recycled aggregate, authors proposed two alternative mixing methodologies [4–8]. In one of them, the aggregate is added dry or with its natural moisture and an extra quantity of water, that necessary to compensate its absorption, is added. In the other methodology, it is added to the mix after being pre-soaked in water for a pre-established time period [9,10]. This aggregate property determines the effective water that influences the final properties of both fresh and hardened concrete and makes difficult to control fresh RC behaviour.

In recent years, some works [11–14] have been conducted aiming to clarify the potential use of recycled coarse aggregate in self-compacting concrete (SCC) production, developing then a new eco-friendly concrete, self- compacting recycled concrete (SCRC).

A well-designed SCC provides similar mechanical properties to its equivalent vibrated concrete. Hence, the fundamental difference between them is the fresh behaviour [15–17]. The literature

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discusses the need to describe flow behaviour of SCC in terms of fundamental physical quantities, then it is clear that, to do so, rheology is the logical tool.

Most of the limited studies about SCRC are specifically focused on basic mechanical properties and only verify the workability criteria [18–21]. There is a lack of knowledge on the rheological behaviour of SCRC, which needs a more in-depth analysis, especially taking into account both the particular characteristics of recycled aggregate and the particular flow behaviour of SCC.

Rheology enables the fresh-state characterization to be assessed through the measurements of rheological parameters in physical units [22–24]. Since the 1970s, the study of rheology of fresh-state concrete has progressed significantly with an increasing use of rheometers. The objective of using rheology measurements is to provide scientific parameters that are comparable and capable of describing multiple aspects of workability even when different devices are used. Three of the key concrete properties that can be measured in a single rheological test (static yield stress, dynamic yield stress and plastic viscosity) [25] would lead to characterize its fresh behaviour as a fluid.

2. Research significance

In hardened-state, SCRC is expected to present properties similar to those of its equivalent vibrated recycled concrete and in fresh-state, is expected to show a greater influence of RC and SCC singularities. In this context, this research focuses on studying the rheological behaviour of self-compacting concrete incorporating recycled concrete coarse aggregate using rheology as a fundamental tool.

The innovation of the study is based on analysing self-compacting recycled concrete rheology considering concrete as a suspension where the aggregates are the solid phase and the mortar is the solvent. This procedure allows authors to detect which variables, different from those considered in SCC, have to be taken into account when SCRC rheology is studied.

Therefore, in recycled concrete, mortar is going to be affected by the recycled aggregate water absorption. So, an extra quantity of water to compensate this absorption was added in all SCRCs. On the other hand, the solid phase is going to be controlled by the intrinsic characteristics of recycled coarse aggregates. Then, they were selected with properties (in terms of overall shape, size and maximum packing fraction) as similar as possible to those of natural aggregates.

Taking these issues into consideration, self-compacting recycled and conventional concretes were designed and their rheological behaviour compared. Then, based on the Krieger-Dougherty equation, the differences measured were thoroughly explained and the main singular parameters and variables affecting SCRCs rheology were detected.

3. Materials and protocols

3.1. Materials and mixes

Portland cement without admixtures labelled CEM-I 52.5R according to European Standard EN 197-1 [26] and a limestone filler were used as powder fraction. A modified polycarboxylate superplasticiser was used.

Table 1 summarizes the basic properties of the aggregates used.

As fine aggregate (NFA – natural fine aggregate), a limestone sand with nominal size 0–4 mm and a fineness modulus of 4.19 was used. A crushed granitic coarse aggregate (NCA – natural coarse aggregate) with nominal size 4–11 mm and a fineness modulus of 7.14 was also used.

Table 1
Basic properties of aggregates.

Property	NFA	NCA	RCA
Fineness modulus (%)	4.19	7.14	6.47
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
Fines percentage (%)	8.40	0.84	3.00
Shape	Crushed	Crushed	Crushed

As recycled aggregate, the size fraction used was a 4–11 mm with a fineness modulus of 6.47.

The grading curves of recycled and natural coarse aggregate presented similar particle size distribution (Fig. 1).

This recycled coarse aggregate (RCA) was obtained from real demolition debris of structural concrete. Actually, according to EN 933-11 [27], it is made up mainly of concrete and stone (more than 90% of natural aggregate and aggregate with mortar) (Fig. 2). On the basis of this result, it can be classified as recycled coarse aggregate from concrete demolition waste and named as type II according to the RILEM specifications [28] or as Rcu_{95} according to EN 12620 [29].

Many researchers have studied the influence of natural aggregates on the rheological properties of fresh concrete. They conclude that knowledge of the solid volume fraction, maximum packing fraction ($Ø_{max}$), shape and particle size distribution is highly important [30].

Both natural and recycled aggregates are crushed aggregates. The shape of recycled coarse aggregate is very similar to that of natural coarse one (Fig. 3). The recycled aggregate may be considered as a sub-angular aggregate (evidence of some wear, but faces untouched) and the natural aggregate as an angular aggregate (little evidence of wear on the particle surface) [31]. Both can be defined as aggregates with low sphericity (Fig. 3).

Regarding surface texture, the recycled coarse aggregate is more porous and rougher than the natural one due to the adhered mortar (Fig. 4). It was also observed that the content of fines in the recycled coarse aggregate was higher than that of the natural coarse aggregate.

Moreover, in Fig. 5, the maximum packing fraction ($Ø_{max}$) of different granular skeletons (designed mixing the natural coarse and fine aggregate with the recycled one using different percentages) is plotted.

Although both recycled and natural coarse aggregates used are crushed aggregates, it is expected that the higher roughness of the former leads to a worse packing density (and, therefore, a worse maximum packing fraction). However, the results indicate that $Ø_{max}$ is quite similar in all mixes (Fig. 5), although a slight ascend-

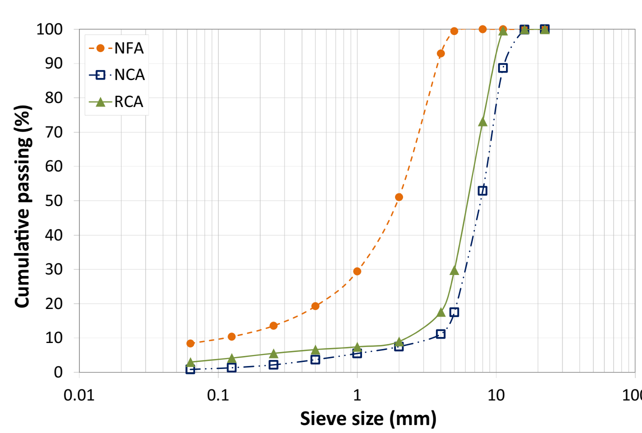

Fig. 1. Grading curves of aggregates.

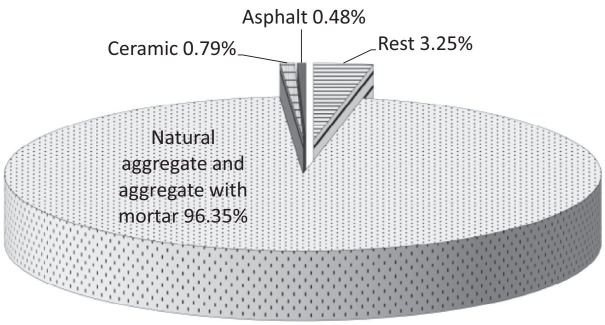

Fig. 2. RCA composition.

ing trend can be noted with the increase in percentage of recycled aggregate due to it is slightly less angular than natural aggregate.

So, in general terms, these similar packing properties can be explained by the fact that they are mostly influenced by processing and, in this research, both aggregates (natural and recycled) are crushed. Moreover, as structural self-compacting recycled concrete was designed in this study, the recycled concrete coarse aggregate used is a high quality recycled aggregate obtained from concrete waste with a low quantity of impurities (Fig. 2). Therefore, the grading curve and shape, variables that influence $Ø_{max}$, are very similar to those of natural coarse crushed aggregate.

When recycled aggregate is used, other important property that should be considered is its water absorption. Water absorption develops over time. Hence, EN 1097-6 [32] establishes that it should be measured after soaking aggregates in water for at least 24 h. In addition to this standard absorption test, in this work, continuous measurement of this property over time was conducted. The procedure consisted of measuring, by hydrostatic weighing, the mass variations of a sample immersed into a thermo regulated bath.

The aggregate sample was dried in an oven at a temperature of 110 ± 5 °C until the difference in mass was less than 0.1%. After drying, the sample was placed in a perforated basket (stainless steel density basket for hydrostatic weighing of 250 × 250 × 250 mm in dimension and with a perforated mesh of 5 mm) which was hung from a balance using a non-elastic wire.

Firstly, the mass of the system was continuously recorded and this recorded value was the mass of oven-dry aggregate sample in air with a balance accuracy of 0.1 g. Then, the thermo regulated bath was moved vertically using a removable tray in order to immerse the sample into the water bath at 20 °C, assuming that the first value recorded after soaking was the mass of the oven-dry aggregate sample in water.

The results show that, at the usual reference time of 10 min [33], recycled coarse aggregate absorbs water to up to 80% of that absorbed at 24 h (Fig. 6).

A reference self-compacting concrete with a water to cement ratio of 0.460 was designed (Table 2). Then it was modified to obtain other two SCCs with different water to cement ratios (the water was increased or decreased a 3%). Therefore, three SCCs were produced: one with a water to cement ratio of 0.447 (w/c −), other with 0.460 (w/c) and the other with 0.473 (w/c +). Finally, the natural coarse aggregate of each SCC was replaced with recycled one using three different replacement percentages, 20%, 50% and 100% (by volume).

In order to control the high absorption of recycled aggregate, it was added dry and its absorption was compensated with additional water. The extra quantity of water was added during mixing and it was calculated to compensate the recycled aggregate absorption at 10 min (i.e. 80% of that at 24 h) (Fig. 6).

3.2. Test protocols and measurements

3.2.1. Concrete rheological measurements

Batches of 100 litres were produced for each concrete. Firstly, the aggregates (sand and coarse aggregates) were mixed with the extra water (that calculated to compensate the recycled aggregate absorption at 10 min) for 2 min and then left to rest for another 8 min. The cement was added along with the filler after the first 10 min. 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. Then the concrete was poured into the rheometer and into different buckets. It was left there to rest until its testing age.

At 15 min from the contact time of water with cement (reference time), two different tests were carried out with the rheometer: a stress growth test and a flow curve test. In this work, the stress growth test started as soon as the rheometer vane was immersed into the concrete (Figs. 7 and 8). The vane was rotated at a low and constant speed (0.025 rps).

After this test, the flow curve test started (Figs. 9 and 10). In this second test, after a period of 20 s at a constant speed of 0.50 rps, the torques at decreasing speeds (from 0.5 to 0.05 rps in seven steps) were measured. The stress growth test is used to determine the static yield stress, while the flow curve test is used to determine the plastic viscosity.

3.2.2. Equivalent mortar measurements

To analyse concrete rheology, different equations have been developed. One of the equations is the Krieger-Dougherty equation which considers that the viscosity of a suspension can be calculated as follows (Eq. (1)):

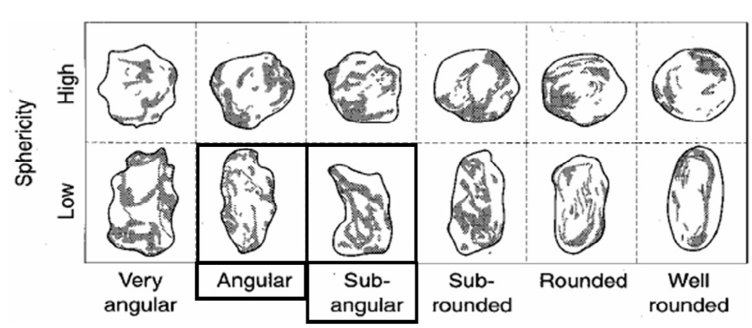

Fig. 3. Shape of coarse aggregates used [31].

Fig. 4. Natural (left) and recycled (right) coarse aggregates.

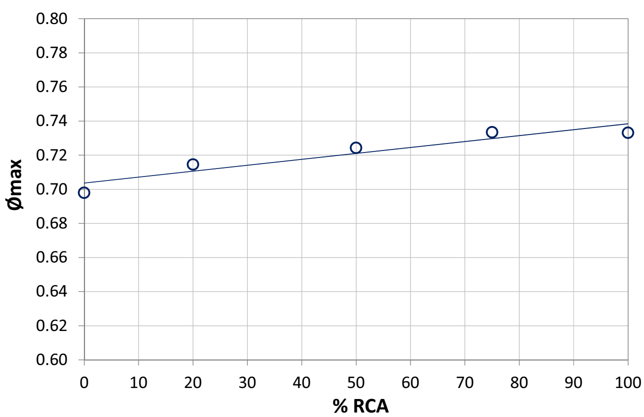

Fig. 5. Maximum packing fraction ($Ø_{max}$) of different granular skeletons.

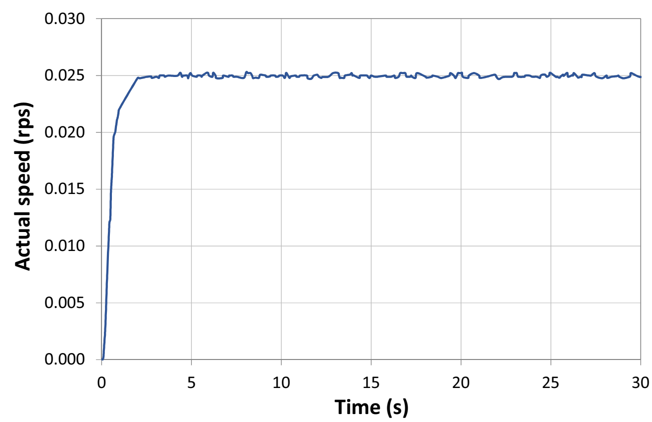

Fig. 7. Speed vs. Time. Stress growth test.

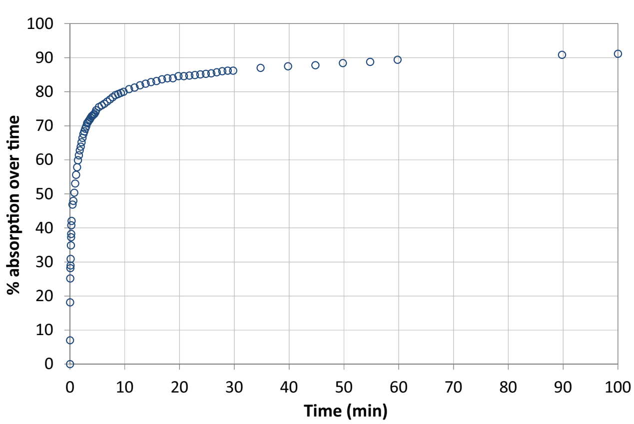

Fig. 6. RCA water absorption evolution from 0 to 100 min.

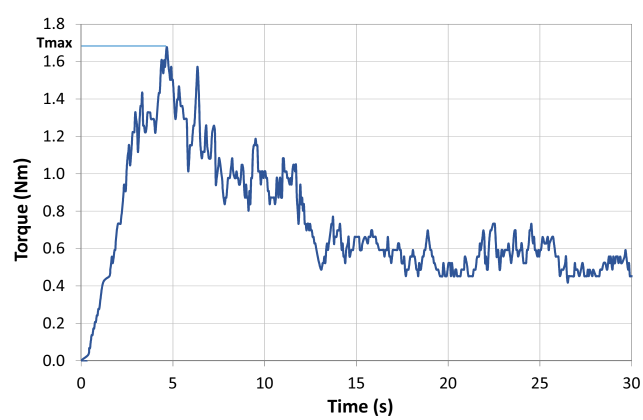

Fig. 8. Torque vs. Time. Stress growth test.

Table 2
Mix proportions of reference concrete (1 m^3).

Dosage	w/c
Cement, c (kg)	400.00
Filler, f (kg)	180.00
Water, w (kg)	184.00
Natural sand (kg)	865.59
Natural coarse aggregate (kg)	768.00
Effective w/c	0.460
Superplasticiser/(c + f) (%)	1.70

$$\mu = \mu_s \left(1 - \frac{\varnothing}{\varnothing_{max}}\right)^{-[\mu]\varnothing_{max}} \tag{1}$$

where:

μ is the viscosity of the suspension (solid phase and solvent)
μ_s is the viscosity of the solvent
$[\mu]$ is referred to as the intrinsic viscosity of the solid phase
$Ø_{max}$ is the maximum packing fraction

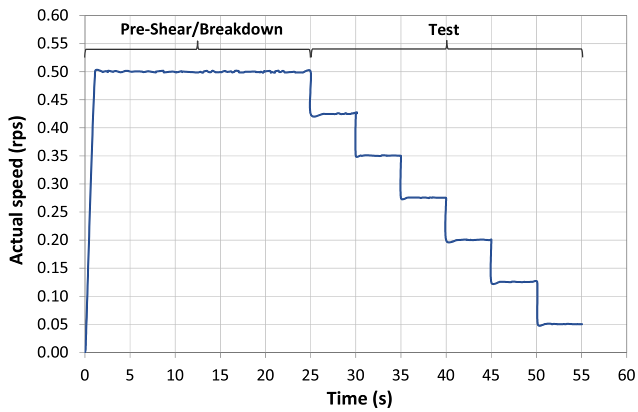

Fig. 9. Speed vs. Time. Flow curve test.

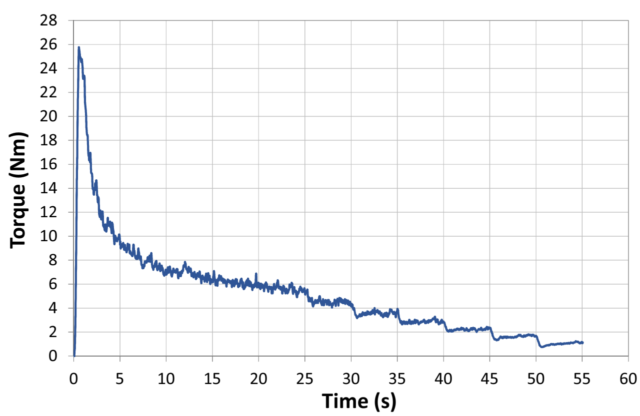

Fig. 10. Torque vs. Time. Flow curve test.

Ø is the solid volume concentration.

In the field of concrete, this means that concrete can be considered as a suspension of coarse aggregates (solid phase) in mortar (solvent). So, concrete viscosity depends on the viscosity of the solvent (mortar), on the intrinsic viscosity of aggregates (that depends on their shape, texture and grading), and on the "solid volume fraction - maximum packing fraction" function (that depends on the solid content and on the shape, texture and grading of aggregates).

Regarding yield stress, based on an analogy with the Krieger-Dougherty equation, the yield stress of concrete can be considered proportional to the yield stress of mortar (Eq. (2)) [30,34].

$$\tau_{0,c} \propto \tau_{0,m} \cdot f\left(\frac{\varnothing}{\varnothing_{max}}\right) \tag{2}$$

Being:

$\tau_{0,c}$ is the yield stress of concrete
$\tau_{0,p}$ is the yield stress of the paste
$\tau_{0,m}$ is the yield stress of the mortar
Ø is the solid volume fraction
$Ø_{max}$ is the maximum packing fraction

Accordingly, in order to analyse the effect of the w/c ratio on SCRC rheology, at a first working stage only the mortar phase was studied. In the designed concretes, the volume of the equivalent mortars was 700 l and they were made with a filler to cement mass ratio of 0.45 (Table 2). At this stage, four mortars were made with different water to cement ratios (0.5, 0.45, 0.43 and 0.40).

The mini-slump flow of the mortars was measured and then turned into yield stress. For high slump or high spread values, Roussel et al. [35] proposed the following relationship (Eq. (3)) to calculate the yield stress as a function of the mini-slump flow results:

$$\tau_{0,m} \propto \frac{1}{SF_m^5} \tag{3}$$

Being:

SF_m is the slump flow of the mortar (valued using mini slump flow test).

The results obtained with the equivalent mortars will be used to analyse the concrete behaviour.

4. Results

4.1. Rheological results

Some authors suggest the use of rheograhs to further understand concrete workability and rheology. A rheograph is a "plastic viscosity – yield stress" diagram established in order to reveal in a systematic way the effects of diverse changes in the constituents on the rheological behaviour of the cement-based suspension (e.g. concrete, mortar and cement paste) [36].

Therefore, a rheograph relating static yield stress and plastic viscosity is plotted to evaluate the influence of the incorporation of recycled concrete coarse aggregate on the rheological behaviour of SCRC (Fig. 11).

The increase in the recycled coarse aggregate content (% RCA) results in an increase in rheological values, i.e. both static yield stress and plastic viscosity.

At 15 min (Fig. 11), as the replacement percentage increases, the yield stress and the plastic viscosity also increase, especially for the highest replacement ratio (100% RCA). Moreover, in general, it can be seen that the influence of recycled coarse aggregate is shown to be quite similar on both rheological parameters. Even so, the incorporation of recycled coarse aggregate up to 50% affects the static yield stress slightly more than the plastic viscosity. In the case of 100% RCA, both properties are affected to the same extent compared with those of conventional SCC (SCRC0).

The incorporation of recycled aggregate may imply some changes that can justify the increased values of the concrete rheological properties. On the one hand, the w/c ratio decreases

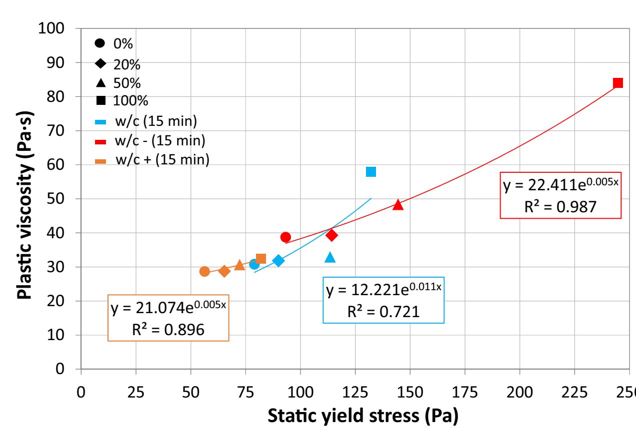

Fig. 11. Static yield stress vs. Plastic viscosity.

because of the evolution of water absorption of the recycled aggregate. On the other hand, the morphological characteristics of this type of aggregate are different from those of the conventional aggregate in different aspects.

4.2. Rheological variations

4.2.1. Mortar variations

According to the mini-slump flow results (Fig. 12) and Eq. (3), with multivariable regression, an expression was adjusted to predict the yield stress variation as a function of the w/c ratio. This is presented using as a reference a mortar with a water to cement ratio of 0.473 (“w/c +” in concrete mixes) (Eq. (4)) (Fig. 12).

$$\frac{\tau_{i,m}}{\tau_{ref,m}} = \left(\frac{SF_{ref,m}}{SF_{i,m}}\right)^5 \qquad (4)$$

It can be seen that high w/c ratios will not imply significant changes in yield stress, whereas at a low w/c ratio small variations can lead to large changes as also observed by other authors [37,38].

4.2.2. Concrete variations

The actual variations in static yield stress and plastic viscosity obtained with SCRCs are calculated (always using as a reference the value of the concrete with a water to cement ratio of 0.473, w/c +). These variations are represented in Figs. 13 and 14 respectively, as a function of the effective water to cement ratio at 15 min, which has been obtained taking into account the evolution of the non-compensated water absorption (Fig. 6).

The SCCs mixes show a tendency similar to the one of the curve adjusted with the mortars, which means that the mortar tested represents accurately the solvent of these mixes. However, as the replacement percentage increases, the yield stress variations are further from those of the reference concrete, concluding then, that the mortar tested does not represent accurately the solvent of the SCRCs (Fig. 13). The same tendency can be seen when plastic viscosity is analysed, especially in the case of the 100% replacement concrete (Fig. 14).

5. Discussion

To further understand the observed different tendency (Figs. 13 and 14), the following equation ((5)) (according to Eq. (1)), which relates concrete rheological variations with those of mortars, has to be considered:

$$\frac{(\mu_c)_{(w/c)_1}}{(\mu_c)_{(w/c)_2}} = \overbrace{\frac{(\mu_m)_{(w/c)_1}}{(\mu_m)_{(w/c)_2}}}^{\text{“Mortar factor”}} \; \overbrace{\left[\frac{1-\left(\frac{\varnothing}{\varnothing_{max}}\right)_{(w/c)_1}}{1-\left(\frac{\varnothing}{\varnothing_{max}}\right)_{(w/c)_2}}\right]^{-[\mu]\varnothing_{max}}}^{\varnothing/\varnothing_{max},[\mu],\varnothing_{max}=\text{“Solid phase factor” in concrete}} \qquad (5)$$

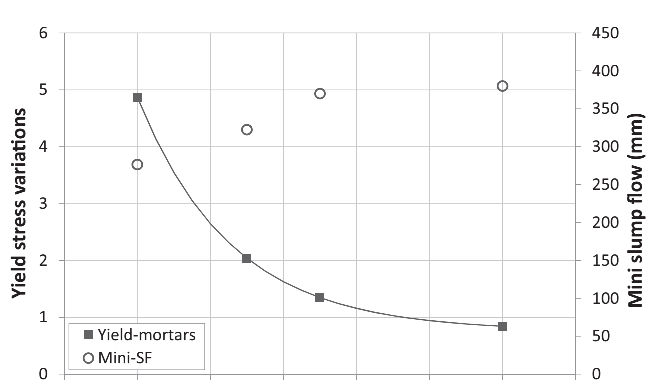

Fig. 12. Yield stress variations vs. w/c ratio (mortars).

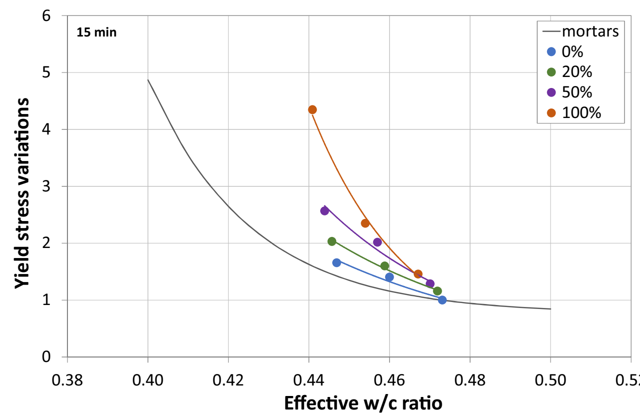

Fig. 13. Yield stress variations vs. $(w/c)_{ef.}$

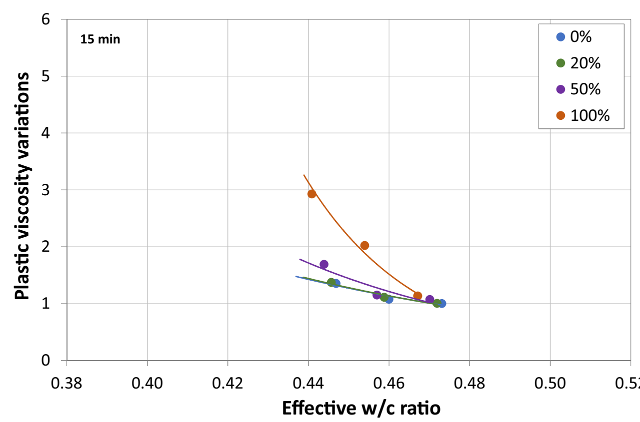

Fig. 14. Plastic viscosity variations vs. $(w/c)_{ef.}$

5.1. Regarding the mortar factor

The “mortar factor” can be studied as a “paste factor” amplified by a “solid phase factor” (Eq. (6)).

$$\frac{(\mu_m)_{(w/c)_1}}{(\mu_m)_{(w/c)_2}} = \frac{(\mu_p)_{(w/c)_1}}{(\mu_p)_{(w/c)_2}} \cdot \underbrace{\left[\frac{1-\left(\frac{\varnothing}{\varnothing_{max}}\right)_{(w/c)_1}}{1-\left(\frac{\varnothing}{\varnothing_{max}}\right)_{(w/c)_2}}\right]^{-[\mu]\cdot\varnothing_{max}}}_{} \qquad (6)$$

“Paste factor”
Water
Cement
Recycled fines with hydraulic activity

“Solid phase factor” in mortar
Sand + Fines of coarse aggregates and generated during mixing

The highest content of fines in recycled aggregate (Table 1) leads to more quantity of fines in SCRCs. These fine particles show a very irregular shape and a very rough texture affecting negatively the SCRC rheology. Moreover, during mixing, more fines are generated due to the loss of the old adhered mortar and some of them can even present hydraulic activity [39–41]. This effect is higher in concretes with low w/c ratio where the friction forces are greater, increasing, then, both the “paste factor” and the “solid phase factor” (Eq. (6)).

Both types of fines modify the characteristics of SCRCs solvent (mortar in concrete) and, therefore, the tested mortars are no longer representative of the mortar of SCRCs, especially in the case of the 100% replacement concrete.

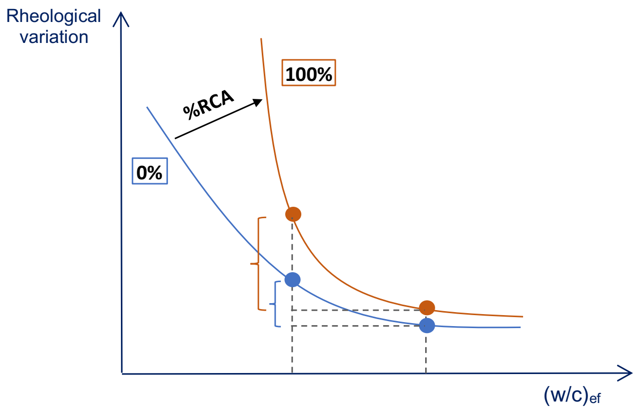

Fig. 15. Rheological variations vs. Effective w/c ratio (SCC vs. SCRC).

5.2. Regarding the solid phase factor in concrete

The maximum packing fraction, $Ø_{max}$, of the aggregate skeleton of SCRCs presents a slight tendency for increasing as the replacement percentage increases (Fig. 5).

The value of "$Ø/Ø_{max}$" is slightly different in the different mixes (due to the different Ø value used in the designed concretes). This makes $\frac{1-\left(\frac{Ø}{Ø max}\right)_{(w/c)_1}}{1-\left(\frac{Ø}{Ø max}\right)_{(w/c)_2}}$ of Eq. (5) slightly different from 1. In SCC mixes, this makes the yield stress variations slightly different from those obtained with the tested mortars (although very similar).

However, recycled aggregate is more porous and much rougher than the natural one due to the adhered cement paste. This fact is considered on the value of [μ], which is higher in recycled coarse aggregate than in the natural coarse aggregate. As $Ø_{max}$ is similar in natural and recycled aggregates, then the value of "$[\mu]\cdot Ø_{max}$" is going to be higher in self-compacting recycled concretes. This makes the "solid phase factor" higher in SCRC than in SCC. Therefore, the "mortar factor" is amplified by a "solid phase factor" that is higher in SCRCs (Eq. (5)).

Therefore, it is expected that the "rheological variations – $(w/c)_{ef}$" curves of a SCRC compared to a SCC are going to be different. For the same w/c variation, these curves predict higher rheological variations in SCRC, especially when the w/c ratio is low, due to the fact that changes are taking place in the high slope region of a high slope curve (Fig. 15).

6. Conclusions

The analysis of rheological behaviour showed that the specificity of SCRC lies in the intrinsic characteristics of recycled coarse aggregate (shape, texture and fines content) and in the quantity of extra water necessary to compensate for the recycled aggregate absorption during the mixing protocol, which affects the effective water to cement ratio.

Mainly the rough texture when both natural and recycled coarse aggregates are crushed-shaped and the fines content in the recycled aggregate and generated during mixing by the wear of old adhered mortar change the baseline mortar.

All these singularities lead to different "rheological variations – $(w/c)_{ef}$" curves in a SCRC compared to a SCC. The SCRC curves present higher slope than the SCC ones, so they predict higher rheological variations, especially when the w/c ratio is low, because changes are going to take place in a high slope region of a high slope curve.

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