# Self-compacting concrete manufactured with recycled concrete aggregate: an overview.

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# ABSTRACT

The use of different types of waste in the manufacture of concrete is increasingly common, due to unabating concerns over climate change and sustainability in the construction sector. It is now widely accepted that the optimal behavior of vibrated concrete produced with the addition of certain wastes can rival the behavior of conventional products. The manufacture of special concretes, such as self-compacting concrete, is also currently under investigation, although the state of knowledge in this field is not so well developed. In this review paper, current and past research articles on the design of self-compacting concrete with recycled concrete aggregate, both by itself and in combination with other wastes, are summarized and assessed. Research is presented into recycled concrete aggregate properties and the mix-design of the self-compacting concretes that contain them, as well as relevant results on the fresh state (workability, rheology), the hardened state (compressive strength, splitting tensile and flexural strength, modulus of elasticity, density, and porosity), durability (resistance to aggressive agents), long-term properties of concrete (shrinkage, creep), and structural elements manufactured with self-compacting concrete containing recycled concrete aggregate. The results under review reaffirm that the incorporation of recycled concrete aggregate can produce a suitable self-compacting recycled concrete, on the basis of careful designs that are essential for successful performance.

**KEYWORDS:** Self-compacting concrete, recycled concrete aggregate, flowability, hardened state, durability, structural elements.

## 1. INTRODUCTION

Emissions of $CO_2$ attributed to the construction sector and its enormous consumption of natural resources are both major environmental concerns at a global level (Sandanayake et al., 2019). Large amounts of energy are consumed by the extraction of natural aggregates (Marques et al., 2017) for use in many engineering activities, such as concrete and asphalt mixes, geotechnical activities (fillings, embankments and some types of dams), and even hydraulic activities such as trench and ditch fillings, and beds for piping systems. Finally, there is the contentious issue of high atmospheric emissions of $CO_2$ from manufacturing processes at cement factories, and at asphalt and concrete plants (Thives and Ghisi, 2017).

Over the past few years, this situation has been firmly noted in the construction sector and initiatives are underway to change what are in many cases considered traditional practices, seeking to reduce environmental impacts and to mitigate climate change (Bostanci et al., 2018). Following some years of economic recession in the construction industry, investment has increased, which has also prompted the emergence of various new fields of research that, in different ways, encourage more sustainable construction patterns:

- Reducing $CO_2$ emissions produced during the raw-material manufacturing process, usually direct atmospheric emissions from cement factories (Carmichael et al., 2018). The main solutions have focused on the search for novel production technologies and materials (Maddalena et al., 2018).
- Controlling indirect atmospheric emissions and evaluating the carbon footprints of construction components prior to their manufacture and the machinery in use (Rossi and Sales, 2014).
- And, the central issue in this paper, the search for different techniques to reduce the consumption of natural resources (Braga et al., 2017).

The areas where the consumption of natural resources can be reduced differ widely. The use of different wastes to replace those aggregates is progressively more extensive, especially in relation to coarse and/or fine Natural Aggregates (NA) in concrete design. Recycled aggregates from Construction and Demolition Waste (CDW) (Soares et al., 2014), roof tiles (Jagadeesh et al., 2017), rubber (Yung et al., 2013), plastics (Preethiwini et al., 2017), and glass (Ali and Al-Tersawy, 2012) are the most common examples of residues that can be added to concrete mixes, provided that the proportion in the mixture is carefully researched and adjusted to the properties of each residue.

Among the above-mentioned residues, CDW has the lengthiest history of use and is currently the most widely used in the manufacture of concrete based on a sustainable approach. CDW, following treatment in certified recycling plants, is an appropriate product for certain types of structural concrete. Its use is regulated in many standards such as the Spanish regulations (EHE-08, 2010) or the Italian one (DM-17/01/2018) and it may be classified into three main types of materials, according to its components: crushed concrete, crushed masonry, and mixed demolition debris.

The use of crushed concrete or Recycled Concrete Aggregate (RCA) has proven to be especially suitable for high-performance concrete, resulting in countless experimental tests (Etxeberria et al., 2007) and many reviews of conventional concrete manufactured with RCA regarding fresh state (Silva et al., 2018), compressive strength (Silva et al., 2015), mechanical behavior (Behera et al., 2014), durability (Guo et al., 2018) and fine RCA performance (Evangelista and De Brito, 2014).

The use of RCA in Self Compacting Concrete (SCC) has only recently been studied, however RCA applications and the use of RCA in SCC are gaining ground, reflecting its particular advantages and a need for continued research in that area. SCC is characterized by very good flowability and workability and its main advantage is that no vibration is required when filling formwork enclosures (Corinaldesi and Moriconi, 2011). These properties are usually assisted through the addition of plasticizers and superplasticizers (Barbudo et al., 2013). Regarding SCC with RCA, there is only one review article elaborated The review article by Santos et al. (2019a) is the only one found to date on the topic of SCC with RCA.

This bibliographic review will firstly set out a brief description of RCA properties (average values from the aggregates used in the different articles studied) and some guidelines for the design of concrete dosages. Then, the results of the different studies will be organized into different sections, each one corresponding to a different concrete behavior: fresh state, hardened state (compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity, among others), durability and long-term properties (shrinkage and creep) and finally, the behavior of structural elements.

Lastly, the subsections will be structured by the type of waste in the concrete mix. The papers that are reviewed all report studies of RCA, although the use of more than one type of waste in concrete manufacture is increasingly widespread and SCC is no exception in that regard. The main combinations include the use of RCA in combination with fly ash (FA) and silica fume (SF), among others.

## 2. CHARACTERIZATION OF RECYCLED CONCRETE AGGREGATE (RCA)

As is widely established, RCA properties are very variable and depend on many aspects, such as the origin of the RCA (precast elements, in-situ manufactured concrete, CDW, laboratory samples, etc.), the dosage and components of the original concrete (pumpable concrete, SCC, type of cement, etc.), and the crushing process of the original elements.

In what follows, a number of interesting studies on the properties of RCA will be highlighted.

Agrela et al. (2011) characterized CDW with a content of concrete higher than 90 %, which can be considered coarse RCA, in a study of 35 mixed recycled coarse aggregates from several CDW treatment Spanish plants. Those aggregates provided the following results (95 % confidence interval):

- Saturated Surface-Dry (SSD) density (kg/dm$^3$): 2.40 ± 0.07
- Water absorption 24h (%): 5.42 ± 1.70
- Soluble sulphate (% $SO_3$): 0.40
- Sulphur content (% S): 0.25

Safiuddin et al. (2013), in their review regarding the use of the RCA for the manufacture of concrete, established the following average values for the coarse RCA, obtained from six references:

- Shape and texture: Angular with rough surface.
- SSD density (kg/dm$^3$): 2.1–2.5.
- Bulk density (compacted) (kg/dm$^3$): 1.20–1.43.
- Absorption (wt. %): 3–12.
- Pore volume (vol. %): 5.6-16.5.

In addition to the information presented above, a summary based on the different references cited throughout this article is presented in Table 1. In view of their high variability, 95 % confidence intervals (*t*-student distribution) of these properties are presented.

*Table 1: Average values of some RCA properties*

| Property | Coarse/ fine RCA | Values (95 % conf. interval) | References used |
|---|---|---|---|
| **SSD density (kg/dm$^3$)** | Coarse | (2.38, 2.48) | (Boudali et al., 2016; Campos et al., 2018; Fiol et al., 2018; Gesoglu et al., 2015a; González-Taboada et al., 2017a; Güneyisi et al., 2016; Kapoor et al., 2016; Kebaïli et al., 2015; Kou and Poon, 2009; Manzi et al., 2017; Omrane et al., 2017; Ortiz et al., 2017; Panda and Bal, 2013; Pereira-De-Oliveira et al., 2014; Rajhans et al., 2018a; Revathi et al., 2013; Salesa et al., 2017; Santos et al., 2017; Silva et al., 2016; Singh and Singh, 2016b; Tang et al., 2016; Uygunołlu et al., 2014; Velay-Lizancos et al., 2016; Vinay Kumar et al., 2017; Yasser Khodair, 2017) |
| | Fine | (2.21, 2.39) | (Campos et al., 2018; Carro-López et al., 2015; Gesoglu et al., 2015a; Güneyisi et al., 2016; Kou and Poon, 2009; Manzi et al., 2017; Omrane et al., 2017; Santos et al., 2017; Vinay Kumar et al., 2017) |
| **Water absorption (%)** | Coarse | (4.53, 6.27) | (Boudali et al., 2016; Campos et al., 2018; Fiol et al., 2018; Gesoglu et al., 2015a; González-Taboada et al., 2017a; Grdic et al., 2010; Güneyisi et al., 2016; Kapoor et al., 2016; Kebaïli et al., 2015; Kou and Poon, 2009; Manzi et al., 2017; Mohseni et al., 2017; Omrane et al., 2017; Ortiz et al., 2017; Panda and Bal, 2013; Pereira-De-Oliveira et al., 2014; Rajhans et al., 2018a; Revathi et al., 2013; Salesa et al., 2017; Santos et al., 2017; Silva et al., 2016; Singh and Singh, 2016b; Tang et al., 2016; Velay-Lizancos et al., 2016; Vinay Kumar et al., 2017; Yasser Khodair, 2017) |
| | Fine | (7.76, 11.06) | (Campos et al., 2018; Carro-López et al., 2015; Gesoglu et al., 2015a; Güneyisi et al., 2016; Kou and Poon, 2009; Manzi et al., 2017; Omrane et al., 2017; Santos et al., 2017; Vinay Kumar et al., 2017) |
| **Fines content (%)** | Coarse | (0.31, 2.65) | (Campos et al., 2018; Fiol et al., 2018; González-Taboada et al., 2017a; Salesa et al., 2017) |
| **Los Angeles coefficient (%)** | Coarse | (28.28, 36.31) | (Fiol et al., 2018; Kebaïli et al., 2015; Omrane et al., 2017; Panda and Bal, 2013; Rajhans et al., 2018a; Revathi et al., 2013; Salesa et al., 2017; Silva et al., 2016; Singh and Singh, 2016b) |

## 3. SCC REFERENCE DOSAGE

In this section, the dosages proposed by different authors are compiled for the production of conventional SCC with natural aggregates and no waste. The aim is to have a reference in the mix design of Self-Compacting Recycled Concrete (SCRC) for subsequent analysis of the incorporation of the different wastes and their effects.

It must be also emphasized that a key property of SCC is flowability. Various authors have underlined the importance of careful design, proper water to cement (w/c) ratios, and suitable types and amounts of plasticizer (or superplasticizer), to achieve good flowability (Hani et al., 2018). Regarding the dosage of a SCC, the addition of superplasticizer is necessary, but a high content of fines is very important as well. Correct dosing will yield a sufficiently compact cement paste that can carry all coarse aggregate particles and thereby prevent segregations. For this reason, the addition of limestone filler is generally essential.

From the references under study, an average reference dosage is obtained, which collects the quantities of coarse aggregate, fine aggregate, cement, water, limestone filler, and superplasticizer that are necessary to obtain 1 m$^3$ of SCC, as shown in Table 2 (95 % confidence interval). The average w/c ratio is also shown, which should be significantly increased with additions of RCA, to compensate the high water-absorption levels of the RCA and obtain optimum flowability values.

*Table 2: Average dosage in reference SCC*

| Component (kg/m$^3$) | Values (95 % confidence interval) | Average value of the interval | References used |
|---|---|---|---|
| **Cement** | (332.54, 409.03) | 370.78 | (Campos et al., 2018; Carro-López et al., 2015; Fiol et al., 2018; González-Taboada et al., 2017a; Grdic et al., 2010; Kebaïli et al., 2015; Kou and Poon, 2009; Manzi et al., 2017; Pereira-De-Oliveira et al., 2014; Revathi et al., 2013; Salesa et al., 2017; Tang et al., 2016; Vinay Kumar et al., 2017) |
| **Water** | (168.11, 202.49) | 185.30 | |
| **Coarse aggregate** | (731.44, 890.01) | 810.72 | |
| **Fine aggregate** | (723.95, 865.51) | 794.73 | |
| **Limestone filler** | (136.91, 248.04) | 192.48 | |
| **Superplasticizer** | (3.43, 4.33) | 3.88 | |
| | Average value: 1.0 %-1.1 % wt. of cement | | |
| **w/c ratio** | (0.44, 0.54) | 0.49 | |

## 4. FRESH STATE PERFORMANCE

As stated earlier, flowability is the main property of SCC that distinguishes it from conventional vibrated concrete. The flowability of SCC is measured in different tests, the most important of which are the slump flow, J-ring, L-box, V-funnel and sieve segregation tests. Studied in very specific cases, direct rheological parameters are a potential field of study for future investigations (Carro-López et al., 2015). The values obtained in all these tests must be in line with the national regulations of each country and the regulations of others relevant bodies, such as the European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC, 2002) or the specifications of the American Concrete Institute (ACI, 2007).

### 4.1. FRESH STATE OF SCC WITH RCA

Grdic et al. (2010), Modani and Mohitkar (2014), and Kebaïli et al. (2015) attempted to develop an SCC manufactured with coarse RCA. In the research work of Grdic et al. (2010) and Modani and Mohitkar (2014), SCC was successfully performed, although its flowability decreased as the proportion of coarse RCA increased. In contrast, Kebaïli et al. (2015) were unsuccessful at manufacturing SCC, which they attributed to two main reasons. First, the water content was so low that it could not compensate the high absorption of the RCA. Second, the aggregate/paste ratio was too high, meaning that particles of aggregate collided against each other, hindering the flow of concrete. Both studies add weight to the fact that a carefully designed dosage is essential to achieve self-compactability.

Campos et al. (2018) designed a concrete mixture with coarse RCA and/or fine RCA in three different combinations (0 % - 20 %, 20 % - 0 % and 20 % - 20 %). The amount of superplasticizer increased with the amount of RCA. The results showed that a suitable SCC can be achieved using these quantities of coarse RCA and fine RCA, if around 9 % more water is added. Their results also corroborated previous observations that fine RCA water absorption is greater than the water absorption of coarse RCA.

Carro-López et al. (2015; 2017) considered a substitution of only the fine fraction of NA in proportions of 20 %, 50 %, and 100 %, maintaining the superplasticizer constant. When examining the flowability of the mixes, which as is well known will decrease over time, they reached the conclusion that the greater the fine RCA content, then the faster the decrease in flowability.

Different humidity conditions of the RCA have been also analyzed. González-Taboada et al. (2017a; 2017c) designed SCC with coarse RCA (substitution percentages of 20 %, 50 %, and 100 %) and three different situations were considered: dry aggregate and extra water (labelled M1), pre-soaked aggregate (labelled M2), and aggregate with 3 % of natural moisture and extra water in the concrete mix (labelled M3). The main conclusion was that the coarse RCA was indeed suitable for the manufacture of SCC and that the best method to guarantee flowability over time was by pre-soaking (M2) the aggregates. In contrast, control over flowability with methods M1 and M3 presented serious difficulties. Although, in conclusion, M2 was the best method, the authors claimed that aggregate pre-soaking as an industrial procedure would require excessive amounts of time and may not be profitable, which explained why M3 was the most widely used option. However, in the case of SCC as a high-performance product, pre-saturation should be considered as an alternative to enhance behavior, besides profitability considerations. However, in the perspective of industrializing RCA-based SCC, the authors of this review considered it more efficient to use RCA with natural moisture and to modify the total water content of the mix, rather than by pre-soaking the aggregates.

González-Taboada et al. (2018a; 2018c) analyzed the different aspects that affect SCC flowability: the variations of water, cement and superplasticizer in the mix-design, and the characteristics of the RCA (shape coefficient, modulus of fine, content of fines...). It was concluded that small changes in these parameters affected SCRC much more than conventional vibrated concrete. The dosages of that type of concrete must be studied further and the conditions of the mixing place (e.g., ambient moisture) must be perfectly controlled.

In terms of density, Manzi et al. (2017) stated that the fresh bulk density of SCRC was lower than that of conventional vibrated concrete and lower than the fresh bulk density of SCC manufactured with NA. They obtained a value of 2.22 kg/dm$^3$ with a 100 % coarse substitution and 2.28 kg/dm$^3$ with a 20 - 40 % substitution rate, compared to 2.34 kg/dm$^3$ of the control concrete. That result was attributed to the lower density of the RCA, mainly caused by the attached mortar.

Salesa et al. (2017) worked with a multi-recycled SCC with a percentage substitution of 100 %. An initial SCRC (named RA1) was produced, which was then crushed, sieved and used to manufacture a second SCRC (RA2). A third concrete (RA3) was then manufactured from the second. The flowability tests worsened, which was explained by the increasing amounts of adhered mortar in each cycle. Some of these results are shown in Table 4.

Assaad (2017) evaluated the effect of coarse RCA on SCC flowability, by comparing the Direct Substitution (DR) by volume and the Equivalent Mortar Volume (EMV) methods to define the dosage. Flowability decreased with the addition of RCA, but the DR method provided better results for low percentages of RCA (20 - 35 %). No SCC was developed using the EMV method for higher coarse RCA contents, so it is not known which method had the better result. The static stability of the SCC improved with RCA and EMV method.

Omrane et al. (2017) used a natural pozzolan in addition to RCA in substitution of cement. They observed that when RCA was used, then pozzolan percentages could be increased by up to 20 %, while the pozzolan percentage could not exceed 15 % with NA if requirements related to slump flow test wanted to be fulfilled (Said et al., 2014). The effectiveness of the natural pozzolan was greater in combination with RCA.

Güneyisi et al. (2014) evaluated some aggregate surface treatment methods and their effects on the properties of SCC made with RCA (100 % coarse RCA replacement). Four different treatments were analyzed: submerging RCA in HCl solution for 24h, submerging RCA in water glass ($Na_2O{\cdot}nSiO_2$ sodium silicate) for 30 min, submerging RCA in cement-silica fume slurry for 30 minutes, and implementing a two-stage mixing process. All the treatments that were tested improved the flowability and the performance of the concrete compared to the control mixture. Among them, the water glass treatment appeared the most effective and was quite brief, so it could be implemented in industrial production, although consideration should also be given to the increased cost (Wang and Zhang, 2016).

The results of some of the investigations commented in this subsection were plotted against relevant parameters, such as the percentage substitution, the w/c ratio and the percentage of superplasticizer. In Figure 1, the relation between RCA percentage and the slump flow $t_{500}$ is shown, differentiating between “fast” and “slow” concretes, based on the representative differences between each one.

Figure 2 shows the relation between passing ability in the L-box test and the w/c ratio. The values used to draw the graphs, obtained from the literature under review, are also shown in Table 3.

*Table 3: Values of some in-fresh properties of SCC manufactured with only RCA*

| **Research** | **Coarse RCA content (%)** | **Fine RCA content (%)** | **w/c ratio** | **% super plasticizer (wt. of cement)** | **Viscosity $t_{500}$ slump flow test (s)** | **Slump flow (mm)** | **Viscosity $t_{500}$ J-ring (s)** | **Maximum dimeter J-ring (mm)** | **Passing ability L-box H2/H1** | **Viscosity V-funnel (s)** | **Sieve segregation (%)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Campos et al. (2018)** | 0 | 0 | 0.45 | 0.47 | 1.17 | 650 | - | - | 0.87 | - | 9.5 |
| | 0 | 20 | 0.48 | 0.55 | 1.53 | 670 | - | - | 0.84 | - | 4.6 |
| | 20 | 0 | 0.46 | 0.60 | 1.80 | 690 | - | - | 0.85 | - | 12.8 |
| | 20 | 20 | 0.49 | 0.70 | 0.81 | 620 | - | - | 0.91 | - | 12.3 |
| **Carro-López et al. (2015; 2017)** | 0 | 0 | 0.48 | 0.43 | 1.70 | 830 | 2.2 | 810 | 0.90 | 8.0 | - |
| | 0 | 20 | 0.49 | 0.43 | 1.80 | 790 | 2.0 | 750 | 0.85 | 11.0 | - |
| | 0 | 50 | 0.53 | 0.43 | 2.80 | 770 | 2.8 | 740 | 0.88 | 8.0 | - |
| | 0 | 100 | 0.59 | 0.43 | 5.40 | 670 | 5.4 | 600 | 0.77 | 11.0 | - |
| **González-Taboada et al. (2017a; 2017b; 2017c; 2018a; 2018c) (M1/M2/M3)** | 0 | 0 | 0.46 | 2.46 | 1.45 | 820 | 2.5 | 820 | 0.90 | 23.0 | 14.0 |
| | 20 | 0 | 0.46 | 2.46 | 1.95 | 740 | 3.0 | 750 | 0.86 | 24.0 | 13.5 |
| | 50 | 0 | 0.46 | 2.46 | 2.40 | 710 | 3.8 | 700 | 0.88 | 31.0 | 12.0 |
| | 100 | 0 | 0.46 | 2.46 | 4.10 | 680 | 4.2 | 680 | 0.84 | 33.0 | 3.5 |
| | 0 | 0 | 0.46 | 2.46 | 1.50 | 820 | 2.5 | 820 | 0.90 | 24.0 | 14.0 |
| | 20 | 0 | 0.46 | 2.46 | 2.25 | 730 | 3.2 | 710 | 0.87 | 34.0 | 14.5 |
| | 50 | 0 | 0.48 | 2.46 | 2.00 | 720 | 4.8 | 660 | 0.89 | 42.0 | 24.5 |
| | 100 | 0 | 0.52 | 2.46 | 2.20 | 750 | 1.0 | 860 | 0.64 | 18.0 | 37.0 |
| | 0 | 0 | 0.46 | 2.46 | 1.45 | 820 | 2.5 | 820 | 0.90 | 23.0 | 14.0 |
| | 20 | 0 | 0.46 | 2.46 | 2.30 | 720 | 3.2 | 730 | 0.85 | 26.0 | 12.0 |
| | 50 | 0 | 0.46 | 2.46 | 2.60 | 710 | 3.9 | 690 | 0.86 | 33.0 | 9.0 |
| | 100 | 0 | 0.46 | 2.46 | 4.40 | 660 | 4.5 | 660 | 0.78 | 22.0 | 4.5 |
| **Grdic et al. (2010)** | 0 | 0 | 0.41 | 0.98 | 5.60 | 730 | - | - | 0.94 | - | 11.7 |
| | 50 | 0 | 0.43 | 0.98 | 5.40 | 730 | - | - | 0.95 | - | 9.3 |
| | 100 | 0 | 0.45 | 0.98 | 6.00 | 720 | - | - | 0.98 | - | 5.2 |
| **Kebaïli et al. (2015)** | 0 | 0 | 0.53 | 1.05 | 2.50 | 730 | - | - | 0.80 | - | - |
| | 40 | 0 | 0.57 | 1.05 | 2.40 | 680 | - | - | 0.10 | - | - |
| | 60 | 0 | 0.59 | 1.05 | 2.90 | 600 | - | - | 0.00 | - | - |
| | 100 | 0 | 0.63 | 1.05 | - | 470 | - | - | 0.00 | - | - |

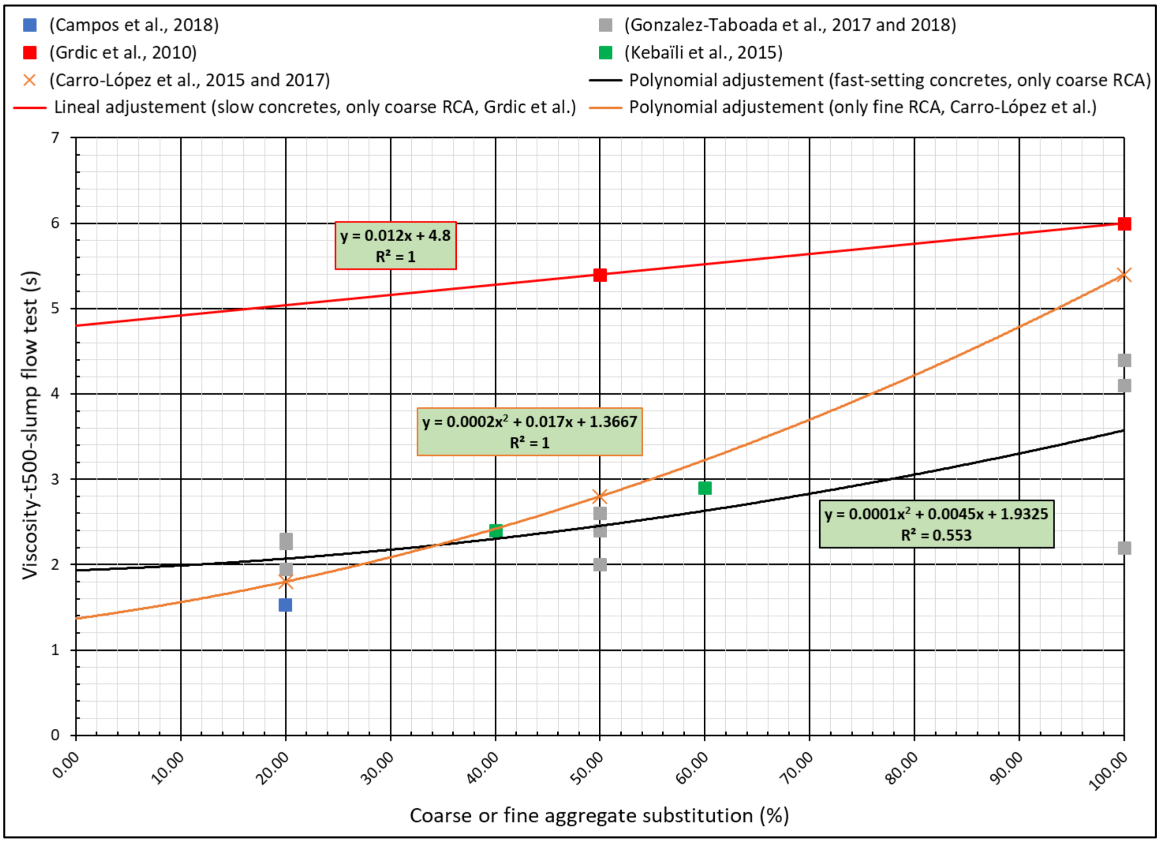

*Figure 1: Viscosity in the $t_{500}$ -slump flow test as a function of coarse aggregate substitution rates*

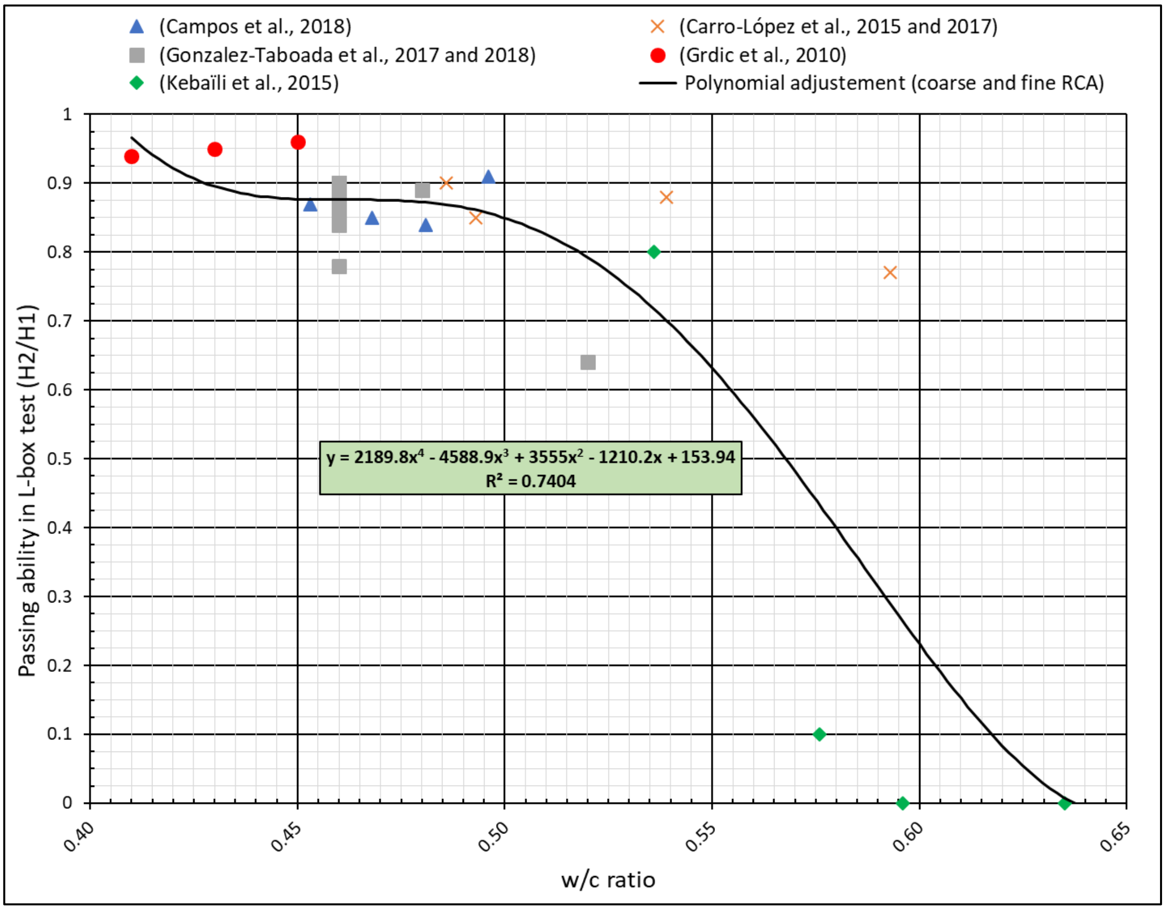

*Figure 2: Passing ability in the L-box test as a function of the w/c ratio*

Through these data, the following conclusions on SCC manufactured with RCA can be established:

- The greater the percentage of RCA substitution, the greater the viscosity of the mixture and the lower its flowability, due to the higher RCA water absorption levels, which are not usually compensated with the additional water added to the mixtures.
- The average flowability values appear to increase slightly with the amount of superplasticizer. Nevertheless, a larger amount of superplasticizer appears not to ensure better flowability by itself, due to the significant influence of other aspects, such as the water absorption and the amount of RCA.
- In principle, a higher w/c ratio should lead to greater flowability. However, increasing amounts of water are required, due to the higher water absorption of the RCA rather than the NA. Additional water can sometimes be insufficient to compensate for the extra-water absorbed by the RCA, making the effective w/c ratio lower when the RCA percentage increases. Finally, despite the increase in the w/c ratio, it can lead to lower flowability and a lower passing ability in the L-box test.

## 4.2. FRESH STATE OF SCC WITH RCA AND OTHER WASTES (FLY ASH, SILICA FUME, RECYCLED ASPHALT PAVEMENT AGGREGATES, RUBBER GRANULES, SLAGS)

In Table 4, the results from several investigations are summarized on the joint use of RCA and other wastes, namely, fly ash (FA), silica fume (SF), recycled asphalt pavement (RAP), ground granulated blast-furnace slag (GGBFS), and rubber. The results are subsequently discussed.

*Table 4: Values of some studies on the SCC flowability tests in concretes with RCA and other wastes*

| Research | Waste Use (replacement rate) | Coarse RCA content (%) | Fine RCA content (%) | Viscosity $T_{500}$ slump flow (s) | Slump flow (mm) | Viscosity $t_{500}$ J-ring (s) | Maximum diameter J-ring (mm) | Passing ability L-box H2/H1 | Viscosity in V-funnel (s) | Segregation (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Salesa et al. (2017) | Multi-RCA[1] | 100 | 0 | SF1 | 640 | - | - | - | - | - |
| | | 100 | 0 | SF2 | 740 | - | - | - | - | - |
| | | 100 | 0 | SF2 | 710 | - | - | - | - | - |
| | | 100 | 0 | SF2 | 660 | - | - | - | - | - |
| (Santos et al., 2019b) (PC-45/PC-65) | FA[2] (90 %) | 0 | 0 | 2.5 | 733 | - | - | 0.80 | 7.5 | - |
| | | 25 | 25 | 2.5 | 690 | - | - | 0.80 | 9.0 | - |
| | | 50 | 50 | 2.5 | 688 | - | - | 0.80 | 8.0 | - |
| | | 100 | 0 | 3 | 698 | - | - | 0.83 | 7.0 | - |
| | | 0 | 100 | 2.5 | 685 | - | - | 0.80 | 7.0 | - |
| | FA[2] (34 %) | 0 | 0 | 2 | 765 | - | - | 0.81 | 9.0 | - |
| | | 25 | 25 | 2.5 | 760 | - | - | 0.84 | 9.0 | - |
| | | 50 | 50 | 2.5 | 700 | - | - | 0.90 | 8.0 | - |
| | | 100 | 0 | 3 | 718 | - | - | 0.80 | 9.0 | - |
| | | 0 | 100 | 2.5 | 683 | - | - | 0.80 | 11.0 | - |
| Hu et al. (2017) | Eco-SCC 1/12.5 RCA FA[2] (25 %) | 0 | 0 | 3.9 | 660 | - | 584 | - | - | - |
| | | 50 | 0 | 9.8 | 610 | - | 457 | - | - | - |
| | | 100 | 0 | 6.2 | 559 | - | 483 | - | - | - |
| Revathi et al. (2013) | FA[2] (56 %) | 0 | 0 | 3.0 | 750 | - | - | - | 7.8 | - |
| | | 25 | 0 | 4.0 | 730 | - | - | - | 7.9 | - |
| | | 50 | 0 | 4.0 | 730 | - | - | - | 8.3 | - |
| | | 75 | 0 | 5.0 | 700 | - | - | - | 8.8 | - |
| | | 100 | 0 | 5.0 | 710 | - | - | - | 10.5 | - |
| Vinay Kumar et al. (2017) | FA[2] (33 %) | 0 | 0 | 1.8 | 710 | - | - | 0.92 | 8.0 | 5.8 |
| | | 20 | 0 | 2.0 | 690 | - | - | 0.91 | 8.0 | 5.3 |
| | | 0 | 20 | 2.0 | 710 | - | - | 0.97 | 8.0 | 5.3 |
| | | 20 | 20 | 2.0 | 640 | - | - | 0.93 | 10.0 | 5.1 |
| Tang et al. (2016) | FA[2] (35 %), SF[2] (6.7 %) | 0 | 0 | 2.9 | 710 | - | - | 0.94 | - | 9.9 |
| | | 25 | 0 | 3.7 | 700 | - | - | 0.95 | - | 7.7 |
| | | 50 | 0 | 3.9 | 720 | - | - | 0.97 | - | 6.3 |
| | | 75 | 0 | 4.1 | 710 | - | - | 0.92 | - | 6.0 |
| | | 100 | 0 | 4.3 | 700 | - | - | 0.93 | - | 5.2 |
| Yasser Khodair (2017) | RAP aggregate[3] | 0 | 0 | 3.0 | 530 | 4.0 | 510 | - | - | 0.0 |
| | | 25 | 0 | 4.0 | 610 | 6.0 | 530 | - | - | 0.0 |
| | | 50 | 0 | 5.0 | 640 | 7.0 | 580 | - | - | 0.0 |
| | | 75 | 0 | 5.0 | 640 | 7.0 | 580 | - | - | 0.0 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aslani et al. (2018)** | FA[2] (75 %), SF[2] (19 %), GGBFS[2] (56 %) | 0 | 0 | 2.0 | 690 | - | 650 | - | - | - |
| | | 10 | 10 | 2.1 | 690 | - | 630 | - | - | - |
| | | 20 | 20 | 2.4 | 650 | - | 560 | - | - | - |
| | | 30 | 30 | 2.3 | 620 | - | 530 | - | - | - |
| | | 40 | 40 | 3.0 | 600 | - | 500 | - | - | - |

[1] The RCA rate indicated in the third column “coarse RCA content” is for Multi-RCA

[2] Percentages respect the amount of cement added to the mix

[3] The values indicated in the third column “coarse RCA content” are the sum of the percentages of RCA and RAP aggregate

Research studies with different percentages of FA and RCA and RCAs of different origin have been carried out. In general, their main observations were that the joint use of RCA and FA provided SCC with appropriate in-fresh performance (Kou and Poon, 2009). The behavior of SCRC was similar to the concrete with natural filler (section 4.1.) (Rajhans et al., 2018a). The use of FA led to a higher w/c ratio than when using only cement and natural filler (Vinay Kumar et al., 2017).

Santos et al. (2019b) developed a concrete by incorporating coarse and fine RCA at several replacement rates (25/25, 50/50, 100/0 and 0/100) and FA, keeping the effective w/c ratio constant. Their results showed that an SCC could be obtained with precise and careful dosing by using an RCA with a high content of fines. Its flowability in the fresh state was similar to the flowability of non-recycled SCC.

Hu et al. (2017) studied the in-fresh performance of an eco-efficient SCC (Eco-SCC) combining FA and RCA in 1/12.5 continuous granulometry. The Eco-SCC was based on an optimal gradation of the aggregate particles, so that the mixture had less need for cement paste. The addition of RCA worsened slump flow and viscosity with regard to common SCC, although the water content was increased.

Singh, R.B. and Singh, B. (2018) and Kapoor et al. (2016) analyzed the joint use of RCA, FA, SF and metakaolin in different combinations. These authors succeeded in obtaining an SCC with good in-fresh behavior, which requires a good dosage, adapted to the waste that is used, and, generally, larger amounts of superplasticizer and, more than anything, a higher w/c ratio (Tang et al., 2016).

The joint use of RCA and FA can be considered commonplace, but lately, the incorporation of new wastes in the concrete mixture is becoming more common. Some authors successfully combined RCA with other types of waste to produce SCC.

Yasser Khodair (2017) studied the performance of SCC using RCA and RAP, in joint percentages of 25, 50, and 75 % of the total. In addition, FA and GGBFS were added to the mix: 70 % FA, 70 % GGBFS and 25 % FA and GGBFS jointly, all of them with respect to the cement mass. The addition of RAP aggregate had no effect on the performance levels recorded for FA incorporated in concrete with RCA. Nevertheless, the use of FA and GGBFS in substitution of cement appeared to increase flowability in the slump-flow test, reaching a greater maximum diameter, although the concrete became slower, because it took more time to reach that maximum diameter.

Aslani et al. (2018) designed a very complete study of three different mixtures in terms of aggregates substitution: one of them with only coarse and fine RCA (shown in Table 4), a second adding rubber granules and a third mix adding coarse and fine RAP aggregates. These wastes were used in replacement of 0 % to 40 % of NA. In addition, partial substitution of cement by FA, SF and GGBFS was also tested in the three mixtures. Regarding flowability, the results showed that the greater the percentage substitutions of RCA, the lower the flowability, as discussed in previous studies. Nevertheless, the joint use of fine RCA and rubber granules stabilized flowability. There again, the use of rubber granules and GGBFS in small percentage substitutions increased flowability compared to SCC manufactured with NA. A precise definition of their behavior will require a separate evaluation of the effects of each co-product.

Silva et al. (2016) evaluated the joint use of RCA and masonry residues, the latter in partial replacement of filler. They found that the flowability of the concrete with masonry residues was equal to or even better than the flowability obtained with RCA and filler. Nevertheless, the bulk density of the concrete increased, due to the greater density of the masonry in comparison with the limestone filler. Uygunoılu et al. (2014) compared a concrete manufactured with coarse RCA and a concrete manufactured with coarse marble waste. The latter showed better flowability, due to its more rounded shape. The irregular shape (crushed aggregate-high angularity) of the RCA hindered higher flowability values. The addition of recycling ceramic waste powder appears to result in improved slump flow if it is added in low percentages (around 10-30 %) and if its granulometry has a high content of fines, less than 10 μm (Ferrara et al., 2019).

A general conclusion can be drawn from all the above studies: the combination of different wastes in the concrete mix yields an SCC with adequate flowability for large-scale use as long as the dosage is adjusted to the amounts of added residues, to their percentage substitution, and to the flowability requirements of the concrete. The interaction of the RCA with each of the aforementioned wastes is different and its behavior must be carefully analyzed, to obtain the dosage that will optimize the performance of the SCC.

### 4.3. FRESH STATE OF SCC WITH RCA AND FIBERS

It is also possible to design Fiber Reinforced Self-Compacting Concrete (FRSCC) with RCA. The properties of the hardened concrete (toughness, impact resistance, etc.) will foreseeably be improved by the addition of fibers (Jena et al., 2018), although the behavior in the fresh state will, in general, worsen.

Nalanth et al. (2014a) and Ortiz et al. (2017) studied steel FRSCC with RCA as a replacement material. Nalanth et al. (2014a) also employed FA in substitution of cement, while Ortiz et al. (2017) used only coarse RCA. Both studies showed that the flowability decreased as the amount of RCA increased. In addition, the decrease in flowability was greater when fibers were incorporated: the higher number of added fibers, the greater the decrease, as was expected. For instance, Nalanth et al. (2014a) observed a decrease of 2.3 % in the slump flow test -with 50 % RCA, compared to a reference concrete without RCA. When 0.5 % vol. of fibers was incorporated, the decrease was around 2.6 % compared to the same reference concrete and, with 1.5 % vol. of fibers, the decrease was around 4.9 %.

Mohseni et al. (2017) and Coppola et al. (2005) analyzed FRSCC with steel and Polypropylene (PP) fibers, obtaining similar performance for both concretes, except in the flowability test, where the addition of PP fibers yielded worse slump flows (e.g. concrete with PP fibers had a slump flow of 5.8 % lower than concrete with steel fibers). That result may be due to the higher surface roughness of the PP fibers. The joint use of RCA and the fibers produced an even worse performance in the fresh state. Mohseni et al. (2017) reported slump flows that were, respectively, 3.3 % and 6.8 % lower when PP fibers and when steel fibers were used with RCA, in comparison with concretes that contained the same percentages of fibers and no RCA.

## 5. HARDENED STATE: MECHANICAL PROPERTIES.

Flowability and workability in the fresh state are the key aspects for a reliable and optimal SCC. However, the properties in the hardened state such as compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity must be likewise suit the purpose for which the concrete is intended.

In Table 5, the values obtained for the mechanical properties in different investigations are summarized. Those values are also explored in the following sections.

*Table 5: Mechanical properties of SCC*

| Research | Waste Use (substitution rate) | Coarse RCA content (%) | Fine RCA content (%) | Compressive strength (MPa) | Splitting tensile strength (MPa) | Flexural strength (MPa) | Static modulus of elasticity (GPa) |
|---|---|---|---|---|---|---|---|
| **Campos et al. (2018)** | RCA | 0 | 0 | 51 | 4.9 | - | 31 |
| | | 20 | 0 | 47 | 4.8 | - | 32 |
| | | 0 | 20 | 46 | 4.6 | - | 30 |
| | | 20 | 20 | 45 | 4.5 | - | 30 |
| **Fiol et al. (2018) (RAC-30/RAC-37,5/RAC-45)** | RCA | 0 | 0 | 49 | 5.2 | 6.2 | 37 |
| | | 20 | 0 | 50 | 5.1 | 6.3 | 39 |
| | | 50 | 0 | 56 | 4.9 | 6.4 | 35 |
| | | 100 | 0 | 57 | 4.9 | 5.6 | 34 |
| | | 0 | 0 | 58 | 5.5 | 6.9 | 39 |
| | | 20 | 0 | 60 | 5.2 | 7.6 | 42 |
| | | 50 | 0 | 59 | 5.2 | 6.2 | 37 |
| | | 100 | 0 | 71 | 5.3 | 6.7 | 36 |
| | | 0 | 0 | 63 | 5.3 | 8.0 | 41 |
| | | 20 | 0 | 64 | 5.2 | 7.8 | 43 |
| | | 50 | 0 | 67 | 5.0 | 7.9 | 38 |
| | | 100 | 0 | 73 | 5.0 | 7.8 | 38 |
| **Manzi et al. (2017)** | RCA | 0 | 0 | 44 | 3.3 | 4.0 | 26 |
| | | 13 | 12 | 45 | 3.2 | 3.8 | 25 |
| | | 21 | 19 | 50 | 2.5 | 3.0 | 29 |
| | | 40 | 0 | 51 | 3.1 | 4.1 | 27 |
| **Panda and Bal (2013)** | RCA | 0 | 0 | 27 | 4.3 | 3.7 | - |
| | | 10 | 0 | 27 | 3.9 | 3.6 | - |
| | | 20 | 0 | 25 | 3.7 | 3.2 | - |
| | | 30 | 0 | 24 | 3.4 | 3.1 | - |
| | | 40 | 0 | 21 | 2.9 | 2.9 | - |
| **Pereira-De-Oliveira et al. (2013)** | RCA | 0 | 0 | 54 | - | - | 40 |
| | | 10 | 0 | 54 | - | - | 39 |
| | | 20 | 0 | 54 | - | - | 39 |
| | | 30 | 0 | 53 | - | - | 39 |
| | | 40 | 0 | 53 | - | - | 38 |
| **Grdic et al. (2010)** | RCA | 0 | 0 | 50 | 7.2 | - | - |
| | | 50 | 0 | 48 | 7.1 | - | - |
| | | 100 | 0 | 46 | 6.2 | - | - |
| **Salesa et al. (2017)** | Multi-RCA[1] | 100 | 0 | 57 | - | - | 35 |
| | | 100 | 0 | 59 | - | - | 31 |
| | | 100 | 0 | 60 | - | - | 31 |
| | | 100 | 0 | 62 | - | - | 30 |
| **Hu et al. (2017)** | Eco-SCC 1/12.5 RCA FA[2] (25 %) | 0 | 0 | 41 | - | - | - |
| | | 50 | 0 | 48 | - | - | - |
| | | 100 | 0 | 38 | - | - | - |
| **Revathi et al. (2013)** | RCA, FA[2] (56 %) | 0 | 0 | 36 | 3.5 | 5.3 | - |
| | | 25 | 0 | 35 | 2.9 | 3.5 | - |
| | | 50 | 0 | 35 | 2.3 | 3.0 | - |
| | | 75 | 0 | 33 | 2.0 | 2.6 | - |
| | | 100 | 0 | 30 | 1.5 | 2.9 | - |
| **Vinay Kumar et al. (2017)** | RCA, FA[2] (33 %) | 0 | 0 | 43 | 3.3 | - | - |
| | | 20 | 0 | 48 | 3.4 | - | - |
| | | 0 | 20 | 46 | 3.9 | - | - |
| | | 20 | 20 | 47 | 3.4 | - | - |
| **Santos et al. (2017) (PC-45/PC-65)** | RCA, FA[2] (91 % for PC-45 and 34 % for PC-65) | 0 | 0 | 38 | 3.9 | - | 30 |
| | | 25 | 25 | 36 | 3.5 | - | 29 |
| | | 50 | 50 | 34 | 2.9 | - | 28 |
| | | 100 | 0 | 32 | 2.6 | - | 28 |
| | | 0 | 100 | 28 | 2.4 | - | 26 |
| | | 0 | 0 | 74 | 5.5 | - | 46 |
| | | 25 | 25 | 72 | 4.9 | - | 41 |
| | | 50 | 50 | 68 | 4.8 | - | 37 |
| | | 100 | 0 | 67 | 4.5 | - | 38 |
| | | 0 | 100 | 65 | 4.2 | - | 35 |
| **Kou and Poon (2009)** | RCA, FA[2] (59 %) | 100 | 0 | 44 | 2.9 | - | - |
| | | 100 | 25 | 45 | 2.7 | - | - |
| | | 100 | 50 | 43 | 2.7 | - | - |
| | | 100 | 75 | 41 | 2.6 | - | - |
| | | 100 | 100 | 39 | º2.5 | - | - |
| **Tang et al. (2016)** | RCA, FA[2] (35 %), SF[2] (6.7 %) | 0 | 0 | 59 | 4.1 | - | 32 |
| | | 25 | 0 | 64 | 4.9 | - | 30 |
| | | 50 | 0 | 65 | 4.1 | - | 30 |
| | | 75 | 0 | 60 | 3.9 | - | 29 |
| | | 100 | 0 | 54 | 3.8 | - | 25 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Gesoglu et al. (2015a) (w/b=0.3, 0 % SF/ w/b=0.3, 10 % SF/ w/b=0.43, 0 % SF/ w/b=0.43, 10 % SF)** | RCA, GGBFS[2] (25 %), SF[2] (0 % for first and third concretes and 15 % for second and fourth concretes) | 0 | 0 | 78 | 4.3 | 5.4 | 26 |
| | | 100 | 0 | 69 | 3.5 | 4.3 | 21 |
| | | 0 | 100 | 62 | 3.2 | 4.2 | 20 |
| | | 100 | 100 | 56 | 2.7 | 3.6 | 17 |
| | | 0 | 0 | 81 | 4.5 | 6.5 | 28 |
| | | 100 | 0 | 70 | 4.1 | 5.4 | 23 |
| | | 0 | 100 | 65 | 3.6 | 4.9 | 21 |
| | | 100 | 100 | 57 | 3.2 | 4.3 | 19 |
| | | 0 | 0 | 67 | 3.5 | 4.8 | 24 |
| | | 100 | 0 | 55 | 2.9 | 4.0 | 21 |
| | | 0 | 100 | 49 | 2.5 | 3.8 | 18 |
| | | 100 | 100 | 46 | 2.2 | 3.3 | 16 |
| | | 0 | 0 | 72 | 3.8 | 6.3 | 25 |
| | | 100 | 0 | 64 | 3.2 | 4.8 | 21 |
| | | 0 | 100 | 61 | 2.8 | 4.5 | 19 |
| | | 100 | 100 | 53 | 2.6 | 3.8 | 17 |
| **Aslani et al. (2018)** | RCA, FA[2] (75 %), SF[2] (19 %), GGBFS[2] (56 %) | 0 | 0 | 25 | 3.2 | - | - |
| | | 10 | 10 | 34 | 3.2 | - | - |
| | | 20 | 20 | 33 | 3.2 | - | - |
| | | 30 | 30 | 31 | 3.2 | - | - |
| | | 40 | 40 | 34 | 3.2 | - | - |
| **Yasser Khodair (2017)** | RCA, RAP aggregate[3] | 0 | 0 | 55 | 5.8 | - | - |
| | | 25 | 0 | 49 | 5.1 | - | - |
| | | 50 | 0 | 43 | 4.4 | - | - |
| | | 75 | 0 | 38 | 4.0 | - | - |
| **Silva et al. (2016)** | RCA, masonry residue[4] (20 %) | 0 | 0 | 36 | 3.1 | - | - |
| | | 25 | 0 | 32 | 2.7 | - | - |
| | | 50 | 0 | 32 | 2.7 | - | - |
| | | 75 | 0 | 33 | 2.4 | - | - |
| | | 100 | 0 | 30 | 2.3 | - | - |

[1] The RCA rate indicated in the third column “coarse RCA content” is for Multi-RCA.

[2] Percentages with respect to the amount of cement added to the mix.

[3] The values indicated in the third column “coarse RCA content” are the sum of the percentages of RCA and RAP aggregates.

[4] Percentages with respect to total amount of filler.

### 5.1. COMPRESSIVE STRENGTH

The most important property of any concrete in the hardened state is its compressive strength. In this section, the effects on that parameter of adding RCA to an SCC, by itself and in combination with other co-products, will be evaluated.

#### 5.1.1. SCC WITH RCA

Various studies have analyzed the performance of SCC manufactured with coarse RCA:

- Panda and Bal (2013) and Pereira-De-Oliveira et al. (2013) analyzed a concrete with percentage substitutions ranging between 0 % and 40 %. In both cases, the compressive strength was reduced, but Pereira-De-Oliveira et al. (2013) registered a slight strength reduction (3 %), while Panda and Bal (2013) only achieved a compressive strength of 75 % compared to the reference SCC. The reduction of the compressive strength was mainly attributed to the higher RCA water absorption values, which led to a greater w/c ratio. Nevertheless, the difference between both studies is mainly attributable to the different origins of the RCA, of decisive influence on the performance and the quality of the RCA concrete.

- Manzi et al. (2017) evaluated low replacement rates of RCA and Fiol et al. (2018) analyzed concrete mixtures with percentages of 50 % and 100 % of RCA. They both obtained compressive strength values for SCRC that were higher than non-recycled SCC (for 100 % of coarse RCA, the compressive strength was around 16 % greater, according to both studies). The authors explained their results in terms of higher RCA water absorption compared to NA, the constant amount of water added to all the mixes and the dry state of the aggregates. All those factors produced a lower effective w/c ratio, which favored a higher compressive strength.

- The above observation was also endorsed in the study of Salesa et al. (2017) on multi-recycled SCC and its behavior. The fact that the amount of water was the same at every stage, while the attached non-hydrated mortar content increased, led to greater absorption and higher compressive strengths of the SCC concrete mixtures of multi-recycling stages.

- Grdic et al. (2010) aimed to compensate the extra RCA water absorption and to maintain a uniform effective w/c ratio for the different percentages under study (50 % and 100 % of the coarse fraction). They observed a decrease in the compressive strength as the RCA content ~~rate~~ increased when the mixtures were designed with a uniform effective w/c ratio.

- Assaad (2017) obtained SCC samples of lower compressive strengths, by adding a high content of coarse RCA, at a constant w/c ratio. The Direct Replacement (DR) method increased the strength of the mixtures.

The incorporation of low amounts of fine RCA in the mix (under 20 %) appeared to have no appreciable effect on compressive strength, according to the studies of Manzi et al. (2017), who used fine RCA percentages between 12 % and 19 %. Those results were corroborated by Campos et al. (2018), who used a percentage substitution of 20 % for fine and coarse RCA, and obtained a decrease in the compressive strength of only 5 %, mainly attributed to the fine RCA. Nevertheless, the same effect was more pronounced at higher substitutions, as Carro-López et al. (2015) demonstrated with 100 % percentage substitution of fine RCA and a constant w/c ratio, which reduced the compressive strength to around 40 %.

According to the studies evaluated, a concrete with coarse RCA and a good compressive strength can be obtained by using a high-quality RCA and reducing the effective w/c ratio.

Other authors have analyzed the performance of SCC with RCA and some different mineral admixtures to replace part of the cement. Boudali et al. (2016) and Omrane et al. (2017) analyzed the addition of natural pozzolans. The results showed that the addition of this admixture, together with RCA, decreased the compressive strength more than with only RCA. Omrane et al. (2017) showed that the substitution of 15 % cement by natural pozzolan decreased concrete compressive strength by around 24 %, while the joint use of 15 % natural pozzolan and a blend of 50 % fine and coarse RCA decreased compressive strength by around 30 %, while the amount of water in each mix was maintained at a constant level.

### 5.1.2. SCC WITH RCA AND OTHER WASTES (FLY ASH, SILICA FUME, RECYCLED ASPHALT PAVEMENT AGGREGATES, RUBBER GRANULES, AND SLAGS)

In various studies, the addition of FA in substitution of cement produced a much more pronounced reduction in compressive strength than the use of RCA alone (Revathi et al., 2013), both with only coarse RCA (Santos et al., 2017) and with fine and coarse RCA (Kou and Poon, 2009). This latter combination of coarse RCA, fine RCA and FA produced the lowest compressive strength. The compressive strength could be recovered to some degree by adjusting the effective w/c ratio, although never as effectively as when only using RCA.

Vinay Kumar et al. (2017) obtained higher compressive strengths than the control concrete with 33 % of FA in proportion to the cement mass for low RCA substitution percentages (20 % coarse RCA, 20 % fine RCA or 20 % of both jointly). The increase in strength was around 6 % and the maximum increase was linked to the use of only coarse RCA (7.3 %).

The optimal packing of aggregate particles produced in an Eco-SCC was beneficial for compressive strength when RCA and FA were used (Hu et al., 2017). It is noticeable that the compressive strength of the mixture with 50 % of RCA increased around 17 % with respect to the control mix.

The joint use of RCA, FA, and SF led to similar results, however, SCRC with higher strengths than the reference concrete was achieved at high replacement percentages up to 75 % (Tang et al., 2016), maintaining the effective w/c ratio at a constant level (Singh et al., 2017). The authors attributed this performance to the use of SF.

Gesoglu et al. (2015a) analyzed an SCC manufactured with coarse and fine RCA and SF. It was observed that concrete with 10 % SF increased compressive strength by approximately 10 %, compared to SCC with the same percentage of RCA and no SF (Kapoor et al., 2016).

As indicated in subsection 4.2., Yasser Khodair (2017) and Aslani et al. (2018) designed a concrete with several wastes: RCA, RAP aggregate, rubber granules, FA, GGBFS, and SF in many different combinations. From all these combinations, some conclusions may be drawn. Firstly, the joint use of RCA and RAP aggregates or RCA and rubber granules had the same performance as RCA alone: the higher the substitution rate, the lower the compressive strength; although this effect was sometimes compensated by additional water with a different result in each case. In contrast, GGBFS appeared to have a better effect than FA. Finally, the effect of SF appeared to be unaffected by the addition of other waste apart from RCA. Nevertheless, the strength performance is unpredictable in multiple residues combination, and, an in-depth and individual specific investigation into each combination is necessary.

Neither masonry residue (Silva et al., 2016) nor marble waste (Uygunoǐlu et al., 2014) appeared to affect the compressive strength of the SCC with RCA. The addition of recycled ceramic waste in powder form reduced the compressive strength, although this decrease can be compensated for by reducing the water content if this waste has a high particle content of less than 10 μm in size (Ferrara et al., 2019).

### 5.1.3. SCC WITH RCA AND FIBERS

Finally, recycled FRSCC can be analyzed. As expected, a higher compressive strength was obtained for the concrete with fibers than for the concrete without fibers. This strength increased as the proportion of fibers increased (Nalanth et al., 2014b), and it decreased as the percentage of RCA increased (Ortiz et al., 2017).

In addition, Mohseni et al. (2017) noted that the effect of steel fibers on compressive strength was far more noticeable than the effect of PP fibers, although the joint use of both fiber types yielded even higher strengths.

### 5.1.4. COMPRESSIVE STRENGTH CONCLUSIONS

The compressive strengths noted in the works on SCC manufactured with only RCA and with both RCA and FA are represented in Figure 3; the abscissa of the graph reflects the coarse RCA substitution rate. The values can also be observed in a summary of the results in Table 5.

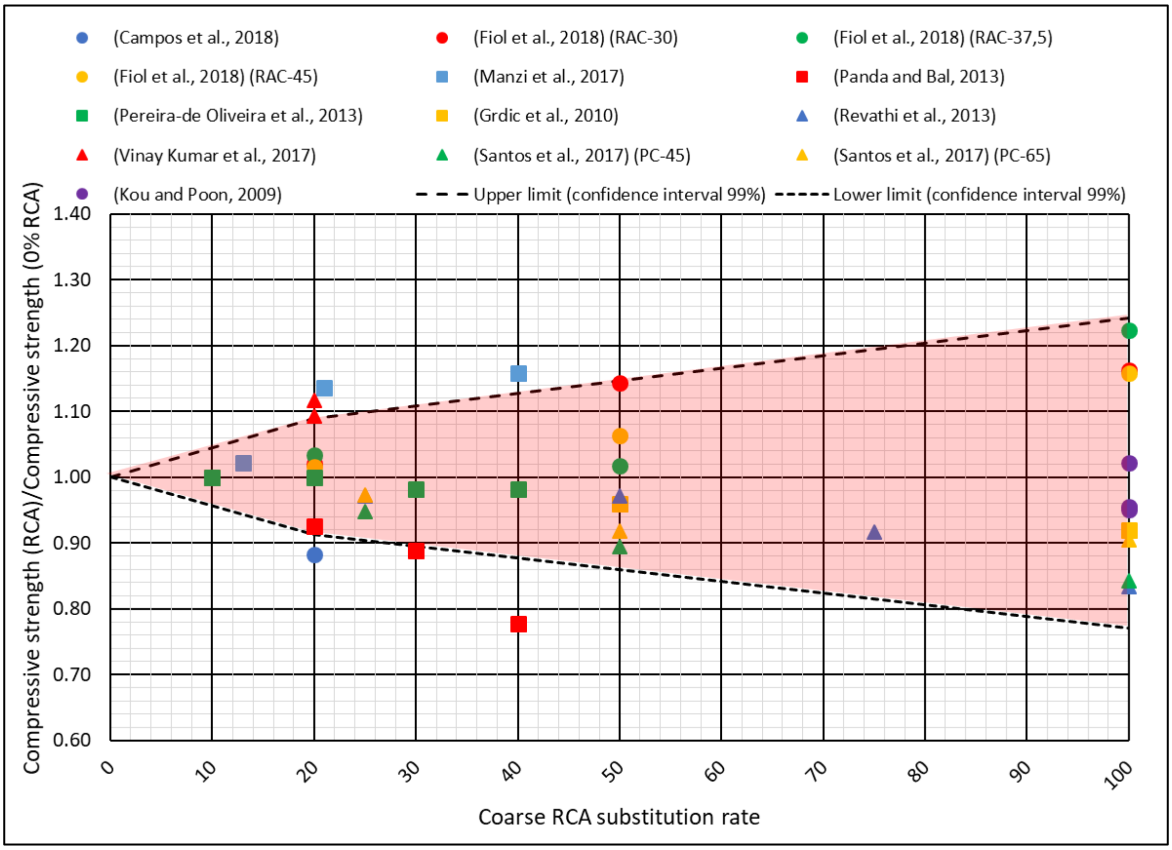

*Figure 3: Compressive strength evolution as a function of coarse RCA substitution rates (99 % confidence interval).*

Some conclusions can be established from the above data that are valid for SCC manufactured with RCA and, optionally, with a reduced percentage of FA:

- A clear trend for the effect of the coarse RCA on the concrete compressive strength cannot be established. There is a high dispersion of the compressive strength values for a certain replacement rate of coarse RCA in the different studies, with values both above and below those of the reference concrete. Moreover, the higher the amount of RCA, the greater dispersion, which shows that the uncertainty increases with the RCA replacement rate. The variables that cause this dispersion are different, such as the origin and quality of the recycled aggregate, the amount of adhered mortar and the compressive strength of the concrete of origin.

- In spite of the aforementioned dispersion, most of the values are within the limits of the confidence interval. These results show that despite the absence of a clear trend, the compressive strength of the concrete with coarse RCA can be delimited. The values that are not within that interval usually corresponded either to studies that presented low-quality RCA (Panda and Bal, 2013), to studies that included both coarse and fine RCA (Campos et al., 2018; Manzi et al., 2017) or to studies in which RCA and FA is used jointly (Vinay Kumar et al., 2017) in which the fine fraction appeared to intensify the dispersion, increasing or decreasing the compressive strength beyond expected levels.

- The substitution of NA by RCA may be expected to decrease compressive strength. Nevertheless, an SCC of greater compressive strength than non-recycled concrete was achieved in three different studies (Fiol et al., 2018; Manzi et al., 2017; Vinay Kumar et al., 2017), as can be seen from Figure 3. This behavior is because the w/c ratio was held constant, so the high absorption of the RCA caused a lower effective w/c ratio. The negative effect of the RCA on compressive strength can very simply be compensated by adjusting the dosage. These factors also favor the dispersion that is mentioned above.

No general conclusions can be drawn with regard to the effect of fine RCA, because the studies that evaluate its use are very scarce and, as with coarse RCA, all the results are highly dispersed. The absence of studies on the behavior of fine RCA may be due to the widely accepted fact that their effects are harmful in non-SCC, based on different studies (Evangelista and De Brito, 2014) and their use is strictly limited in standards and regulations (EHE-08, 2010).

## 5.2. SPLITTING TENSILE STRENGTH AND FLEXURAL STRENGTH

Splitting tensile strength and flexural strength values are also affected by the replacement of NA for RCA with other waste co-products, which will be evaluated in this section.

### 5.2.1. SCC WITH RCA

In all studies on the use of RCA alone, the reference SCC manufactured with NA achieved the highest splitting tensile strength (Grdic et al., 2010). The higher the substitution rate, the lower the splitting tensile strength (Panda and Bal, 2013). In that case, the splitting tensile strength was not related to the effective w/c ratio as much as the compressive strength (Fiol et al., 2018), so that strength value could not be compensated by decreasing the effective w/c ratio (Manzi et al., 2017).

Flexural strength behavior (Fiol et al., 2018) appeared very similar to splitting tensile strength behavior in various studies (Panda and Bal, 2013). As a property, it is rarely analyzed in the different research lines, because it is largely conditioned by the segment of the test sample that is placed under traction.

### 5.2.2. SCC WITH RCA AND OTHER WASTES (FLY ASH, SILICA FUME, RECYCLED ASPHALT PAVEMENT AGGREGATES, RUBBER GRANULES, AND SLAGS)

The behavior of concrete manufactured with both RCA and FA can be inconsistent, mainly due to weaker bonding between the RCA and the FA than between the RCA and the cement matrix.

In all the referenced studies in which RCA and FA were jointly examined (Kou and Poon, 2009), similar behaviors for splitting tensile strength and for compressive strength were observed: weaker strengths with higher additions of RCA (Revathi et al., 2013). However, unlike concretes with only RCA, the reduction of an effective w/c ratio in concretes with both RCA and FA appeared to compensate the overall decrease in strength as the RCA content increased (Vinay Kumar et al., 2017), but only if the replacement percentage of RCA was low (less than 20 %). At higher RCA rates, that reduction will no longer be compensated and when the amount of RCA increases, the strength will decrease too (Santos et al., 2017).

The behavior of concrete with combinations of either RCA, FA and SF or with RCA and SF was stable. The splitting tensile strength presented very similar performance to the compressive strength, increasing the strength without reducing the effective w/c ratio (Tang et al., 2016), although again only at low RCA contents, no higher than 25 % (Gesoglu et al., 2015a).

Revathi et al. (2013) presented a study on coarse RCA and FA, in which they observed lower flexural strengths, due to the additions of FA, as the percentage of coarse RCA increased. For instance, the flexural strength of a concrete with 25 % coarse RCA and 56 % FA (as a proportion of the cement mass) decreased by around 17 % in relation to the reference concrete. However, in a concrete with 100 % coarse RCA, that decrease was around 59 %. Gesoglu et al. (2015a) observed the same performance in a concrete with only RCA and SF.

The influence of the other wastes on the splitting tensile strength and flexural strength values was similar to their effect on compressive strength. Masonry and marble waste appeared to have no influence (Silva et al., 2016), unlike RCA, the effects of which appeared to be fundamental (Uygunoƚlu et al., 2014). Recycled ceramic waste in powder form affected compressive strength in a similar way to flexural strength (Ferrara et al., 2019). In comparison with FA, slag was found to reduce any decrease in strength compared to FA (Yasser Khodair, 2017) and multi-material SCRC showed no clear pattern of behavior in the analysis by Aslani et al. (2018).

### 5.2.3. SCC WITH RCA AND FIBERS

The use of fibers can compensate the decrease in splitting tensile strength and flexural strength that is produced by the addition of RCA and, in some cases, RCA concrete can have a greater strength than the reference SCC specimen: the addition of 0.5 % vol. of fibers was found to compensate the strength loss caused by increases of up to 40 % in RCA content (Nalanth et al., 2014a). Mohseni et al. (2017) found once again that strength improvements were better with steel rather than with PP fibers, although the joint use of both fiber types produced higher strengths. The formulas for flexural strength values included in the standards provided results that were in line with the empirical values (Ortiz et al., 2017).

### 5.2.4. GENERAL CONCLUSIONS

The evolution of splitting tensile strength is shown in **¡Error! No se encuentra el origen de la referencia.** as a function of the percentage substitution of NA by coarse RCA. Flexural strength is not represented, due to a scarcity of data, but its behavior is expected to mirror the behavior of splitting tensile strength. Table 5 also shows the values used in this graph.

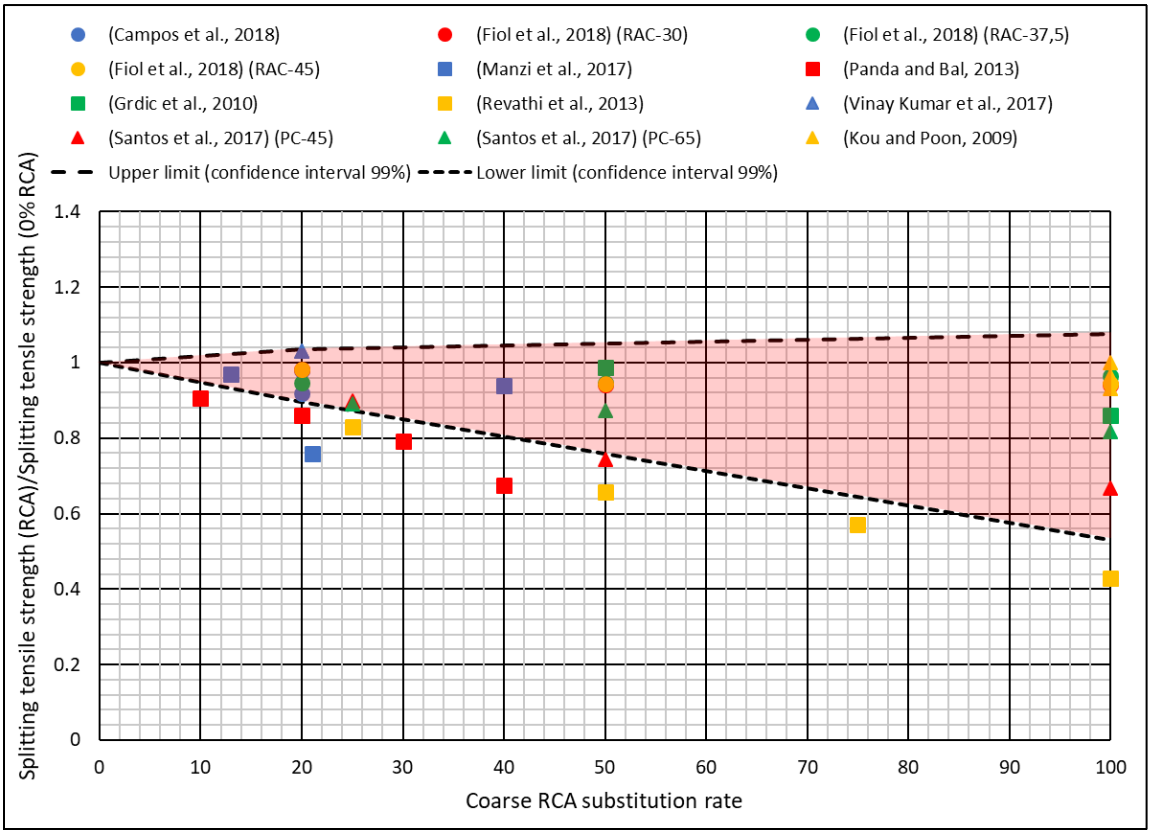

*Figure 4: Splitting tensile strength evolution as a function of coarse RCA percentage substitutions (99 % confidence interval).*

- Firstly, a clear downward trend of splitting tensile strength can be globally observed as the percentage of RCA increases (most strength ratios between the SCRC and the reference concrete were less than one). The lower limit of the interval clearly reflects this trend.
- Secondly, the values show a high dispersion for each RCA replacement rate. Moreover, in this case, the points of the four studies below the lower limit of the confidence interval (Manzi et al., 2017; Panda and Bal, 2013; Revathi et al., 2013; Santos et al., 2017) cannot all be justified with the use of fine RCA, as opposed to compressive strength.

Once again, the scarcity of studies on fine RCA means that its effect of the strength of SCC cannot be assessed. However, the detrimental effect of fine RCA on the splitting strength on non-self-compacting concretes, even more so than on their compressive strength, has been demonstrated (Behera et al., 2014).

## 5.3. MODULUS OF ELASTICITY

The modulus of elasticity defines the deformational behavior of concrete in the elastic zone. It is used to estimate stiffness and, consequently, stress and strain distributions within structural components should be carefully studied, bearing in mind the effects of RCA.

### 5.3.1. SCC MADE WITH RCA

Pereira-De-Oliveira et al. (2013) and Fiol et al. (2018) assessed the dynamic modulus of elasticity in an SCC manufactured with coarse RCA. Both concluded that the modulus of elasticity was lower (albeit only marginally), at higher percentages of RCA. According to Fiol et al. (2018), the decrease was around 9 % for 100 % coarse RCA. The relationship between the dynamic and the static moduli, at approximately between 60 and 70 %, was similar to other studies.

The performance of the static modulus of elasticity was evaluated by Fiol et al. (2018) and Campos et al. (2018). It was very similar to the dynamic modulus described above, in both cases descending as the proportion of RCA increased. However, the static modulus was even higher than that of the control concrete, at low RCA percentages. In addition, the decrease in the static modulus was slightly lower at high RCA ratios than the dynamic modulus of elasticity, e.g. for 100 % of RCA, the decrease was around 6 % (Fiol et al., 2018). Nevertheless, Manzi et al. (2017) obtained values that were 4 % higher than those of the control concrete at 100 % replacement percentages.

It can be concluded from the above that the modulus of elasticity does not depend heavily on the RCA content, but on the RCA and its properties (the quality of the RCA, roughness, amount of attached mortar...). In addition, whenever a high modulus of elasticity was obtained, it was evidence of good adhesion between the old and the new mortars.

Interestingly, the lineal relationship between the compressive strength and modulus of elasticity was maintained (Bordelon et al., 2009), regardless of the percentage substitution or the RCA fraction in use (Safiuddin et al., 2011).

### 5.3.2. SCC WITH RCA AND OTHER WASTES (FLY ASH, SILICA FUME, RECYCLED ASPHALT PAVEMENT AGGREGATES, RUBBER GRANULES, AND SLAGS)

If FA is added to the mix, the decrease in the modulus of elasticity is much more noticeable, because of the worse adherence of the aggregate to the FA than to cement (Santos et al., 2017). These authors obtained a decrease of around 15 % with respect to the control concrete. The addition of SF to concrete containing RCA led to a lower decrease of the modulus of elasticity (Gesoglu et al., 2015a), so the adverse effect of the addition of FA can be compensated by the addition of SF, leaving any decrease in the modulus of elasticity at around 10 % (Tang et al., 2016).

In addition, Gesoglu et al. (2015a) established that the modulus of elasticity in an SCC with RCA and SF continued to show a linear relationship with the compressive strength, as in the case where only RCA is used.

According to Uygunoğlu et al. (2014), the joint use of RCA and marble waste produced a much lower modulus of elasticity. The decrease was around 33 %, mainly due to the marble waste, because the decrease was around 8 % with only RCA. Moreover, concrete with both wastes was, in consequence, less rigid and fragile. Again, the combinations of other wastes followed no clear pattern, with different values in each case (Aslani et al., 2018).

### 5.3.3. SCC WITH RCA AND FIBERS

Ortiz et al. (2017) affirmed that the content, particle size, and nature of RCA have a greater impact on the value of the modulus of elasticity than on the other mechanical properties analyzed above (compressive strength, splitting tensile strength…), mainly because of the configuration of the granular skeleton. So, the addition of fibers in this case could not compensate the decrease caused by the RCA, producing only a negligible improvement.

## 5.4. VOLUMETRIC PROPERTIES AND OTHERS

The density of hardened SCC manufactured with RCA and, optionally, with other wastes, has been evaluated in several research works. Pereira-De-Oliveira et al. (2013) and Fiol et al. (2018) manufactured their concrete with only coarse RCA and, for all the substitution percentages, found that the density of the concrete decreased slightly as the substitution percentage increased, by around 0.5 % for 25 % RCA, and, by around 3 % for 100 % RCA, regardless of the compressive strength of the concrete. The addition of FA to the mixture slightly intensified the decreased density, by an additional decrease of around 1 %, due to the lower specific weight of FA with respect to the cement (Santos et al., 2017). Either masonry residue (Silva et al., 2016) or fibers at low percentages of around 0.5 % (Ortiz et al., 2017) hardly appeared to affect this property. The concrete density was mainly dependent on the RCA.

The density is highly related to the porosity of the concrete. Fiol et al. (2018) reported that, for a 100 % substitution percentage of coarse RCA, open porosity increased by around 1.5 -1.8 %. In addition, Manzi et al. (2017) observed that the higher the flowability in the fresh state, the lower the open porosity.

Ultrasonic Pulse Velocity (UPV) is, in turn, related to the measurement of both porosity and the quality of any Interfacial Transitions Zones (ITZ) present in the concrete that hinder the UPV wave propagation. It also depends on the density of the concrete. This property decreased with larger amounts of RCA. Fiol et al. (2018) found that UPV reduction was, on average, around 4 %. Other wastes combined with RCA, such as masonry (Santos et al., 2017) and marble (Uygunoğlu et al., 2014), had negligible effects compared to the use of RCA by itself.

Abrasion resistance and fracture energy (Bordelon et al., 2009) were analyzed in a concrete with both RCA and FA (Tang et al., 2016). Once again, their values were lower when the RCA substitution rate increased, but an increase in FA improved those properties (Santos et al., 2017). In contrast, the use of SF, jointly with RCA, caused a more brittle behavior (low characteristic length) (Gesoglu et al., 2015a).

Velay-Lizancos et al. (2016; 2017) analyzed the influence of temperature on the compressive strength of SCC. They found that the higher the substitution percentage, the greater the difference in strength at different temperatures, with an optimum of 20ºC at all ages.

## 6. DURABILITY

In Table 6, durability and other long-term properties evaluated by the main articles in this review are shown, followed by a discussion of their results.

*Table 6: Durability properties analyzed by different research lines*

| Research | Waste used | Durability properties analyzed |
|---|---|---|
| **Grdic et al. (2010)** | RCA | Water absorption |
| **Fiol et al. (2018)** | RCA | Water absorption |
| **Pereira-De-Oliveira et al. (2014)** | RCA | Permeability |
| **Boudali et al. (2016)** | RCA | Resistance to sulphate attack<br>Compressive strength after sulphate attack is analyzed (immersion-drying cycles and total immersion) |
| **Manzi et al. (2015, 2017)** | RCA | Creep<br>Drying shrinkage<br>Shrinkage |
| **Salesa et al. (2017)** | Multi-RCA | Water absorption |
| **Omrane et al. (2017)** | RCA (and natural pozzolan) | Resistance to penetration of chloride ions<br>Resistance to sulphate attack |
| **Santos et al. (2019b)** | RCA, FA | Water absorption<br>Capillary absorption<br>Oxygen permeability<br>Resistance to penetration of chloride ions<br>Electrical resistivity<br>Carbonation depth |
| **Rajhans et al. (2018a, b)** | RCA, FA | Water penetration depth<br>Resistance to penetration of chloride ions<br>Carbonation depth<br>Creep<br>Drying shrinkage |
| **Kou and Poon (2009)** | RCA, FA | Penetration of chloride ions<br>Drying shrinkage |
| **Vinay Kumar et al. (2017)** | RCA, FA | Resistance to sulphate attack<br>Resistance to acid attack |
| **Singh and Singh (2016b)** | RCA, FA, metakaolin | Carbonation depth |
| **Singh, N. and Singh, S.P. (2018a)** | RCA, SF | Carbonation depth |
| **Yasser Khodair (2017)** | RCA, RAP aggregate | Permeability<br>Drying shrinkage<br>Shrinkage |
| **Silva et al. (2016)** | RCA, masonry residue | Water absorption<br>Percentage of voids<br>Capillarity absorption |
| **Gesoglu et al. (2015b)** | RCA, SF | Water absorption<br>Water permeability<br>Gas permeability<br>Resistance to penetration of chloride ions |
| **Kapoor et al. (2016, 2017, 2018b)** | RCA, SF, metakaolin | Water absorption<br>Penetration of chloride ions |
| **Mohseni et al. (2017)** | RCA (FRSCC) | Water absorption<br>Penetration of chloride ions |

### 6.1. SCC WITH RCA

It is widely acknowledged that in vibrated concretes (Verian et al., 2018), the mortar attached to the RCA has a negative effect on the water absorption of the manufactured concrete. That effect is due to the non-hydrated cement present in the attached mortar, which increases the water absorption levels of the concrete manufactured with RCA. An effect that is accentuated when using fine RCA (Yacoub et al., 2018).

The same behavior was observed in various studies in the case of the SCC mixes. Coarse RCA with low amounts of adhered mortar implied slightly higher water absorption values (Fiol et al., 2018), while high amounts of that mortar mean the concrete will have higher water absorption values (Grdic et al., 2010). The water absorption values of multi-recycled SCC were found to be higher in accordance with the number of times it had been recycled (Salesa et al., 2017).

Pereira-De-Oliveira et al. (2014) analyzed water permeability, capillarity coefficients, and water penetration. From their results, the authors affirmed that the addition of RCA was favorable because the non-hydrated cement present in the mortar adhering to the RCA built up some barriers in the porous structure reducing the water movement. Moreover, preconditioning of aggregates (pre-soaking) originated a higher number of pores and higher water absorption by capillarity.

Omrane et al. (2017) designed SCC manufactured with coarse and fine RCA (in equal percentages of 50 %) and a natural pozzolan. Two durability characteristics were evaluated: resistance to the penetration of chloride ions (full immersion) and resistance to $H_2SO_4$ attack. For both tests, the concrete with higher amounts of RCA and natural pozzolan experienced lower levels of penetration of that type of ion.

Boudali et al. (2016) evaluated the exposure of concrete samples to sulphate attack. All the tests that were performed, showed that SCRC presented a better behavior than the reference SCC. Again, this improvement was explained by the continuity of the matrix hydration reaction (due to the non-hydrated cement adhered to the aggregate), which created barriers that prevented the passage of external agents. The voids were filled by the hydrated cement, which increased the compressive strength, despite the attack of those agents.

## 6.2. SCC WITH RCA AND OTHER WASTES (FLY ASH, SILICA FUME, RECYCLED ASPHALT PAVEMENT AGGREGATES, RUBBER GRANULES, AND SLAGS)

Santos et al. (2019b) evaluated water absorption, by both total immersion and capillarity, in mixtures with RCA and FA at different ages (28, 91 and 182 days). The water absorption level increased with increased amounts of RCA and the mixes with 100 % coarse RCA and 0 % fine RCA improved the behavior of the mixture with 50 % of both fine and coarse RCA. Neither FA neither (Rajhans et al., 2018a, b) nor sulphate attack (Vinay Kumar et al., 2017) appeared to influence water permeability.

In contrast, FA increased the effect of the fine RCA in some properties (Vinay Kumar et al., 2017), such as the chloride penetration test (Kou and Poon, 2009). The tests carried out by Santos et al. (2019b) also showed a similar performance against chlorides attack. The mixes with high amounts of coarse RCA improved the performance of mixtures with low percentages of fine RCA. In addition, according to the aspects discussed in the previous section, FA seems to amplify this negative effect. In relation to oxygen permeability, this effect was not so noticeable, but it also existed. From the comments in this paragraph and in section 6.1, it can be affirmed that coarse RCA leads to a lower SCC deterioration by chloride ions than fine RCA, especially if FA is added to the mix.

Kapoor et al. (2017) evaluated chloride ion penetration in a SCC with coarse and fine RCA, FA and 10 % metakaolin as cement replacement. The resistance to chloride penetration of the mix with 100 % of RCA and 10 % of metakaolin was higher than that of the control mix (without metakaolin). In addition, the joint use of fine RCA and metakaolin reduced the initial absorption rate of water.

The electrical resistivity of SCC (Santos et al., 2019b) is lowered by the addition of RCA (Singh and Singh, 2016b). Depending on the application, this effect may be either positive or negative.

The carbonation process of SCC jointly manufactured with RCA and FA was also assessed in various studies (Singh and Singh, 2016a); the results showed that the greater the percentage substitution, the deeper the carbonation depth. An observation that was attributed to the attached mortar, because the mortar adhering to RCA can have many micro cracks, voids, and pores that facilitate carbonation processes (Rajhans et al., 2018a, b). In addition, the performance of coarse RCA was improved over time, with carbonation depth becoming similar to that of control concrete at 182 days, especially in mixtures with high cement content (Santos et al., 2019b). Moreover, the addition of FA appeared to produce a negative effect, increasing that penetration index. However, the effect of each waste (RCA and FA) could not be separately quantified. As a final point, the authors proposed the existence of a linear relationship between the depth of carbonation and the compressive strength, which was valid at any age, and for concretes with both RCA and FA (Singh and Singh, 2016a).

In an SCC with no RCA, SF fills up all the pores and cracks, and has a waterproofing effect on the aggregate particles. This waterproofing effect occurs to a greater extent in concrete with RCA. It all reduces porosity and hinders water circulation (Rajhans et al., 2018a, b). In addition, the improvement was notably greater as the concrete aged; from 0 to 60 days a certain improvement occurred, but from 60 to 120 days, the improvement was twice as effective (Kapoor et al., 2016, 2018a). However, SF could not compensate all the negative effect caused by RCA (Gesoglu et al., 2015b).

Other observations suggested that the masonry residue appeared to have no influence on the durability performance of the concrete (Silva et al., 2016). Moreover, while GGBFS is detrimental to any resistance to chloride ion penetration, RAP aggregate increased this resistance, which can be attributed to the highly viscous asphalt mortar and binder surrounding the RAP aggregate (Yasser Khodair, 2017).

### 6.3. SCC WITH RCA AND FIBERS

In their study, Mohseni et al. (2017) determined that the incorporation of fibers within the concrete mixes had no notable effect on water absorption; in contrast, fiber addition did indeed affect chloride ion penetration. The chloride ion penetration resistance of a concrete with RCA and fibers decreased when the amount of RCA increased, while in the case of concrete with RCA, but no fibers, the effect was the opposite. This contrary effect was attributed to the high conductivity of the fibers incorporated in the mixture. The effect of either steel fibers or PP fibers separately was similar, although the effect of steel fibers was slightly worse, due to their higher conductivity, and a combination of both fiber types provided the best solution.

## 7. LONG-TERM PROPERTIES: SHRINKAGE AND CREEP

Shrinkage and creep define the long-term deformational behavior of concrete and the effect upon those two parameters of RCA is important, due to its high water-absorption level. The main studies on these properties will be discussed in this section.

### 7.1. SHRINKAGE

Highly influenced by the hydration process, shrinkage is more pronounced during the first hours and days, due to the hydration reaction of the cement – known as drying shrinkage. Subsequently (around a week after the hydration), long-term shrinkage commences. Although very slight compared to the previous shrinkage process, long-term shrinkage lasts throughout the whole life of the concrete, tending towards an asymptotic value (Behera et al., 2014). This shrinkage process is similar for SCC, although the higher content of water and the use of different kinds of superplasticizers, among other aspects (Fiol, 2016), means that shrinkage is usually more pronounced in SCC than in conventional concrete (Bocciarelli et al., 2018).

Manzi et al. (2015, 2017) observed that the drying shrinkage experienced by all the concretes was the same regardless of the amount of coarse RCA. Kou and Poon (2009) and Rajhans et al. (2018a, b) found that the higher the percentage substitution of NA by coarse RCA, then the greater the water absorption and the higher the drying shrinkage of the concrete. That result contradicted the findings of Manzi et al. (2015, 2017), which may either be because the effective w/c ratio remained constant or it may be due to the addition of FA, which formed a less compact paste with more pores and voids, facilitating the absorption of water, and leading to greater shrinkage.

On the contrary, the greater the amount of fine RCA, then the greater the drying shrinkage, which could be due to the high water absorption of fine RCA (Kou and Poon, 2009). After two months (long-term shrinkage), the shortening was slightly higher for the control SCC (only NA) and for the concrete with low substitution rates of RCA (25 % of RCA) than for concretes with high RCA percentages (50 %, 75 % and 100 % of RCA) (Kou and Poon, 2009). The presence of non-hydrated cement in the mortar adhered to the aggregates caused a decrease of the effective w/c ratio, which led to less excess water and, in brief, to less shrinkage. In contrast, SF appeared to decrease shrinkage (Gesoglu et al., 2015b), an effect also produced by the addition of recycled ceramic waste in powder form of a very small size (Ferrara et al., 2019). As opposed to FA and SF, which affected shrinkage, neither RAP aggregate nor slag appeared to have any effect on that property (Yasser Khodair, 2017).

### 7.2. CREEP

Both creep and shrinkage behavior were very similar: very intense at first, when the effects were more pronounced, followed later on by stabilization.

However, Manzi et al. (2015, 2017), noted a remarkable long-term difference between shrinkage and creep. On the one hand, shrinkage was almost the same for all the concretes, regardless of the RCA percentage of substitution. On the other hand, the creep levels of the concretes with different RCA contents were very different, although the concretes with a higher creep were still those with a lower RCA content, as with the study on shrinkage.

The addition of FA led to a greater difference regarding creep strain between concretes with different RCA substitution rates. Separate addition of the components in the mixing process were again demonstrated to produce a concrete with better characteristics and lower creep (Rajhans et al., 2018a, b).

## 8. STRUCTURAL ELEMENTS: BEAMS AND COLUMNS

Li et al. (2012; 2011a) tested the flexural strength of different beams manufactured with coarse RCA. In all cases, the performance of the RCA beams was quite similar to those made with NA. The cement and RCA bonds were good, although the use of this kind of aggregate led to a lesser stiffness and to a larger mid-span deflection (Li et al., 2011b).

Later on, Li et al. (2018) evaluated the performance of three reinforced concrete beams under flexural testing. Each beam was manufactured with a different replacement rate of coarse RCA in the SCRC dosage: 70 %, 85 % and 100 %. The authors found that the crack development process in the beams manufactured with RCA was the same as that of the reference concrete beam. The crack distribution of the 85 %-beam was more uniform than in the 100 %-beam and the 70 %-beam. A result that was explained, on one hand, by the many micro-cracks and minor defects found in the coarse RCA, which meant that the 100 %-beam had more cracks where there were high concentrations of RCA. On the other hand, the higher quality of the coarse NA in the 70 %-beam explained why the highest number of cracks were found in the regions where the RCA was concentrated, avoiding the regions with NA.

Another interesting aspect analyzed by Li et al. (2018) was that the Plane Section Assumption could also be used as the basis for the theoretical calculation of SCC with RCA beams. It is remarkable that the failure loads of the three beams were very similar: the failure load decreased slightly as the percentage substitutions increased and was consistent with the overall conclusions on the compressive strength of SCRC. Nevertheless, the real moment of failure was higher than the theoretical moment, at both high and low RCA replacement percentages, an observation that was also noted in the investigations of Jagannadha Rao et al. (2012) and Gao et al. (2018), thereby demonstrating the suitability of this concrete for structural use. Finally, the maximum crack width between the coarse RCA beams and the coarse NA beams manufactured with SCC appeared not to make a significant difference

Velay-Lizancos et al. (2018) analyzed eight similar beams in flexural and shear tests. Four types of concrete were designed, with the same percentage of coarse RCA and fine RCA in each of them: M-0, with 0 % coarse and fine RCA; M-20, with 20 % coarse and fine RCA; M-35, with 35 % coarse and fine RCA and M-50, with 50 % coarse and fine RCA. The study sought to compare the results obtained experimentally in the beams with those obtained by means of two calculation methods: a traditional method, applying the expressions collected in EC-2 (2010) and EHE-08 (2010), and a modern Finite Element Method (FEM) (Chandra Paul et al., 2018). As a general conclusion, it was established that traditional methods were quite valid, at low substitution percentages, that are very often used with conventional concrete. At higher percentages (over 50 %), more complete methods such as the FEM should be used, due to the loss of precision of the traditional methods.

Tanaka et al. (2002) and Zhou et al. (2011) concluded that the performance of SCC columns with RCA and different kinds of reinforcements was similar to that of RCA vibrated concrete columns (Khan et al., 2019), because of the predominantly similar levels of compressive strength in both.

## 9. OTHER RELEVANT ASPECTS

Non-destructive methods (e.g., hammer rebound test) were also valid for SCC with RCA, so that in structures already built with these types of concretes, those tools can be used to determine the compressive strength *"in situ"*. The linear relationship between compressive strength and those properties could be established (Singh, N. and Singh, S.P., 2018b). Models that can be used to correlate compressive strength from those indirect measures represent a field of study in which important advances are still possible.

González-Taboada et al. (2018b) evaluated the thixotropy of SCRC or variations of its viscosity when agitated and when left to stand in the fresh state. The authors observed that the thixotropic level of change was similar in all the concretes, regardless of the RCA replacement percentage.

Finally, the thermal analysis suggested an appreciable change in thermal behavior in comparison with the reference mix without RCA. For example, Fenollera et al. (2015) found that thermal conductivity was reduced by 15 % when raising the RCA percentage from 20 % to 50 %.

## 10. CONCLUSIONS

Considering the literature on RCA and other industrial wastes reused in SCC that has been reviewed and commented upon in this paper, the following conclusions can be presented:

- The decrease in SCC flowability caused by the high water-absorption levels of RCA, compared to NA, can generally be compensated by the addition of a larger quantities of water.
- The mechanical properties of SCC present high sensitivity to dosage changes, so a decrease in the effective w/c ratio can compensate for the negative effect of the replacement of NA by RCA on these properties. This high sensitivity leads to high dispersion in the overall results, such that no clear trend of the effect of RCA on compressive strength can be established, as shown in section 5.1.4. In section 5.2.4, the results of splitting tensile strength, a property that was less affected by the water content of the mixture, showed a clearly negative effect of RCA.
- The two previous conclusions show that the negative effect of RCA on flowability and strength can be solved by adjusting the water content. For this reason, it is necessary to define the aspect that should be optimized in the SCC with RCA, since improving one of these aspects leads to worsening of the other. The addition of RCA with other co-products sourced from industrial wastes should be studied on a case-by-case basis, due to the variety of possible behaviors.
- The effect of RCA on both the durability and the long-term behavior of SCC is unclear. Properties such as permeability and carbonation resistance are significantly worsened when RCA is used. However, other studies showed that resistance to sulphate attack or water absorption by capillarity action improved with additions of RCA. This variety may be because some SCCs have a better sealing of the voids of the RCA due to their greater flowability. It is necessary to carry out more studies, to clearly define the influence of RCA and flowability on durability properties.
- The differences between this concrete and conventional concrete in structural elements, for example, with regard to cracking patterns or the validity of FEM, were notable. Although SCC with RCA appears to be a suitable structural material for use in beams and columns, the validity of traditional structural design procedures must be checked on full-scale elements. Following that strategy, these co-products may be widely added to concrete mixes used for the construction of many common structures.

Currently, the development of a more sustainable construction sector is essential. If the pressure on natural resources is to be reduced, then the reuse of different residues is also essential, as a pathway that has to be followed. In this particular case, further research related to the combination of SCC and RCA is still needed. Nevertheless, all the research that has been reviewed represents important advances within this field that all move closer to combining waste products and especially RCA in SCC. The authors of this article wish to express their thanks to all the researchers for their studies and their important contributions to progress in this field and would urge them to continue with their valuable research.

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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