

# Behavior in fresh and hardened state of a self-compacting concrete with added coal slag and manufactured with coarse recycled concrete aggregate<sup>1</sup>

## Comportamiento en estados frescos y endurecido de un concreto autocompactante, adicionado con escoria de carbón, y elaborado con agregado grueso de concreto reciclado<sup>1</sup>

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### Abstract

The constant growth of the construction, demolition and remodeling activities in populated cities generates large volumes of demolished concrete residues, which today have become a serious environmental problem. Furthermore, the need for increased efficiency in terms of energy and material consumption shows that it is opportune to study materials for their recyclability, especially with concrete, which nowadays is the most produced and with a high environmental impact residue in the world. In this sense, this research paper evaluates the effects of partial and total substitution of the natural aggregates with recycled aggregates that were obtained from the milling of construction and demolition waste, and its behavior in fresh and hardened state of a self-compacting concrete mix. The results show that the addition of these recycled aggregates does not affect significantly the behavior in fresh state, but it does affect the hardened state, since it causes a decrease of the compression resistance (15 – 29%) and a slight raise in permeable pores in function of the amount of natural aggregate that was substituted with recycled (25, 50, 75 and 100%).

**Keywords:** construction and demolition waste; recycled aggregates; natural aggregates; Portland cement concrete; self-compacting concrete.

### Introduction

Increasing the efficiency in the materials and energy consumption is a global need. Likewise, it is a priority to study materials for their recycling, especially concrete, which nowadays is the most produced and with a high

environmental impact residue in the world (Behera et al., 2014). Today, more than 10 billion metric tons of concrete are produced worldwide, which is more than one metric ton per capita/ year. In Colombia, though the index is lower, it is one of the most dynamic and of most incidence in the economic development of the country. One of the consequences that are derived from the construction industry is the generation of considerable volumes of residues. The residues that come from the construction and demolition industries (RCD's) or "Escombros", as they are called in some Latin-American countries, are a construction waste, generated throughout the different construction process stages, including structures and refused materials, those that have been used and discarded, and even those derived from the activities of cleaning and excavation of the construction site when the activity is finished, amongst others. Demolition waste is also generated from the constructions that have been affected by natural phenomena, such as earthquakes, floods, landslides, etc. The concrete residues are notorious due to their size. (Torgal and Jalali, 2011; Oikonomou, 2005; Poon and Chan, 2007).

The high demand of natural aggregates for the production of concrete mixes, as the result of the continuous development of the construction industry, has rendered the question of until when the rock quarries and rivers will be able to provide the non-renewable materials in Latin-American countries as Colombia, in which the estimated amount used annually is 18 million cubic meters of natural aggregates for the production of 35 million metric tons of concrete. In that sense, one of the alternatives that spawn for the addition of value to the RCD's is their use as starting grounds for the production of recycled sands and gravels, that are apt for their use as aggregates in the preparation of self-compacting concrete (CAC) (Maltese et al., 2012; Desponded et al., 2011; Shim et al. 2005; You and Lee, 2014; Tam et al., 2014).

The CAC has been described as "the most revolutionary development in the concrete construction industry." and can be defined as such that can flow on its own weight and fill completely a cofferdam or casting mold without the need for vibration, while maintaining homogeneity. It is characterized by its properties in fresh state such as: flow capacity (limited fluidity), resistance to segregation (stability) and filling capacity (non-limited fluidity)(Okamura and Ouchi, 2003). These characteristics,

special for this type of mixes, is a measurement of the workability or easiness for the mix to settle and self-compact, dealing with a complex combination of aspects such as fluidity, cohesiveness, compactability and viscosity (Domone, 2006).

It has been established that recycled aggregates can have satisfactory properties and characteristics for their use in self-compacting concretes, in spite that in most occasions, the obtained resistance values are lower than with natural aggregates. That is why it becomes an option of residue upcycling, that is environmentally friendly. This research paper is a comparative analysis of the effects of the addition of recycled aggregates to a self-compacting concrete in both fresh and hardened states. The aggregates were obtained from the milling of RCD's that were waste product of remodeling and demolition activities at Universidad del Valle (Cali, Colombia).

## Methodology

For the development and execution of this research, the method proposed is the one shown in the figure 1: the self-compactability properties were determined through the Abrams' cone flow settling essays, V-shaped funnel flow time and locking ratio in L-shaped box. Looking to reduce the workability loss in the variability of the test results, the properties in fresh states were determined within a 15 minute time frame after pouring the mix.

The properties in hardened state of the CAC's such as compression resistance, indirect traction and flexing resistance were measures according to the ASTM C39, C496 and C293, respectively. On the other side, the permeability properties such as water absorption, density and porosity were evaluated according to ASTM C642 and C1585.

## Materials

### Cement

Type I Portland cement for general purpose, was used. It is primarily composed by the compounds detailed in the following chart:

**Table 1.** Chemical composition of Concrete

Component	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	PI
% in weight	20.20	4.52	4.45	61.54	1.58	0.16	0.27	2.48	4.8

## Carbon slag

The carbon slag used as addition to the reference mix was molturated to a grain particle of 19.1  $\mu\text{m}$ , similar to that

of cement. The principal physicochemical characteristics and its composition can be seen on Tables 2 and 3.

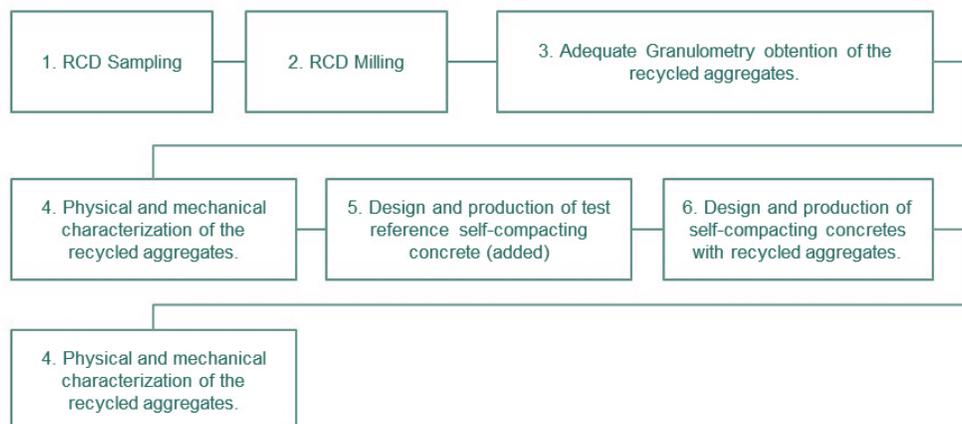


Figure 1. Methodology applied during the research.

Table 2. Carbon Slag characterization

Parameter	Result
Initial particle size	4 mm
Particle size (ground)	19.1 $\mu\text{m}$
Density	2280 $\text{Kg}/\text{m}^3$
Loss % with fire	4.17%
Humidity %	0.18%
Puzolanicity index	92.58%

Table 3. Chemical composition of Carbon Slag

Component	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	TiO <sub>2</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	MgO	S	P <sub>2</sub> O <sub>5</sub>	Ba
% in weight	50.99	27.45	6.53	4.92	1.53	1.30	1.11	0.74	0.21	0.17	

## Superplastifying additive

The superplastifying additive (SP) used in the mix samples was SikaPlast 326, which is a liquid additive, water reducing, of ultra-high power for long workability times and composed of synthetic resins and last-mile polymers. SikaPlast 326 meets all the ASTM C494 standards and is classified in this standard as type A and F, being its density of 1.130  $\text{Kg}/\text{m}^3$ .

## Fine aggregate

The sand used is siliceous, extracted from a river in the area (natural) and presented a 2.61 thinness module

with predomination of rounded particles. Its principal characteristics are shown in Table 4.

## Coarse aggregate

Two types of coarse aggregates were used, natural and recycled. For both types of aggregates, a maximum size of 12.5 mm was guaranteed. Table 5 shows the principal characteristics presented.

The granulometric distribution of the coarse aggregates can be observed in figure 2, where the recycled aggregates present a finer granulometry in comparison to the natural aggregates, which is in relation to the thinness

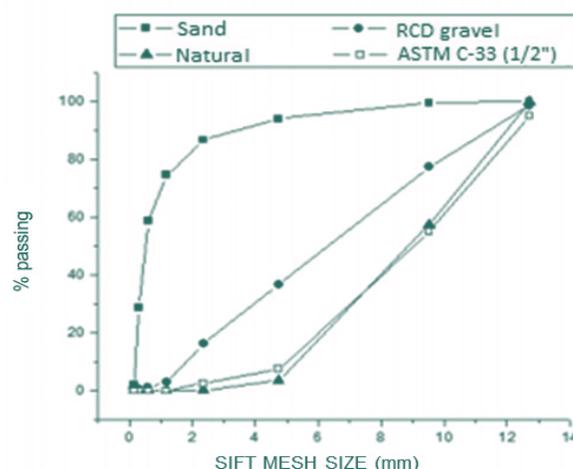
module obtained: 6.38 and 5.64, respectively. It can also be observed that the maximum size of the aggregates is 12.5 mm like it has been mentioned before.

**Table 4.** Physical composition of sand

Characteristic	Code	Result
Apparent Density (bulk)	NTC 237	2.58 gr/cm <sup>3</sup>
Absorption	NTC 237	1.89%
Loose unitary mass	NTC 92	1.63 gr/cm <sup>3</sup>
Compact unitary mass	NTC 92	1.74 gr/cm <sup>3</sup>
Fineness module	NTC 77	2.61
Nominal Maximum size	NTC 77	2.36 mm
Maximum size	NTC 77	12.5 mm

**Table 5.** Physical and mechanical characteristics of coarse aggregates

Characteristic	Code	Natural	Recycled
Apparent Density (Bulk)	NTC 176	2.54 g/cm <sup>3</sup>	2.26 g/cm <sup>3</sup>
Absorption	NTC 176	2.01 %	7.28 %
Loose unitary mass	NTC 92	1.47 g/cm <sup>3</sup>	1.26 g/cm <sup>3</sup>
Compact unitary mass	NTC 92	1.59 g/cm <sup>3</sup>	1.46 g/cm <sup>3</sup>
Fineness module	NTC 77	6.38	5.64
Nominal max. size	NTC 77	12.5 mm	12.5 mm
Maximum size	NTC 77	12.5 mm	12.5 mm
di/DI ratio (morphology)	UNE 933-4	0.493	0.499
Angel Coefficient	ASTM C-131	16.4 %	33.7 %



**Figure 2.** Granulometric aggregate distribution

## Mix design

For the self-compacting concrete mix design, an amount of concrete with 480Kg/m<sup>3</sup> and a cement to water ratio of 0.45, with the objective of achieving a minimal compression resistance of 35 Mpa after 28 days of curing. However, for the reference matrix (M-30), the substitution of 30% of the cement by carbon slag was possible. To ensure the meeting of fresh state properties and a settling higher than 520 mm (SF1), the superplasticizing agent was added in a dosage corresponding to 0.5-0.6%. Looking forward to study the effect in the fresh and hardened behavior of the coarse recycled aggregates, substitutions were conducted in weight ratios of 25, 50, 75 and 100% of natural gravel for recycled gravels in its dosages, as it can be observed in table 6.

**Table 6.** Recycled aggregate concrete mix dosage (dry weight)

MIX	CEMENT (KG/M <sup>3</sup> )	SLAG (KG/M <sup>3</sup> )	WATER (KG/M <sup>3</sup> )	SP (KG/M <sup>3</sup> )	NATURAL GRAVEL (KG/M <sup>3</sup> )	REC GRAVEL (KG/M <sup>3</sup> )	SAND (KG/M <sup>3</sup> )
Control	480	0	216	2.64	643	0	965
M-30	336	144	216	2.64	643	0	965
RCD-25	336	144	216	2.64	482	161	965
RCD-50	336	144	216	2.64	322	322	965
RCD-75	336	144	216	2.64	161	482	965
RCD-100	336	144	216	2.64	0	643	965

## Results

### Fresh state essays

Characteristical essays were conducted for these types of high fluidity concretes such as Abrams’ cone, the L-shaped box and the V-shaped funnel (figure 3), whose criteria and parameters are shown in table 7.



Figure 3. Fresh state tests, setting (left), V-Shaped funnel (center), and L-shaped box (right)

The results obtained from these essays are presented in table 8, in which it can be observed that the incorporation of the recycled aggregates in the reference concrete mix, did not produce significant increments in the water demand and the superplastifying additive amount required to meet the design properties in fresh state and the minimum conformity criteria according to EFNARC (Table 8).

Table 7. Conformity criteria for fresh state, self-settling, concretes, according to EFNARC

Property	Criteria	Structural application
Settling class SF1	≥ 520 mm. ≤ 700 mm	Light Reinforcement
Settling class SF2	≥ 640 mm. ≤ 800 mm	Medium Reinforcement
Settling class SF3	≥ 740 mm. ≤ 900 mm	High Reinforcement
V-shaped funnel test class VF1	≤ 10 s	High Reinforcement
V-shaped funnel test class VF2	≥ 7 s. ≤ 27 s	Medium Reinforcement
Passing capacity class PA1	≥ 0.75	
Passing capacity class PA2	≥ 0.75	

Table 8. Fresh state behavior of the tested concrete mixes

Property	M-30% (reference)	RCD-25	RCD-50	RCD-75	RCD-100
a/c Ratio	0.45	0.45	0.45	0.45	0.45
% SP	0.55%	0.55	0.55	0.56	0.56
Settling (cm)	62.5	57	55.5	54	52.8
V-shaped funnel (seg)	8.74	4.14	5.22	5.04	10.15
L-shaped box (H2/H1)	0.77	0.74	0.72	0.71	0.68

However, it could be appreciated that the addition of recycled aggregates affects slightly the settling of the mix, in function of the substitution percentages (Hadiwidodo y Mohd, 2008; Leite et al., 2013 and Safiuddin et al., 2011), phenomena due to 2 factors: the first, that the recycled aggregates present higher rugosity on their surface after being submitted to grinding and milling process, in comparison to the natural aggregates; and the second, that these types of recycled aggregates have a larger amount of fines (#4 pasant) that result from the process of grinding

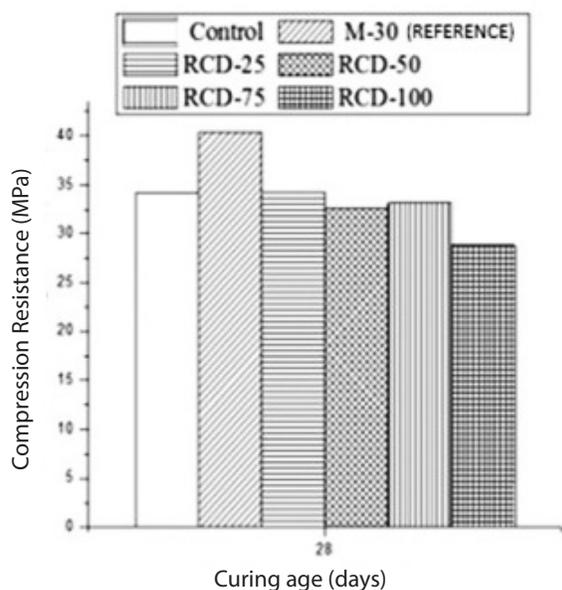
and could demand more water, which affects the settling of the mix, even more when it is close to 100% substitution. Although, this behavior was less notable in the V-shaped funnel case, in which times under the reference value, were achieved. Finally, it was observed that in the L-shaped box test, the incorporation of recycled aggregates did not generate increments in the blocking ratio (H2/H1), which means that even though the risk of the arid blockage was not lowered, all the mix samples met the minimum passage capacity parameter in order to be considered as CAC.

In rheological terms, if you consider the settling flow parameters and flow times as indirect measurements of the tension threshold and mix viscosity, it can be observed that the mixes with added recycled aggregates reach adequate combinations of good fluidity (low tension threshold) and moderate viscosity, which avoids segregation of the components (Robayo et al., 2013; Silva et al., 2013), managing to achieve that all the mix formulas can be considered as self-compacting concretes (CAC) and that their properties are promising, so that these CAC can be used in the forming of medium and high-reinforcement structures, as the conformity criteria established by the EFNARC.

## Hardened state essays

### Compression resistance

The results obtained through compression resistance essays (ASTM C39), can be observed in figure 4. They show that the addition of coarse recycled aggregates in the reference matrix (M-30) causes a decrease of the resistance to compression, which varies from 15% to 29%, depending on the percentage of natural aggregate that was substituted with recycled aggregate.

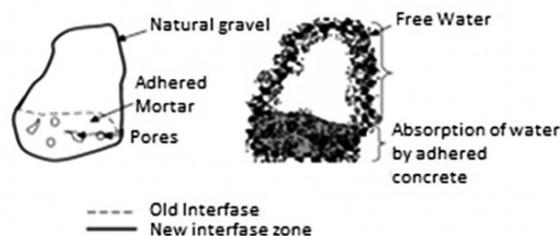


**Figure 4.** Compression resistance of tested concrete formulas after curing for 28 days

This behavior has been studied by diverse researchers around the world. Some, such as Kou and Poon (2009); Leite et al. (2013); Tam et al. (2005); Etxeberria et al. (2007) and Safiuddin et al. (2011), state that this is due to factors such as free water, adhered mortar, porosity and diverse

cracks and faults present in recycled aggregates, as it can be observed in figure 5.

The adhered mortar to the obtained aggregates from RCD grinding is probably the weakest zone of them; their porous structure and the cracking caused by the molturation process while it is being recycled debilitate the capacity to withstand large compression efforts and for that reason, the mechanical performance of the compound is affected (Mardani et al., 2014; McNail and Kang, 2013; Behera et al., 2014). Besides, the characteristics of the old interface influence directly on the mechanical behavior of the new concrete, because if it no longer possesses the adequate properties, it could generate the concentration of efforts when the material is subjected to load and provoke material failure (Xiao et al. 2012). However, the new interface is also a critical area, according to Behera et al. 2014; Wang et al. 2013; Shayan and Xu (2003); Tam et al. (2009); Khoshkenari et al., (2014) and Leite et al., (2013), the porous structure of this old mortar could liberate some of that water after saturating, generating an increment of the water/cement ratio of that zone and provoke the reduction of the resistances to affect the compound directly.



**Figure 6.** Interface zone and recycled aggregate water absorption

Both interfaces can be observed in figure 6 (left), in which through a stereoscope, the importance of the old mortar is evidenced, as it was mentioned previously, from it depends whether or not the aggregate becomes a macrodefect. (figure 6, right), but it has the capacity to withstand efforts similar to those that a perfectly adhered aggregate to matrix bond can support, and contributes to the achievement of the design resistances of the concretes fabricated with natural aggregates.

### Resistance to indirect traction

The results obtained in the indirect traction test or Brazilian essay (ASTM C496) are shown in table 9, in which it can be observed that the resistance to indirect traction

with the substitution of the natural aggregate with recycled aggregate decreases, being this effect more evident when approaching 100% substitution values, passing from 3.08 MPa in the M-30 mix to 2.03 in RCD-100. Some researchers such as Xiao et al., (2008) Zhou et al. (2010) and Cheng (2005), report that the decrease in resistance values to uniaxial efforts can be given by the fact that the failure does not begin in the interface area between the cement paste and the recycled aggregate, but also internal failures in the aggregate itself, which could have been produced during demolition and milling of the RCD's; these defects are intensified by the uniaxial efforts and propagated throughout the matrix until failure or collapse of the material when their load capacity is exceeded.

**Table 9.** Indirect traction test results after 28 days of curing

Formula	Maximum load (N)	Indirect Traction Resistance (MPa)
Control	56197	3.08
M-30	58725	3.22
RCD-25	41220	2.26
RCD-50	40730	2.23
RCD-75	44190	2.42
RCD-100	37060	2.03

### Resistance to flexion

The results of flexion resistance show a similar behavior to the one shown in the compression essay, being a slight decrease notable in the resistance values but in this case due to flex-traction efforts (ASTM C293). It is observed that the RCD-25 mix is the one with best performance amongst the other RCD mix formulas that contain recycled aggregates, however, the other preparations with added RCD, have an almost equal behavior. These results match the obtained by diverse researchers, which include Soto and Mendoza (2006); Xiao et al., (2012); Hu (2007); Cheng; (2005) and Topçu and Sengel (2004), who affirm that the resistance to flexion can vary from 0% to 40%, depending on the dosage of the recycled aggregates. They even emphasize that the incorporation of such aggregates affects the rigidity of the mixes, which is reflected in a slight change of the slope of the load/arrow curve, as it can be seen in table 10 for mix formulas with RCD's.

**Table 10.** Flexion test results for tested formulas after 28 days of curing

Formula	Maximum load (N)	Rupture Module (MPa)
Control	6871	6.32
M-30	7657	6.65
RCD-25	5688	5.12
RCD-50	4975	4.21
RCD-75	5077	4.46
RCD-100	4541	4.16

### Physical essays

#### Absorption, density and porosity

The results obtained through the absorption, density and porosity essays, established on ASTM C642 normativity, reflect the effect on the physical properties of the mix formulas elaborated with RCD's, demonstrating that the addition of recycled aggregates generates an increment in the volume of the permeable pores in function of the amount of natural aggregate substituted by recycled. This effect has as direct consequence that the density of the concretes decrease, as well as the absorption capacity increases, as it can be appreciated in table 11. These results match those obtained and presented by Leite et al. (2013), Safiuddin et al. (2011), Tam et al. (2005), y Etxeberria et al.,(2007), who attribute this behavior to the porosity present in the mortar that is adhered to the recycled aggregates, which generates a decrease in density in relation to the natural aggregates and in consequence, influence the density of the final concrete.

#### Capillar suction

The results obtained through the capillary suction essay method (ASTM C1585) can be observed graphically in figure 6. In table 12, the average absorption rate, K, the resistance to penetration, M, and effective porosity,  $\epsilon_e$ , calculated for the different mix formulas after 28 days of curing.

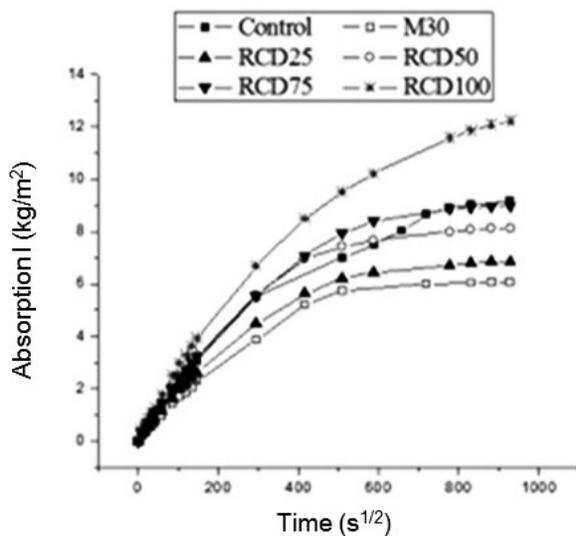
These results reflect that the incorporation of recycled aggregates in the reference mix, cause a slight decrease in the resistance to penetration, m, besides from an increment of effective pore percentage, proportional to the amount of recycled aggregate added to the formulas. However, these changes are not significant; as it can be observed when the obtained values for K, the absorption rate, are compared.

Perhaps, the most representative is the increase of the percentage of effective pores, which is altered as the percentage of recycled aggregate increases, passing from 7.53% in the reference mix (M-30) to 11.85% for the RCD-100 mix- This behavior is similar to the one presented by these same formulas in the absorption, density and porosity tests. On the other hand, the debate whether the increment of the volume of the permeable pores, since this

phenomena is attributed to the new ratio of cement/water that is generated in the new mix formula, because of the remaining water that is free and the recycled aggregates do not absorb completely because the mixing water (concrete pour) from the mix is more than the absorption rate in that instant; for that reason, this remaining water escapes afterwards to the surface leaving capillary pores in its path which affect the material's density (Belin et al, 2014).

**Table 11.** Absorption, density and porosity test results after 28 days of curing

Mix Formula	Absorption %		Density ( $\times 10^3$ )(Kg/cm <sup>3</sup> )		Pores (%)	
	After immersion	After immersion And soak	After immersion	After immersion And soak	apparent	Permeable pore volume
Control	5.16	5.54	2.48	2.49	2.71	13.07
M30	4.68	5.09	2.49	2.50	2.70	12.10
RCD25	6.05	6.25	2.35	2.36	2.57	13.85
RCD50	7.01	7.16	2.27	2.27	2.50	15.17
RCD75	8.12	8.30	2.22	2.22	2.47	17.01
RCD100	7.96	8.06	2.19	2.20	2.43	16.38



**Figure 7.** Suction kinetics after 28 days of curing

**Table 12.** Capillary Suction test results after 28 days of curing

Mix Formula	K(kg/m <sup>2</sup> s <sup>1/2</sup> )	m ( $\times 10^7$ ) (s/m <sup>2</sup> )	Effective Porosity E <sub>o</sub>
Control	0.021	1.99	9.23 %
M-30	0.015	2.51	7.53 %
RCD-25	0.017	2.40	8.48 %
RCD-50	0.022	1.66	8.82 %
RCD-75	0.021	2.60	10.65 %
RCD-100	0.026	2.10	11.85 %

If the porosity results obtained in the density, absorption and porosity tests (ASTM C642) are compared, with those from the capillary suction tests (ASTM C1585) it can be observed that the effects caused by recycled aggregates on open porosity and total porosity is similar, managing to raise in very close values both porosities. It can be highlighted that all the porosity present in the mixes, a fraction close to 2/3 is interconnected. This phenomena, according to diverse researchers, is caused by the free water that escapes to the surface leaving behind passages that connect most of the pores in a network (Henkensiefken et al., 2009).

## Conclusions

Based on the results of this research, the following conclusions can be extracted:

The use of recycled aggregates obtained from the milling of construction waste for the production of self-compacting concretes as partial substitute for natural gravel, is completely feasible, since the mixes presented a good flow, good resistance to segregation, exudation and excellent passing and filling capacities. Furthermore, in hardened state, it has an adequate aesthetic aspect and acceptable mechanical properties that allow its use for medium and highly reinforced structures. These mix formulas have a proper manageability time frame to achieve a proper settling and pouring.

The incorporation of the recycled aggregates generated a slight decrease in the properties when compared to the hardened reference mix, in a proportional manner to the amount of recycled aggregate present in the mixes. It must be highlighted that the 25% recycled aggregate addition formula rendered the best mechanical behavior amongst the other RCD formula, having an 85% relative mechanical performance when compared to the reference mix formula.

The substitution of coarse natural aggregates with the aggregates obtained from RCD's in the prepared mixes generated a slight increase of the volume of the permeable pores, in function of the amount of recycled aggregate added present in the mix formula. This had as direct consequence that the concretes' densities decreased up to 15% and in consequence the absorption capacity was increased.

All of the above indicate that the addition of aggregates obtained from the milling of RCD's generates a slight decrease in the mechanical performance of the concretes prepared with them. However, it must be annotated that their usage with a product as versatile as CAC, opens up the possibility to be used in places where natural aggregates are not available or where the overexploitation of these non-renewable resources has generated an irreversible environmental impact that limits its sustainability in the future.

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