Influence of design parameters on the fresh and durable properties of self-compacting concrete with recycled aggregate

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Abstract. The objective of this paper is to analyse the influence of design parameters on the fresh and mechanical properties in the manufacture of self-compacting concrete with recycled fine and coarse aggregates. Design parameters such as water-cement ratio, water/paste ratio, total aggregate to cement ratio, fine aggregate to coarse aggregate ratio, water to solid ratio in percentage, superplasticiser content, RCA replacement percentage and RFA replacement percentage are analysed. The design parameters are found to affect the evolution of the fresh and mechanical properties of SCC with recycled aggregates.

Keywords: self-compacting concrete; recycled aggregates; design parameters; fresh concrete properties; mechanical properties; mix design.

1. Introduction
One of the most widely used products in the world today are aggregates, specifically sand and gravel, which are used in construction. After water, concrete is the most consumed product on the planet.

Therefore, there is evidence of an increase in the generation of concrete waste related to the construction process and demolition activities [1],[2]. The development of civil works generates a large amount of waste that can be reused that could be used as landfill for the development of new civil works or disposed of in municipal landfills competing for space with municipal solid waste when managed in the same facilities [3], or improperly abandoned generating an environmental impact by the loss of landscape quality in different localities, and environmental pollution [4], [5].

In terms of figures, it should be noted that (1) for the year 2010, worldwide 36% of waste corresponded to construction and demolition [6]; (2) the global average generation of special construction and demolition waste corresponds to 1.68 kg/inhabitant/day in 2018. Based on this reality, researchers and specialists from universities and research and quality control centres around the world have focused on providing management solutions. In addition, several countries have adopted legislation to promote and incentivise the reuse of waste; this has been reflected in the statistics. The amount of waste recovered in the EU has been increasing; it has risen from 45.4% in 2014 to 53.2% in 2018. 37.8% of the waste generated in the EU in 2018 was recycled, 9.9% was used as landfill and 5.6%
was used for energy recovery. The remaining 46.8% was landfilled (38.8%), incinerated without energy recovery (1.0%) or otherwise disposed of (7%). In this context, the long-term European Strategy is to turn the world into a recycling society, avoiding waste and using it as a resource wherever possible. The aim is to achieve much higher levels of recycling and to minimise the extraction of additional natural resources.

Currently, there are numerous studies that support the use of construction and demolition waste in the production of conventional concrete [7–11]. However, despite the increasing trend in the reuse of demolition waste; it has been shown that the use of recycled aggregates (RA) can limit or decrease the properties of concrete (strength, durability and serviceability) due to old binding mortar, irregular shape and increased porosity. In other words, there is a direct dependence between concrete properties and the degree of substitution used with RA [12], [13]. Several tests have concluded that the incorporation of recycled products (coarse aggregates) should not exceed 20% to preserve the properties of recycled concrete, which is a worldwide normative recommendation. In the case of fine material, although it is not regulated or permitted, scientific studies have shown that there is no alteration when it does not exceed 10% substitution, and it can improve with the granulometric gradation in the addition of fine material, generating greater cohesiveness [14], [15], [16].

Given the high energy consumption of the concrete industry due to the high demand for natural resources and the environmental risks involved, RA have been used as partial or full substitutes to minimise the environmental impact, taking an important step towards establishing a sustainable society and boosting the circular economy [12], [17], [18]. RA is a type of composite material whose quality depends directly on the origin of the waste, the place and reason for demolition and the original characteristics of the concrete [19]. Therefore, it should not be lost sight of the fact that any change in the aggregate, however small it may seem, will have a significant effect not only on the properties of the concrete but also on the cost of production, transport and marketing.

Regarding the relationship of the mechanical properties of concrete (compressive and flexural strength) obtained with RA, some studies have been carried out, using different substitution percentages, finding for example that the use of varying amounts of aggregates between 10%-40% by weight (waste from a 25 year old building) generates a decrease in properties with the most favourable value being 30% by weight substitution [20]. It is also indicated that with up to 40% by weight substitution of recycled coarse aggregate (RCA) and recycled fine aggregate (RFA), a self-compacting structural concrete is obtained without significant differences with conventional concrete [21]. Compressive strength, tensile strength, flexural strength and elasticity have developed well even with 100% substitution, as a consequence of the improved microstructure. On the other hand, hardening properties, stiffness and flexural toughness may decrease with the addition of aggregates [22]. In addition, self-compacting concrete (SCC) usually has a higher water absorption than normal concrete due to the lower specific gravity of the old mortar that binds to the original concrete. Also, the density of SCC with aggregates is lower than that of conventional concrete due to its high porosity [20]. Due to the need to optimise the management of solid waste associated with construction activities and the demand for materials that, in addition to being more sustainable, have adequate mechanical properties that guarantee high durability, research has been carried out on the mechanical properties (e.g. compressive and tensile strength) of SCC obtained conventionally or with the use of RA, using different raw materials, design parameters and verification tests; Therefore, it is necessary to carry out an updated general review to compile the advances achieved so far in this area of knowledge that will serve as a substantial contribution to the establishment of criteria for the implementation in civil works, in the establishment or adaptation of existing regulations.

The main objective of this review is to understand the role of design parameters on the fresh and mechanical properties of SCC with recycled aggregates (RCA and RFA). For this purpose, more than 250 SCC mixes with RA from the available literature have been analysed and grouped into 6 families according to their compressive strength of control mixes.
2. Material properties of SCC ingredients

The origin of SCC can be diverse, but there is a definite role of ingredients properties on the SCC fresh concrete properties. Hence, it is necessary to understand the properties of ingredients used in SCC. The average value of ingredients used for SCC other than RA by various researchers is tabulated in Table 1. From Tables 1 and 2, it is observed that the physical properties of natural aggregate are higher than that of the RA due to old mortar adhering to it. The specific gravity of RA is lower than that of natural aggregate is observed by most researchers, this leads to a density of RCA mixture as lower than that of the natural aggregate mixture. Higher water absorption of RA is observed from Table 2 when compared to Table 1 and it is reported by most authors.

Table 1. Average value for the properties of ingredients other than recycled aggregate used in the literature.

| Ingredients          | Specific Gravity | Fineness modulus | Blaine’s surface area | Water absorption | Bulk density |
|----------------------|------------------|------------------|-----------------------|------------------|--------------|
| Cement               | 3.108            | 3495.5           |                       | Tuyan et al., 2014 [23], Pereira-de-Oliveria et al., 2014 [24], Señas et al., 2016 [25], Duan et al., 2020 [17], Tang et al., 2016 [26], Djelloul et al., 2018 [27], Aslani et al., 2018 [29], Ouldkhaoua et al., 2020 [30], Nieto et al., 2019 [31], Gupta et al., 2020 [32], Singh et al., 2019 [2], Abed et al., 2020 [33], Xavier et al., 2020 [34], Dapena et al., 2011 [35], Rajhans et al., 2011 [36] |
| Fine aggregate       | 2.651            | 2.76             | 1.35                  | 1632.5           |
| Coarse aggregate     | 2.646            | 6.05             | 1.24                  | 1440.25          |

Table 2. Recycled aggregate properties used in the literature.

| References            | Source                              | Types            | AS\(^a\) (mm) | FM\(^b\) (mm) | CF\(^c\) (%) | SG\(^d\) | W\(^e\) (%) | BD\(^f\) (kg/m\(^3\)) |
|-----------------------|-------------------------------------|------------------|---------------|---------------|-------------|----------|-----------|---------------------|
| Tuyan et al., 2014 [23] | Waste laboratory made concrete      | RCA              | 9.5           | 5.78          | -           | 2.48     | 4.80      | 1410                |
| Pereira-de-Oliveria et al., 2014 [24] | Construction and demolition waste | RCA              | 19            | 6.92          | -           | 4.05     | 1485      |
| Señas et al., 2016 [25] | Construction work                  | RCA              | 12.5          | 3.77          | -           | -        | -         | -                   |
| Duan et al., 2020 [17] | Waste infrastructure component     | RCA              | 12            | 2.59          | -           | 6.53     | 1220      |
| Tang et al., 2016 [26] | Construction and demolition waste facility | RCA          | 10            | -             | -           | 7.75     | 1450      |
| Djelloul, 2018 [27] | Waste from laboratory concrete      | RFA              | 3.8           | -             | 2.27       | 8.87     | 1258      |
| Sasanipour et al., 2019 [28] | Residential and sanitary buildings | RCA             | 9.5           | -             | 2.39       | 7.39     | 1172      |
| Abed et al., 2020 [33] | Demolition waste                   | RCA              | 12.5          | -             | 2.4        | 3.21     | 1154      |
| Nieto et al., 2019 [31] | Concrete, bricks, asphalt, glass, others, aggregates | RCA              | 17            | -             | -           | 5.60     | 1612      |
| Gupta et al., 2020 [32] | Demolished building                | RCA              | -             | -             | 2.54       | 3.33     | 1220      |
| Ouldkhaoa et al., 2020 [30] | Cathode ray tube funnel glass      | RFA              | 2.16          | -             | 2.75       | -        | -         | -                   |

\(a\) Aggregate size (mm)  
\(b\) Fineness modulus  
\(c\) Content of fineness (%)  
\(d\) Specific gravity  
\(e\) Water absorption (%)  
\(f\) Bulk Density (kg/m\(^3\))

Table 3. Average of reference mix proportions (control mix) used by several authors from 2010-2020.

| Ingredients (Kg/m\(^3\)) | Average values | Standard deviation | References |
|---------------------------|----------------|--------------------|------------|
| Cement                    | 386.31         | 83.64              | Tuyan et al., 2014 [23], Pereira-de-Oliveria et al. [24], Señas et al., 2016 [25], Duan et al., 2020 [17], Tang et al., 2016 [26], Djelloul et al., 2018 [27], Sasanipour et al., 2019 [28], Aslani et al., 2018 [29], Ouldkhaoa et al., 2020 [30], Nieto et al., 2019 [31], Gupta et al., 2020 [32], Singh et al., 2019 [2], Abed et al., 2020 [33], Xavier et al., 2020 [34], Dapena et al., 2011 [35], Rajhans et al., 2011 [36] |
| SCM                       | 191.4          | 80.84              |            |
| Filler                    | 166.5          | 182.37             |            |
| Fine aggregate            | 823.95         | 214.93             |            |
| Coarse Aggregate          | 749.26         | 113.77             |            |
| Water                     | 194.07         | 23.52              |            |
| SP                        | 3.62           | 1.67               |            |
| Unit weight               | 2335.61        | 46.12              |            |
3. Results and discussion

3.1 Influence of design parameters on fresh concrete properties

For each fresh SCC properties and every author, the results/findings obtained are presented in the form of a table/graph and the new tendencies are identified and studied based on the design parameters obtained from the mix design. A comparison for similar kinds of experiments is made from various authors to understand the RCA trends on fresh properties. The researchers concluded that several parameters are used to evaluate the slump flow which is defined as free fluidity and flow in the absence of barriers. Parameters considered are the time required by SCC takes to form a 500mm circle, called flow time (T500), and the slump flow (SF) diameter. A common observation made by most researchers is that increase in replacement of coarse aggregate by RA results in T500 increases with SF decreases (Figure 1). Safiuddin et al. [37] reported that the increase in incorporation ratio results in increased segregation resistance up-to lower replacement levels of NCA. For higher replacement levels of NCA, the segregation resistance decreases because the increase in RCA content leads to an increase in the fineness content of the mixture. Grdíc et al. [38] found that the increase in RCA content leads to an increase in the W/C ratio, result in a decrease in segregation resistance. An increase in replacement percentage of natural aggregate by the coarse aggregate result in an increase in flow time is observed in Figure 2.

![Figure 1. Effect of slump flow on the percentage of recycled coarse aggregate](image1.png)

![Figure 2. Effect of T500 flow time on the percentage of recycled coarse aggregate](image2.png)

3.2 Influence of design parameters on Strength

From the available literature, the results are grouped into six families based on the compressive strength grade. Twenty-eight days compressive strength of control or reference SCC mix is used to classify the proportions irrespective of the size of the specimen, shape of the specimen, and various international standards or codes used for testing of the specimen. For example, Family I consist of data based on the reference or control 28 days compressive strength lies in the range of 70 MPa to 80 MPa. In a similar fashion, family II, family III, family IV, family V, and family VI consists of 28 days compressive strength that lies in the range of 60 MPa to 70 MPa, 50 MPa to 60 MPa, 40 MPa to 50 MPa, 30 MPa to 40 MPa, and 20 MPa to 30 MPa, respectively. Corresponding split tensile strength at 28 days is also tabulated irrespective of nature of size, the shape of the specimen, and international standards or codes. Effect of different parameters on the strength is shown in figure 3.
Figure 3. (a) Effect of W/C ratio on various compressive strengths of SCC concrete with RA according to the literature. (b) Effect of W/C ratio on various split tensile strength of SCC concrete with RA according to the literature. (c) Effect of the W/B ratio on various compressive strengths of SCC concrete with RA according to the literature. (d) Effect of the W/B ratio on various split tensile strength of SCC concrete with RA according to the literature. (e) Effect of TA/C ratio on various compressive strengths of SCC concrete with RA according to the literature. (f) Effect of TA/C ratio on various split tensile strengths of SCC concrete with RA according to the literature. (g) Effect of FA/CA ratio on various compressive strengths of SCC concrete with RA according to the literature. (h) Effect of the FA/CA ratio on various split tensile strengths of SCC concrete with RA according to the literature.
4. Conclusion
An intensive review on the impact of design parameters was conducted in order to make a simplified design procedure for the design mix of SCC made with recycled aggregates. The overall summarized report on the review is stated below:

- Increase in replacement of coarse aggregate by RA results in T500 increases with SF decreases.
- An increase in replacement percentage of natural aggregate by the coarse aggregate result in an increase in flow time.
- Increase in W/C ratio results in a decrease in compressive strength and split tensile strength.
- W/B ratio less than 0.30 produces higher compressive strength and, simultaneously, higher split tensile strength. Further increase in the W/B ratio results in a decrease in compressive strength and split tensile strength.
- The lower the TA/C ratio is, the higher the compressive strength will be.

Detailed investigation on the effect of design parameters on the properties of SCC with recycled aggregate will help researchers and engineers to develop a minimum requirement for a SCC mix with recycled aggregates.

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