THIXOTROPY AND INTERLAYER BOND STRENGTH OF SELF-COMPACTING RECYCLED CONCRETE

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Abstract

This work is focused on assessing the thixotropy of self-compacting recycled concrete (SCRC) and on evaluating the interlayer bond strength. To do so, four SCRC mixes with 0%, 20%, 50%, and 100% of recycled coarse aggregate (by volume) were studied. This aggregate was used in dry-state conditions and an extra quantity of water was added during mixing in order to compensate its absorption.

Three testing methods were used to assess the degree of thixotropy of SCRC: structural breakdown curves at various rotational speeds, hysteresis loop flow curves and yield stress at rest. To evaluate the effect of the structural build-up at rest on SCRC interlayer bond strength, two methods were used: flexural tests and water permeability tests.

The results indicate that the increase of thixotropy and interlayer bond strength with the replacement percentage is due to the difference in the effective w/c ratio, result of the non–compensated water absorption, to the higher amount of fines in the recycled aggregates and generated from the old adhered mortar and also to the higher internal friction of recycled aggregates. Moreover, as water absorption is compensated in the mixing protocol, changes over time in the effective w/c ratio are negligible. Therefore, the thixotropic changing rate is similar in all studied mixes.

Keywords: self-compacting concrete; recycled coarse aggregate; thixotropy; bond strength; interlayer.

1 INTRODUCTION AND OBJECTIVES

Thixotropy is by definition a time-dependent, isothermal and reversible process [1, 2]. When a cementitious suspension is sheared, its network structure is broken into smaller agglomerates and, with continued shearing, eventually there is an equilibrium state in which the agglomerates cannot be broken down into smaller fragments. When the suspension is at rest, the particles can form weak physical bonds and agglomerate into a network [3].

In this way, when a fresh concrete is subjected to deformation (shearing), thixotropy describes the reversible and time-dependent reduction of its viscosity, which is caused by the build-up of a structure in fresh concrete at rest [4]. This structure, which provides an initial resistance to deformation, is destroyed once sufficient deformation is applied to the concrete [5]. This means that the physical structure building up with time in the material at rest can be broken down and that the steady-state rheology characterising the material before rest can be regained [6]. In the absence of shear during rest, the damaged structure rebuilds. The physical origin of this rebuilding might find its foundations in the Brownian motion that could induce a slow rearrangement of the particle configuration or in an evolution of the colloidal interactions between particles [7, 8].

For cementitious materials, however, an irreversible chemical reaction is also under way from the moment the cement is intermixed with water. In practical terms, this appears as a loss in slump over time [1]. Then, the structural build-up phase of cementitious materials is a function of both the reversible structural changes from the thixotropic phenomena and the irreversible structural changes due to hydration mechanisms and the resulting microstructure [3]. The thixotropic properties of cement pastes that are measured macroscopically are strongly dependent on microstructural considerations [9].

The apparent viscosity of the material is permanently evolving [10]. Over short timescales, flocculation and de-flocculation processes dominate, which lead to rapid thixotropic (reversible) effects, while over larger timescales, hydration processes dominate, which lead to irreversible evolutions of the behaviour of the fluid. These two effects might in fact act at any time. As a consequence of this, it is reasonable to consider that there is an intermediate period, at about a couple thousand seconds, in which irreversible effects have not yet become significant. This means that it seems possible to model thixotropy and only thixotropy during short periods of time (not more than 30 min as an order of magnitude) during which the irreversible evolutions of the concrete can be neglected [11].

Thixotropy is strongly dependent on the composition of the mixture: cement characteristics, chemical admixtures, supplementary cementitious materials and water to cement (w/c) ratio are parameters that affect the thixotropic phenomenon. In addition, external parameters such as mixing and vibration influence thixotropy [9].

The total amount of powders in the mixture, as the particles contained in these various powders are the only particles at the origin of thixotropy in SCC [12]. It is accepted that thixotropy should increase when powder content increases.

The weight ratio between water and powders affects the average distance between cement (or other alternative powders) particles and thus their mutual interactions. Thixotropy should increase when water to powder ratio decreases. It should also increase with the specific surface of the powders. The fineness of powders affects the structuration rate as the amplitudes of Brownian and colloidal effects increase when particle size decreases [13]. Then, a lower water to cement ratio and a higher content of powder (i.e. content of fines) implies a higher degree of thixotropy.

Regarding coarse aggregates, their effect in thixotropy will be more related to their volume concentration, i.e. the amount of granular skeleton (sand and gravel) in mixture. In fact, both the sand-to-total aggregate ratio and the volumetric ratio of the paste-to-coarse aggregate were found to affect thixotropy due to the increase of the degree of internal friction resulting from greater coarse aggregate content. The aggregate-to-aggregate contact, that induces greater degree of internal friction within the mixture, will increase the shear stresses necessary to break down the material. The decrease of paste volume or increase of coarse aggregate volume can lead to higher thixotropy [14].

Moreover, Mahaut et al. [15] considered (Eq. 1) that if the mechanical impact of the coarse particles is to increase the yield stress by a factor f(Ø), then their impact on the structuration rate of the paste is to also increase it by a factor f(Ø). It is thus sufficient to measure the cement paste yield stress evolution in time (i.e. A_{thix}) and to measure the increase of the yield stress with the volume fraction (i.e. f(Ø)) for a single resting time to infer the A_{thix}·f(Ø) value of the structuration rate of the suspension (and more generally of fresh concrete).

$$\tau_c\,(\emptyset, t) = \tau_c\,(0) \cdot f(\emptyset) + A_{thix} \cdot f(\emptyset) \cdot t$$

(1)

τ_c is the yield stress of concrete

Ø is the solid volume fraction

t is the elapsed time

A_{thix} is the structuration rate of the paste

Mahaut et al. [15] concluded that it is sufficient to know how the interstitial cement paste evolves in time to predict the suspension evolution at rest (suspension of coarse particles in a cement paste). This is important for fresh concrete as its behaviour is hard to measure. Their results showed that the knowledge of the cement paste structuration rate at rest (A_{thix}) is sufficient to predict the fresh concrete structuration rate.

Lastly, it can be concluded that thixotropy is of particular interest to users of SCC, as it may provide another link into predicting its flow behaviour [16]. The rheological behaviour of concrete is related to this network structure and the rate at which it can form. Thixotropy, which is manifested in the difference between static and dynamic yield stress or in the breakdown area between upward and downward rheometer flow curves, contributes by increasing segregation resistance and reducing formwork pressures. Too much thixotropy, however, reduces placeability and can affect interlayer bond strength [5, 17].

In this work, self-compacting recycled concrete (SCRC) is defined as a self-compacting concrete made with recycled concrete coarse aggregate. This concrete has not been suitably researched yet. Most of studies focus on workability and strength characteristics [18, 19] and recent works have also studied some SCRC rheological properties [20-23]. The effective water to cement ratio of SCRC evolves over time according to the evolution of the recycled aggregate water absorption. It is expected that the time-dependent rheological behaviour of a SCRC will be different from a conventional SCC, especially when water absorption is not compensated, when high percentages of recycled aggregate are used, when SCRC is designed with a lower w/c ratio and/or when long term self-compacting behaviour is measured [24]. However, there is still a gap in the knowledge about how recycled aggregate can influence on thixotropy of a self-compacting concrete and on the possible risk of the development of cold joints between successive layers of SCRC.

Therefore, the first objective was to analyse the degree of thixotropy developed in SCRC mixes according to the following methods: structural breakdown curves at various rotational speeds (steady state approach), hysteresis loop flow curves and yield stress at rest (also referred to as static yield stress and shear-growth yield stress).

Moreover, the structural build-up developed after a certain period of rest (due to thixotropy) can affect interlayer bond strength in SCRC. Then, the second objective was to evaluate the effect of the structural build-up at rest on interlayer bond strength in SCRC throughout the following two methods: interlayer bond strength using flexural tests and interlayer bond strength using water permeability tests.

2 EXPERIMENTAL PROCEDURE

2.1 Materials and concretes

Regarding materials, a Portland cement and a limestone filler were used as powder fraction. The Portland cement, CEM-I 52.5-R, showed a density of 3.11 t/m^3, a specific surface (BET) of 1.02 m^2/g, an initial setting time of 190 min and a final setting time of 260 min. The physical properties of the limestone filler were a density of 2.71 t/m^3, loss on ignition (1000 ^{o}C) of 41.8% and a specific surface (BET) of 1.77 m^2/g. The chemical composition of both materials is shown in Table 1.

Table 1. XRF analysis of cement and limestone filler

Oxide/Element	% mass (Cement)	% mass (Limestone 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

Oxide/Element	% mass (Cement)	% mass (Limestone filler)
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	-

A modified polycarboxylate was used as superplasticiser. A limestone sand was used as natural fine aggregate (NFA) and two types of coarse aggregates, natural (NCA) and recycled (RCA), were used. The recycled aggregate was obtained from real demolition debris of structural concrete. It was made up mainly of concrete and stone. Table 2 shows the basic properties of all aggregates.

Table 2. Basic properties of aggregates

Property	NFA	NCA	RCA
Fineness modulus (EN 933-1)	4.19	7.14	6.47
Fines percentage (EN 933-1) (%)	8.40	0.84	3.00
Saturated-surface-dry density (EN 1097-6) (kg/m^3)	2720	2560	2340
Water absorption (EN 1097-6) (%)	1.00	1.12	6.96
Flakiness index (EN 933-3) (%)	-	5.41	5.33
Shape	Crushed	Crushed	Crushed

Four concretes were studied, a reference concrete and three recycled concretes (Table 3). The replacement percentages of natural by recycled coarse aggregate were 20%, 50% and 100% (by volume).

Table 3. Mix proportions of concretes (1 m³)

Dosage	% RCA			
	0%	20%	50%	100%
Cement, c (kg)	400.00	400.00	400.00	400.00
Filler, f (kg)	180.00	180.00	180.00	180.00
Water, w (kg)	196.00	196.00	196.00	196.00
NFA (kg)	832.76	832.76	832.76	832.76
NCA (kg)	768.00	614.40	384.00	0.00
RCA (kg)	0.00	140.40	351.00	702.00
w/c	0.49	0.49	0.49	0.49
Superplasticiser/(c+f) (%)	0.63	0.63	0.63	0.63

Dosage	% RCA			
	0%	**20%**	**50%**	**100%**
w/(c+f)	0.34	0.34	0.34	0.34

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 80% of recycled aggregate total absorption, which corresponds to the 10 min water absorption. This result has been presented in a previous paper where a continuous measurement of the recycled aggregate water absorption over time is shown [25].

Firstly, the mixing sequence consisted of mixing the aggregates (sand and coarse aggregates) with the extra water (that calculated to compensate the recycled aggregate absorption) for 2 min and then they were 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 time of 2 minutes. Then the concrete was poured into the rheometer and into different buckets. It was left there to rest until its testing age.

2.2 Test methods

2.2.1 Methods to assess thixotropy

In order to assess thixotropy, a rotational rheometer where a four-bladed vane rotates with axial symmetry at a variable speed was used. The following three different methods were carried out (Figure 1):

- Structural breakdown curves at various rotational speeds (steady state approach).

- Hysteresis loop flow curves.
- Yield stress at rest (also referred to as static yield stress and shear-growth yield stress).

In the first method, structural breakdown curves, the concrete was subjected to different constant rotational speeds of 0.3, 0.5, 0.7 and 0.9 rps. The rest period established between each of the four structural breakdown tests was 5 min. During this period the concrete was not subjected to any shearing action. It should be noted that just after each test the concrete in the rheometer bowl was rehomogenized and then left to rest.

In the second method, hysteresis loop flow curves, shear stress was plotted as a function of shear rate, and the up (loading) and down (unloading) curves were obtained. The material was sheared with a continuously increasing shear rate and continuously down again to zero shear rate. The rotational speed was applied for 60 s from zero to 0.5 rps and then from 0.5 rps to zero. This rheological test was carried out at 15, 30, 45 and 75 min since the cement-water contact (that corresponds to 5, 15, 15 and 30 min resting time). Two measurements at 15 min were developed to better verify the results.

The protocol adopted for the determination of yield stress at rest consisted of applying a minute and constant rotational speed to a vane immersed in the fresh material and recording the obtained torque as a function of time. The speed was set at 0.03 rps. This was chosen so that the maximum torque is not affected by the rotational speed of the vane. The 60 s time was enough to measure the maximum torque and to reach the steady state region. This protocol was carried out at 15, 30, 45 and 75 min since the cement-water contact (again 5, 15, 15 and 30 min resting time). Before conducting the first test, the SCRC was placed in the bowl of the rheometer and allowed to rest for 5 min. After each test, the vane was removed, concrete remixed with a shovel and left to rest until the next testing time.

2.2.2 Methods to assess the influence of thixotropy on interlayer bond strength

In this research, two methods were used to assess the influence of thixotropy on interlayer bond strength of SCRC (Figure 1): 1) interlayer bond strength using flexure tests; 2) interlayer bond strength using water permeability tests.

In the first method, small beams with dimensions of 100 mm in width and height and 600 mm in length were cast. Small notches were formed during casting at mid-length point to ensure that the failure takes place at mid-span. For each type of concrete, two reference beams were cast in one layer, and seven beams were cast in two layers considering the interface between layers at mid-span. The delay time between casting the first and the second layer was 0, 15, 30 and 60 min (15, 30, 45 and 75 min since the cement-water contact, respectively). Each prismatic specimen was subjected to a three-point bending test. The maximum flexural strength of the specimen was determined.

In the second method, prismatic specimens with dimensions of 100 mm in width and height and 200 mm in length were cast. Small notches were formed during casting at mid-length point. In this case, for each type of concrete, two reference specimens were cast in one layer, and four specimens were cast in two layers. The delay time between casting the first and the second layer was 0, 15 and 60 min. Two specimens were considered for each delay time. The permeability test was carried out according to European Standard EN 12390-8 at an age of 28 days through the interlayer. Finally, each specimen was subjected to a three-point bending test considering the vertical interface between layers at mid-span. Once it was divided into two parts, the water penetration depth was defined.

Three batches for each concrete were made. In the first one, the four structural breakdown tests were carried out. In the second batch, the hysteresis loop test was conducted and the specimens to evaluate interlayer bond strength under flexure tests were made. In the third batch, the protocol adopted for the determination of yield stress at rest was executed and the specimens to develop water permeability tests were fabricated.

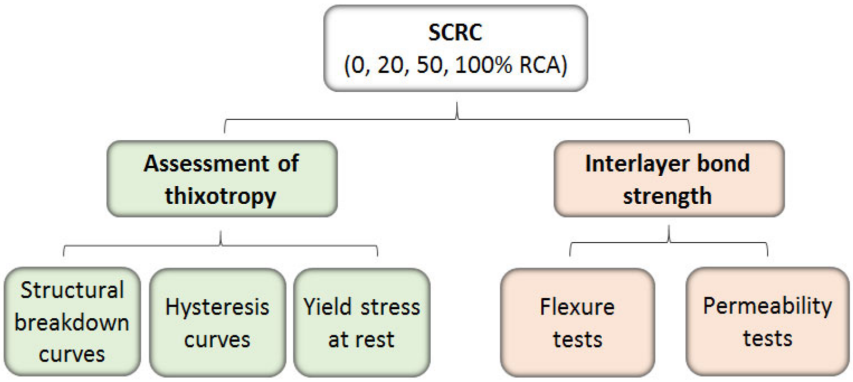


Figure 1. Testing program

3 ASSESSMENT OF SCRC THIXOTROPY

3.1 Structural breakdown curves

The evaluation of thixotropy with the structural breakdown curves can be made analysing two indices. The first is the difference between the peak shear stress (τ_i) and the shear stress at equilibrium (τ_e), for any given rotational speed. The peak shear stress corresponds to the initial structural condition. The shear stress at equilibrium, which is the average of the five smallest measurements over the 25 s duration at each rotational speed, corresponds to an equilibrium condition that is independent of the shear history, for that speed. The difference provides a measurement of the amplitude of the structural modifications inside the tested concrete.

Secondly, peak and equilibrium shear stresses obtained at each speed can be used to draw a graphic “shear stress (τ) versus speed (N)” with an “initial flow curve (τ_i(N))” and an “equilibrium flow curve (τ_e(N))”. The enclosed area between the initial flow curve (τ_i(N)) and the equilibrium flow curve (τ_e(N)) quantifies the thixotropic phenomenon. This area, known as the "breakdown area (A_b)" (Eq. 2), provides a measurement of the energy required per unit time and unit volume to break the structural build-up developed.

$$\text{Breakdown area } (A_b) = \int_{0.3}^{0.9} (\tau_i(N) - \tau_e(N))\, dN \qquad (2)$$

A greater difference between initially shear stress and shear stress at equilibrium ($\tau_i - \tau_e$) implies a higher degree of thixotropy. A greater "breakdown area (A_b)" implies a higher energy necessary to break the initial linkages and internal friction to pass from the initial state into a state of equilibrium.

Figure 2, Figure 3, Figure 4 and Figure 5 show the structural breakdown curves for each SCRC mix. From these figures, it can be deduced that the shearing action induces a considerable amount of breakdown in SCRC mixes in just a few seconds, as it occurs in conventional SCC [9]. This breakdown increases with rotational speed.

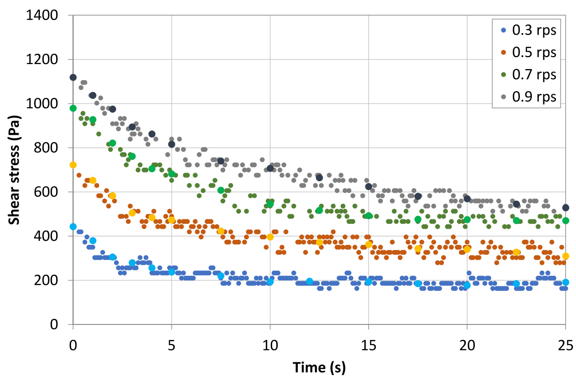


Figure 2. Structural breakdown curves for SCRC0 mix

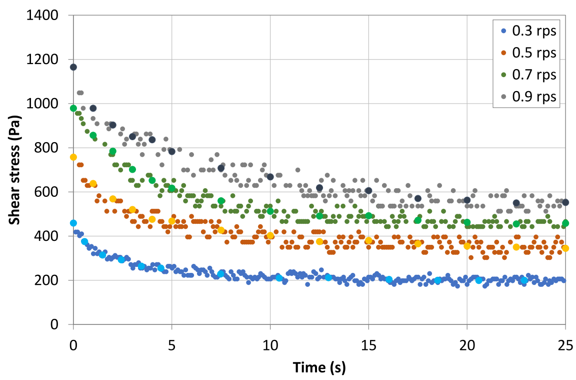
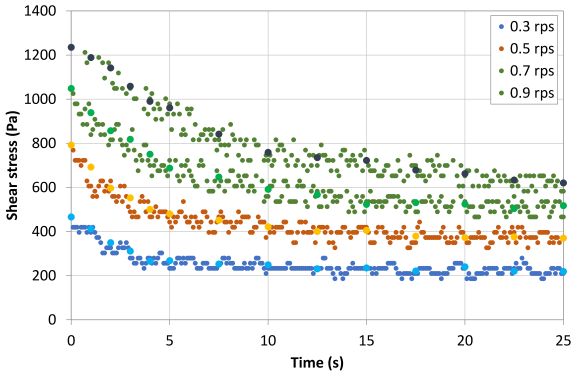


Figure 3. Structural breakdown curves for SCRC20 mix

A similar behaviour can be observed between the reference SCC and the 20% replacement concrete (Figure 2 and Figure 3), i.e. their structural breakdown curves are similar. In the case of 50% of recycled aggregate, a slight increase in the values of shear stress can be seen (Figure 4). The 100% replacement concrete shows this increasing tendency more clearly (Figure 5).



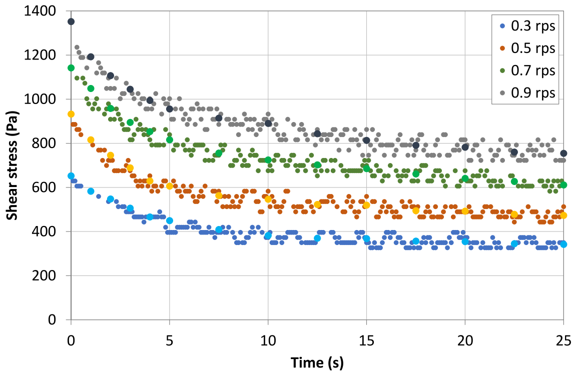


Figure 4. Structural breakdown curves for SCRC50 mix **Figure 5. Structural breakdown curves for SCRC100 mix**

In Figure 6, the variations of τ_i and τ_e with the increase in rotational speed are plotted for the four SCRC mixes. It can be noted that the incorporation of high replacement percentages contributes to increase the τ_i and τ_e values. Moreover, the difference between the τ_i and τ_e values, that offers a measurement of the degree of thixotropy, shows a slight increase with the percentage of recycled coarse aggregate at any rotational speed.

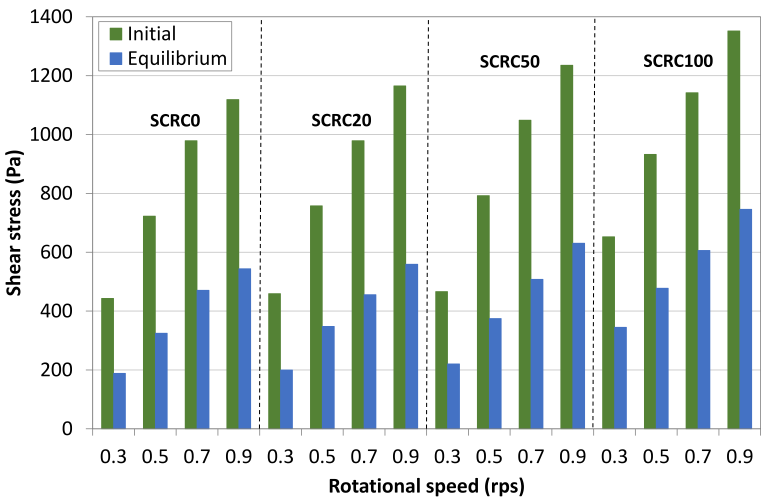


Figure 6. τ_i and τ_e at each rotational speed for each SCRC. Structural breakdown curves

The τ_i vs. N and τ_e vs. N plots for each SCRC mix are reported in Figure 7, Figure 8, Figure 9 and Figure 10. These figures show the A_b value considered between the initial flow curve (τ_i vs. N) and the equilibrium flow curve (τ_e vs. N) for each concrete.

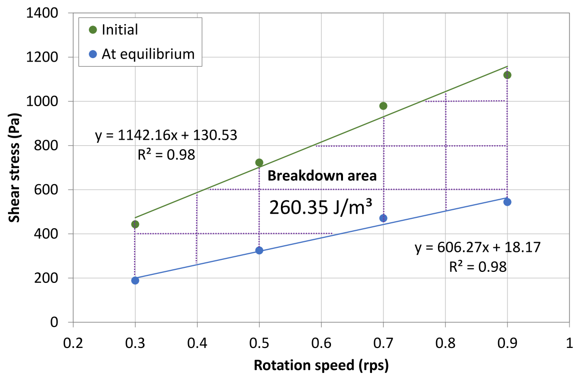


Figure 7. Breakdown area of SCRC0 mix

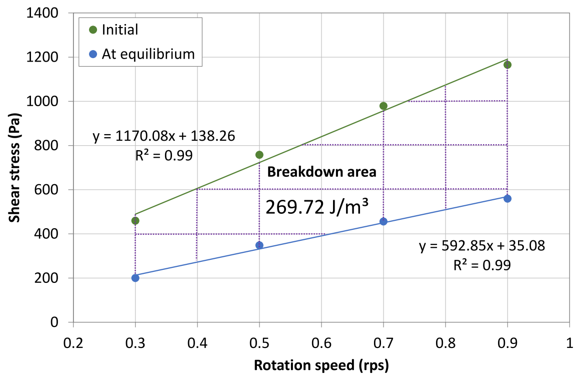


Figure 8. Breakdown area of SCRC20 mix

Regarding the "breakdown area", the A_b values show a slight increase with the increase in the percentage of recycled coarse aggregate. Such increase was of 3.60% for the 20% replacement concrete regarding the reference mix value. In the same way, it was 4.25% and 9.73% for mixes made with % RCA values of 50 and 100% respectively.

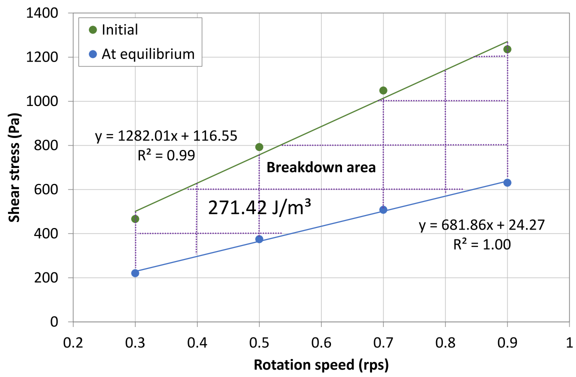


Figure 9. Breakdown area of SCRC50 mix

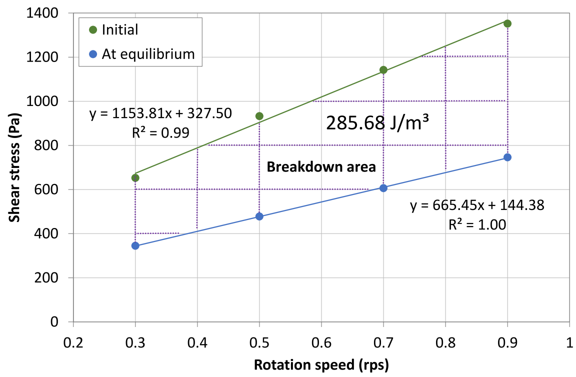


Figure 10. Breakdown area of SCRC100 mix

Therefore, compared to the reference mix (SCRC0), the results indicate that concrete made with recycled aggregates resulted in slightly higher thixotropic measurements, as indicated by the increase in ($\tau_i - \tau_e$) and A_b (Figure 11).

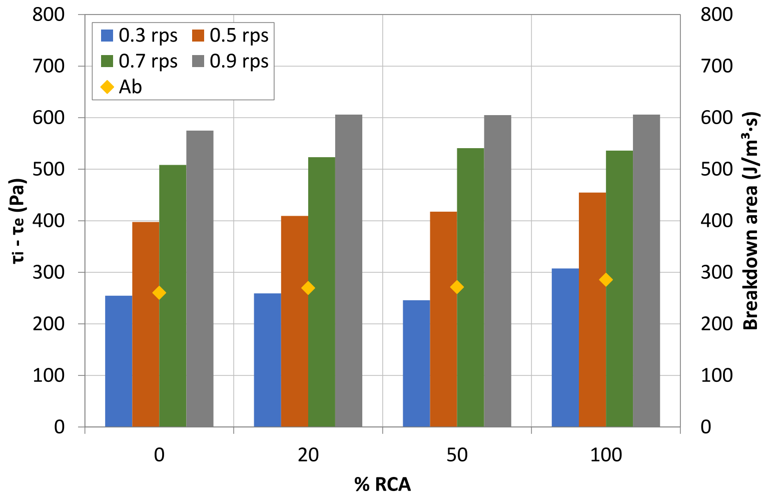


Figure 11. "(τ_i - τ_e) vs. % RCA" and "Breakdown area vs. % RCA"

3.2 Hysteresis curves

For a given resting period, the enclosed area between the up-curve of each hysteresis loop and the corresponding equilibrium line was used to evaluate the rebuilding that occurred in the mix. This area (A_h) has the physical dimension of energy per unit time and unit volume. A greater hysteresis loop area implies a higher degree of thixotropy.

It is explained that hysteresis loops normally measure transient flow properties somewhere between the peak and equilibrium stresses for a given shear rate [9]. Conversely, the previous structural breakdown approach enables measuring the entire shear stress range as a function of time for any given shear rate.

Hysteresis loops are said to have a number of bad points. Firstly, a loop test is often carried out too quickly. Secondly, a test where both shear rate and time are changed simultaneously on a material where the response is itself a function of both shear rate and time is a bad experimentation [9, 26]. However, the use of the hysteresis loop test can be useful to evaluate the structural build-up of cement-based materials as long as it is carefully run and interpreted [3].

Figure 12 shows the results of "hysteresis area (A_h)" for each SCRC mix at each resting time. The A_h values are shown to be quite similar, with a slight increasing tendency when the percentage of recycled coarse aggregate increases (Figure 12). Such increase was of 22.44%, 19.12% and 40.95% at 5 min resting time for mixes made with RCA replacement percentages of 20, 50 and 100% respectively regarding the reference concrete value. The same increase was of 2.73%, 11.07% and 15.63% at 15 min and 2.78%, 3.16% and 8.28% at 30 min respectively.

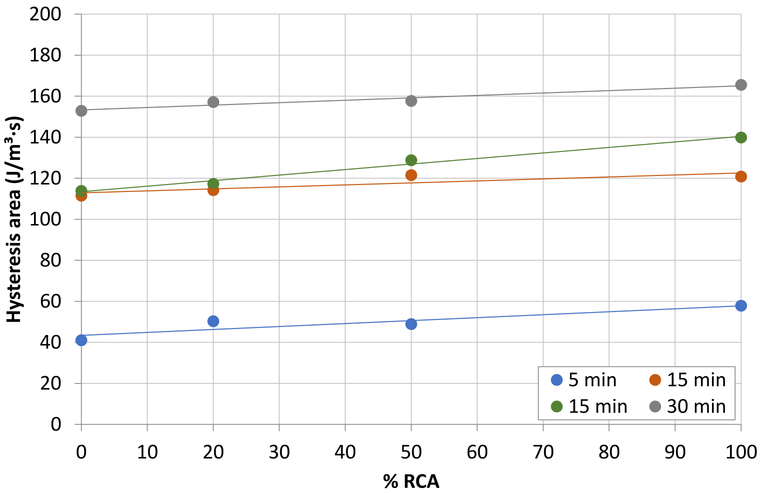


Figure 12. Hysteresis area vs. % RCA

Finally, Figure 13 shows the change in thixotropy (measured with the hysteresis areas) with the elapsed time. It can be seen that all concretes show a similar trend.

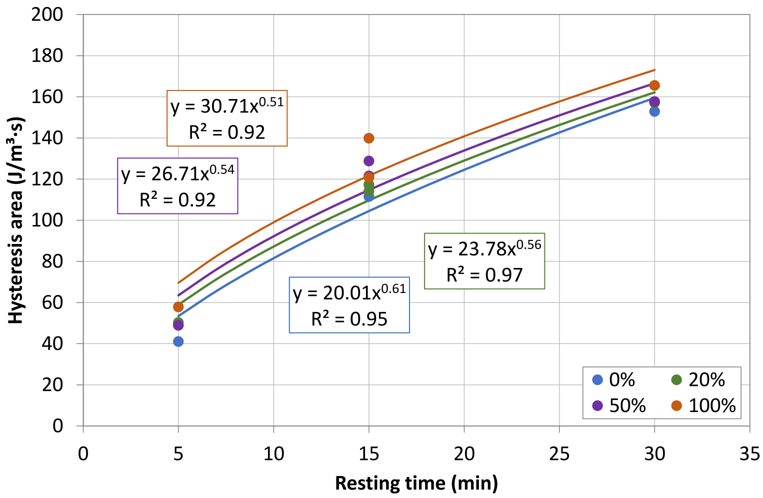


Figure 13. Hysteresis area vs. Resting time

3.3 Yield stress at rest

Figure 14, Figure 15, Figure 16 and Figure 17 show the shear stress-time profiles for each SCRC mix. The evaluation of thixotropy with this test can be made analysing two parameters. The first one is the value of yield stress at rest (τ_0). The yield stress at rest is an index of thixotropy since when reached, the majority of the bonds are broken allowing the flow of the material. The second one is, again, the difference between the peak shear stress (in this test, τ_0) and the shear stress at equilibrium (τ_e). As aforementioned, this provides a measurement of the amplitude of the structural modifications inside the tested concrete. A greater difference between both values implies a higher degree of thixotropy.

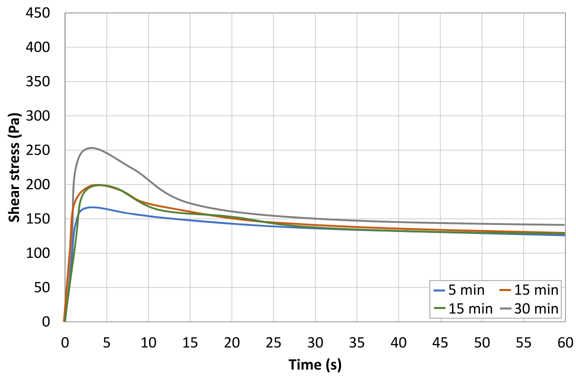


Figure 14. Shear stress-time for SCRC0 mix

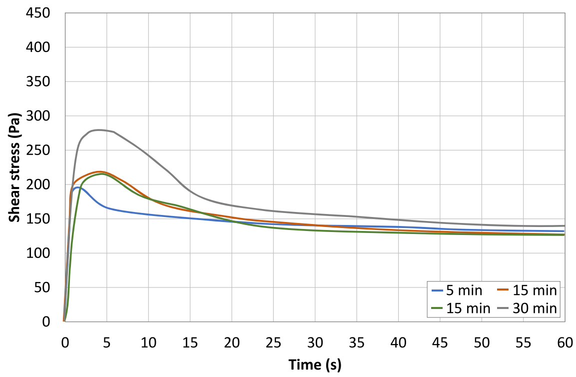


Figure 15. Shear stress-time for SCRC20 mix

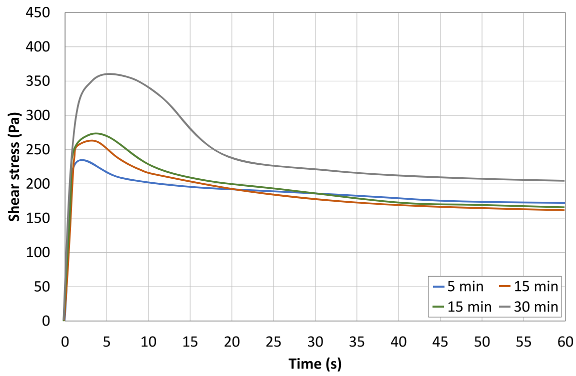


Figure 16. Shear stress-time for SCRC50 mix

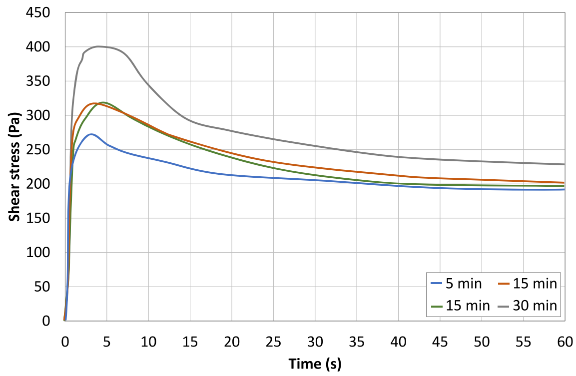


Figure 17. Shear stress-time for SCRC100 mix

Figure 18 summarizes the yield stress at rest (τ_0) and shear stress at equilibrium (τ_e) values for the SCRC mixes. The longer the concrete is maintained at rest, the more the thixotropic structural build-up becomes significant requiring higher initial yield stress to breakdown the structure. The histogram plotted in Figure 18 clearly shows this tendency. Due to the fact that the speed is kept at 0.03 rps, the equilibrium shear stress is similar for each concrete at any time.

When the replacement percentage moves from 0% to 100%, the τ_0 value increases about a 15.71%, 44.29% and 65.09% at 5 min resting time for mixes made with RCA replacement percentages of 20, 50 and 100% respectively regarding the reference concrete value. The same increase was of 10.48%, 37.50% and 62.60% at 15 min and 10.60%, 41.94% and 58.16% at 30 min respectively.

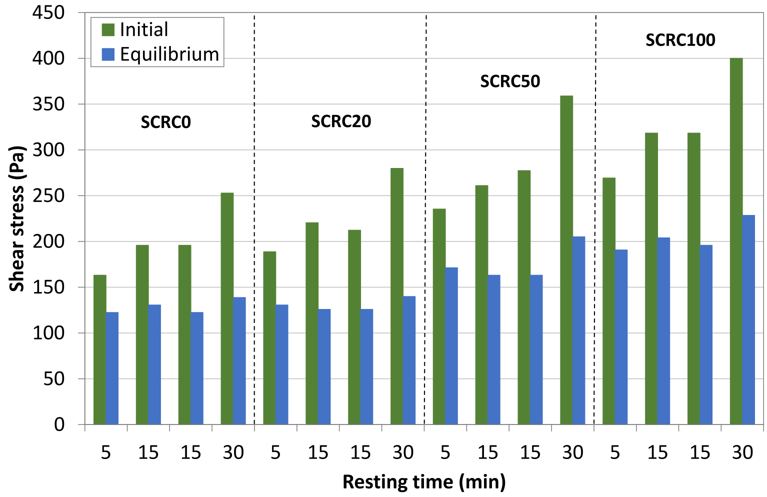


Figure 18. τ_i and τ_e at each resting time for each SCRC. Yield stress at rest

Figure 19 shows the (τ_0 – τ_e) parameter. In parallel with τ_0, this parameter increases about a 42.86%, 57.14% and 92.91% at 5 min resting time for mixes made with RCA replacement percentages of 20, 50 and 100% respectively regarding the reference concrete value. The same increase was of 31.22%, 52.78% and 71.12% at 15 min and 22.45%, 34.69% and 50.20% at 30 min respectively.

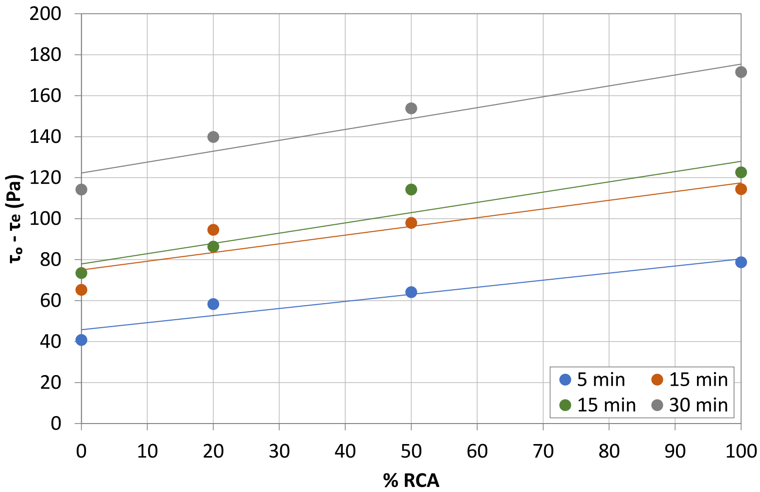


Figure 19. $\tau_0 - \tau_e$ vs. % RCA

As in the previous sub-sections, compared to the reference mix (SCRC0), the results indicate that concrete made with recycled aggregates resulted in slightly higher thixotropic parameters.

Finally, again, Figure 20 shows the change in thixotropy (measured with yield stress at rest test) with the elapsed time. It can be seen that, in agreement with the results obtained with the hysteresis curves test, all concretes show a similar trend.

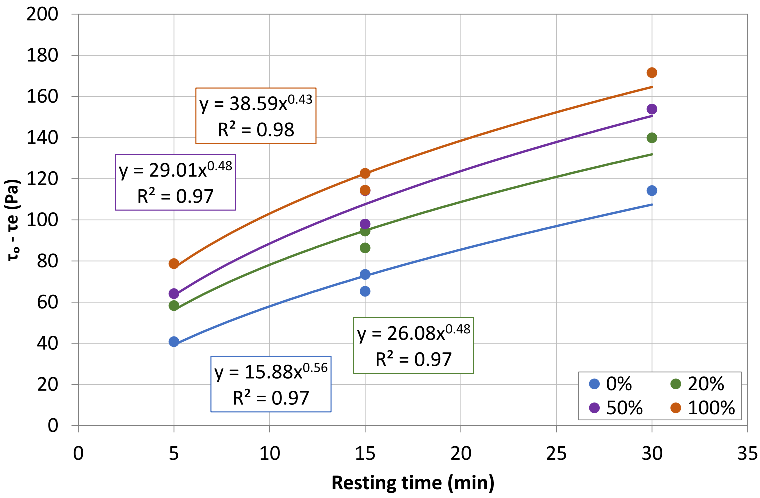


Figure 20. $\tau_0 - \tau_e$ **vs. Resting time**

As thixotropy depends on the paste composition, and the paste composition of all concretes is similar, small differences in all SCRC mixes are found when analysing any of the indices used to measure this property. Only a slight increase with the replacement percentage can be observed. This increase is due to the difference in the effective w/c ratio of the self-compacting recycled concretes, as a result of the non–compensated water absorption. Moreover, the incorporation of recycled coarse aggregate introduces a higher amount of fines from the crushing of the adhered mortar. These fines can present hydraulic activity and then contribute to change the paste composition, decreasing, also, the effective w/c ratio of SCRC. Finally, as other authors have stated [27], also the higher internal friction of recycled aggregates (due to their higher intrinsic viscosity) is affecting SCRC thixotropy. All these effects are, obviously, more significant in concretes with high replacement percentages.

In addition, the behaviour over time of the SCRC depends on the quantity of water compensated in the mixing protocol. This controls SCRC fresh behaviour over time and therefore, the thixotropic changing rate. In this work, due to the designed effective w/c ratio (0.49), changes in this ratio over time are negligible. Thus, its time-dependent evolution until the testing times does not imply significant changes in the SCRC paste composition compared to that of SCC. Therefore, the thixotropic changing rate is similar in all studied mixes.

In conclusion, thixotropy of the studied SCRCs is slightly higher when high replacement percentages are used, showing all concretes a similar thixotropic changing rate. Therefore, it is expected that SCRCs hardly show differences in their interlayer bond strength when compared with the baseline SCC.

4 INTERLAYER BOND STRENGTH OF SCRC

This section is focused on the second objective: the evaluation of the interlayer bond strength of SCRC and the assessment of the influence of thixotropy on this property.

During placing, a layer of a self-compacting concrete has a short time to rest and flocculate before a second layer of concrete is cast on it. If it flocculates too much and its apparent yield stress increases above a critical value, then the two layers may not intermix properly and, as vibrating is not allowed in the case of SCC, this creates a weak interface in the final structure [11].

A highly thixotropic SCC mix (high level of structural build-up at rest) can show a low interlayer bond strength depending on the delay time between layers. The resulting bond associated with multi-layer casting can decrease with the increase in waiting period between successive castings, which will result in an increase in static yield stress (and viscosity) of the concrete cast in the lower lift [28].

Then, a low interlayer bond strength is related to a high thixotropy. This means that if the thixotropy of a mix is high enough, then its interlayer bond strength will be lower than if the mix is less thixotropic.

Figure 21 shows the results obtained on these flexure tests. The residual flexural strength with delay time is also plotted in Figure 22. This residual flexural strength between two layers at a certain delay time was calculated by dividing flexural strength of specimen of the same delay time, $f_{cf\ (delay\ time)}$, by flexural strength of reference specimen, $f_{cf\ (zero\ time)}$.

Khayat et al. [28] found that the residual flexural strength for a delay time of 15 min of SCC with low thixotropy can be very high (around 95%). However, for a delay time of 60 min, the residual flexural strength of SCC with a high thixotropy degree can decrease considerably (around 50%). Keeping this statement in mind, the studied concretes show a low thixotropy level.

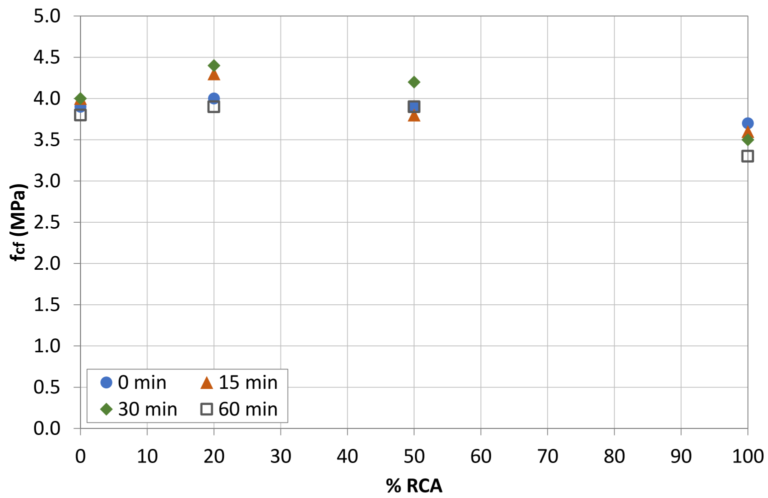


Figure 21. Flexural strength at each delay time vs. % RCA

Moreover, the residual flexural strength is similar in all concretes at any time, although it can be noted that for the total replacement percentage, the decrease in flexural strength is a little more noticeable. This is due to the thixotropy that is slightly higher when high replacement percentages are used.

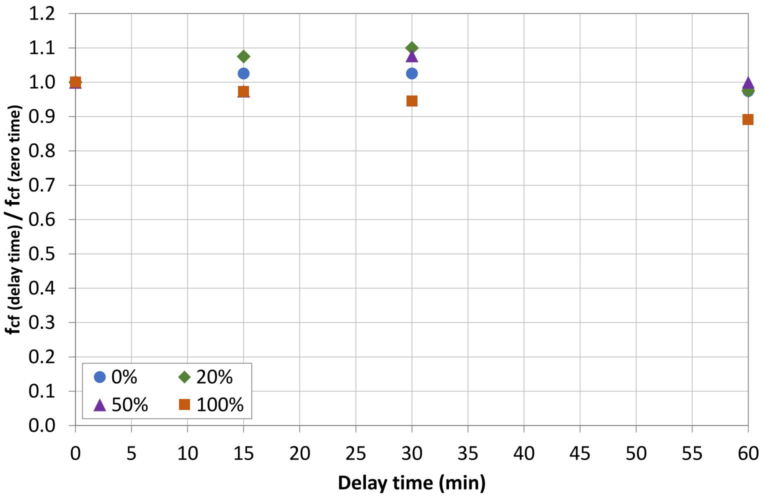


Figure 22. Residual flexural strength for each % RCA vs. Delay time

Regarding water permeability tests, Figure 23 shows the results obtained regarding the water penetration depth for each SCRC mix and taking into account the aforementioned delay times between successive layers.

Water permeability increases with w/c ratio and with the percentage of recycled aggregate [29]. However, some studies showed that when the w/c ratio is low (around 0.45), the water penetration depth of recycled and conventional concretes is similar [30]. Moreover, properly designed and cast, SCC can lead to a more homogeneous microstructure and denser interfacial zone with coarse aggregate particles, leading to low water penetration depths. In this work, the water penetration depth of all concretes is very low (Figure 23).

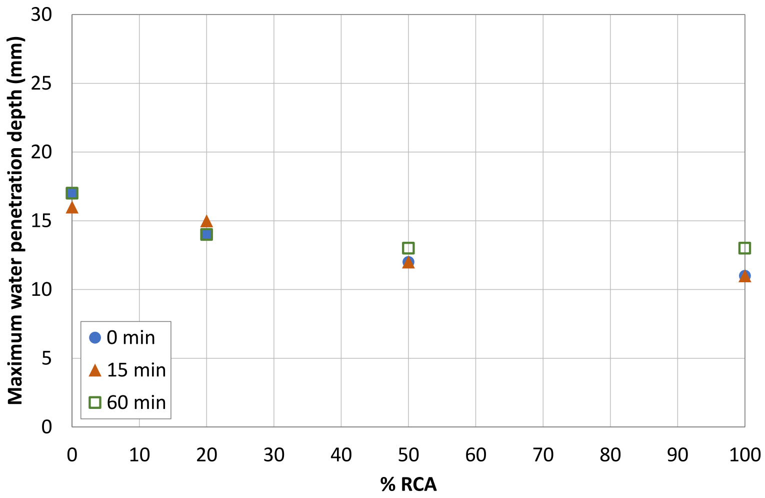


Figure 23. Water penetration depth at each delay time vs. % RCA

In addition, the variation of water penetration depth (penetration at a delay time / penetration at zero delay time) is shown in Figure 24. This variation is an index of the concrete thixotropy. A high thixotropic concrete shows a greater variation than a lower one. In this work, due to the low values of water penetration depth, it is difficult to discuss the differences of behaviour with the delay time between layers and with the replacement percentage. Only when the delay time is 60 min, it can be noted that for the total replacement percentage the increase in the variation of water penetration depth is slightly more noticeable (Figure 24), which can be attributed, again, to the slightly higher thixotropy of SCRC100.

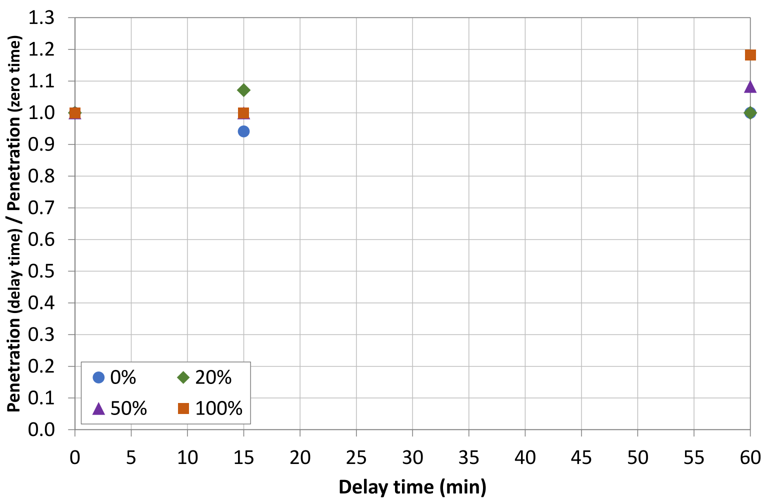


Figure 24. Variation of water penetration depth for each % RCA vs. Delay time

5 CONCLUSIONS

The degree of thixotropy and its influence on the interlayer bond strength of self-compacting recycled concrete (SCRC) were evaluated using several testing methods and protocols. From the data presented in this chapter, the following conclusions can be drawn:

- Similar findings about the degree of thixotropy of each SCRC can be obtained with the three testing methods used, that is, they led to the same qualitative conclusions. It was also observed that the measurement of thixotropy throughout the structural breakdown curves and the yield stress at rest provide the most sensitive thixotropic parameters.
- As thixotropy depends on the paste composition, and the paste composition of all concretes is similar, small differences in all SCRC mixes are found when analysing any of the thixotropic indices. Only a slight increase with the replacement percentage can be observed. This increase is due to three issues: the higher amount of fines incorporated by recycled aggregate and those generated during mixing (from the wear of old adhered mortar), the lower effective w/c (because the 80% water absorption was compensated, not the 100%) and the higher internal friction of recycled aggregates (due to their higher intrinsic viscosity). All these issues lead SCRC to show a different paste composition from that of conventional SCC. This justifies the slight increase detected in the thixotropy of SCRC vs. SCC. These effects are, obviously, more significant in concretes with high replacement percentages.
- Moreover, as 80% of the recycled aggregate water absorption had been compensated in the mixing protocol, changes over time in the effective w/c ratio are negligible. Thus, its time-dependent evolution until the elapsed time in this work does not imply significant changes in the SCRC paste composition compared to that of SCC. Therefore, the thixotropic changing rate is similar in all studied mixes.

- Results obtained measuring the residual flexural strength and the variation in water penetration depth indicate that SCRCs hardly show differences in their interlayer bond strength when compared with the baseline SCC for the considered delay times. Only when the delay time is 60 min, it has been observed that for the total replacement percentage the decrease in the flexural strength is slightly more noticeable. This is due to the fact that the thixotropy of the studied SCRCs is slightly higher when high replacement percentages are used.

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