Design Optimization of Self-Compacting Concrete with Residues for Different Scenarios

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Abstract. There is a need to promote high performance and sustainable construction materials such as Self-Compacting Concrete (SCC) made from various wastes. In concrete manufacturing, there is a general tendency to worsen the workability and mechanical behavior when working with wastes instead of natural raw materials. It is therefore necessary to use multi-criteria algorithms to analyze the impact of using sustainable materials, and to balance the increase in sustainability with the deterioration of certain performances, such as flowability and strength. In addition, it is also necessary to include a cost analysis in the study, which allows us to find the most suitable products for varied real-life applications.

In this research, 19 SCC mixes have been manufactured, where conventional materials (CEM I, natural aggregates, and limestone filler) are progressively substituted by more sustainable ones (Ground Granulated Blast Furnace Slag -GGBFS- replacing cement, and Recycled Concrete Aggregate -RCA- in coarse, fine and filler sizes of the aggregate). The designed mixes are analyzed based on different criteria: mechanical criteria (flowability, compressive strength and modulus of elasticity), sustainability (carbon footprint) and cost. Five different scenarios are proposed for different priorities or situations, which are evaluated using three multi-criteria algorithms.

Some of the conclusions of the study show that coarse RCA and limestone fines perform adequately in most scenarios. Fine RCA rates above 50% were not recommended in any of the scenarios. A versatile design would be an SCC with RCA coarse aggregate, limestone fines, GGBFS and 0% fine RCA.

Keywords: Carbon Footprint, Ground Granulated Blast Furnace Slag, Recycled Concrete Aggregate, Self-Compacting Concrete; Concrete Optimization.

1 Introduction

There is a need to promote high performance and sustainable construction materials such as Self-Compacting Concrete (SCC) made from various wastes. In general terms, when seeking to increase concrete´s sustainability, there is a general tendency to worsen its fresh performance and mechanical behavior, when replacing natural raw materials with residues [1].

It is necessary, therefore, to address this sustainability from a multi-criteria approach, which allows to balance the results of incorporating sustainability with the necessary engineering performance, according to the uses of the designed element [2]. In addition, if these sustainable concepts are to be incorporated into the industrial world, it is essential to include a cost analysis in the study.

This can be done optimally through multi-criteria decision-making algorithms, which allow to assess the impact of incorporating residues or more sustainable materials from a comprehensive approach. In addition, they allow to evaluate different scenarios depending on the needs of the company at each moment, prioritizing different aspects of the product over others, according to their sensitivity or needs [3].

In this research, 19 types of SCC mixes have been produced, incorporating various types of sustainable materials: GGBFS instead of cement, powders with lower fineness of grinding, which allow lower energy consumption during production, and Recycled Concrete Aggregate (RCA) in coarse, fine and filler fractions of the aggregate.

In the first phase of the research, the necessary tests and calculations have been conducted to address the temporal loss of flowability and the mechanical behavior of the mixes in terms of their compressive strength and modulus of elasticity, as well as their carbon footprint and associated costs.

Then, by means of three multi-criteria algorithms, in which five different scenarios have been designed, the previous results have been used as inputs to evaluate the resulting products and make customized recommendations.

2 Materials and methods

2.1 Materials

Two types of binders were used. The conventional one was Portland cement (CEM I 52.5 R). In the sustainable mixes, GGBFS with a density of 2.90 Mg/m^3 and a Blaine specific surface of 460 m^2/kg was used. Water was provided from the city supply system. Admixtures, such as plasticizer and viscosity regulator, were also added. In the mixes with CEM I or GGBFS, the admixtures made up 2.2% and 1.6% of the binder mass, respectively.

As powders, the next materials were employed: at first, conventional limestone filler with granulometry under 0.063 mm. Then, it was replaced by two more sustainable alternatives: limestone fines < 0.5 mm of the same nature, but with lower energy consumption [4], and finally the most sustainable alternative, RCA powder.

Conventional siliceous gravel 4/12.5 mm and siliceous sand 0/4 mm were obtained from a local supplier. Their density was 2.61 and 2.59 Mg/m^3 and their water absorption 0.84% and 0.25%, respectively.

The RCA was supplied in two fractions: coarse RCA 4/12.5 mm and fine RCA 0/4 mm. The density of the RCA (2.41 and 2.38 Mg/m^3, their respective fractions) was quite lower than that of the Natural Aggregates (NA), but its water absorption was significantly higher (6.25% and 7.36%).

A very detailed description of all these materials can be found in Revilla-Cuesta et al. [5].

2.2 Mix design

Table 1 displays the components of each mixture. The reference mix was given the designation of RSCC, while the remaining 18 SCC were designated: at first, a letter referring to the type of binder (C for CEM I and G for 45% of GGBFS); next, another letter referring to the aggregate powder type (R for RCA powder, F for limestone filler and L for limestone fines); finally, a number refers to the percentage of fine RCA (0%, 50%, or 100%).

The mixing procedure was developed in three phases to optimize its flowability, designed empirically in a previous phase of the investigation [6].

Table 1. Composition of the SCC mixes (kg/m^3) [6].

	CEM I # GGBFS	Water	Coarse NA # Coarse RCA	Fine NA # Fine RCA	Limestone filler # Limestone fines # RCA powder
RSCC	300 # 0	165	575 # 0	1,100 # 0	165 # 0 # 0
C-F-0		185		1,100 # 0	
C-F-50	300 # 0	210	0 # 530	550 # 505	165 # 0 # 0
C-F-100		235		0 # 1,010	
G-F-0		185		1,100 # 0	
G-F-50	235 # 190	210	0 # 430	550 # 505	165 # 0 # 0
G-F-100		235		0 # 1,010	
C-L-0		185		940 # 0	
C-L-50	300 # 0	210	0 # 530	475 # 435	0 # 355 # 0
C-L-100		235		0 # 865	
G-L-0		185		940 # 0	
G-L-50	235 # 190	210	0 # 430	475 # 435	0 # 355 # 0
G-L-100		235		0 # 865	
C-R-0		200		940 # 0	
C-R-50	300 # 0	220	0 # 530	475 # 435	0 # 0 # 305
C-R-100		245		0 # 865	
G-R-0		200		940 # 0	
G-R-50	235 # 190	220	0 # 430	475 # 435	0 # 0 # 305
G-R-100		245		0 # 865	

2.3 Multi-criteria analysis methodology

The assessment of the SCC performance for the multi-criteria study was performed through the following steps:

- Flowability in the fresh state was evaluated through the slump-flow test, following EN 12350-8 [7], after 60 minutes of mixing.
- The hardened behavior of the concrete mixture was evaluated through its compressive strength (CS), according to EN 12390-3 [8], and the modulus of elasticity (ME) following EN 12390-13 [9], at 28 days.
- The sustainability of the product was calculated through its carbon footprint, obtained through the weighted sum of the carbon footprint of its components, assuming equal transportation and manufacturing conditions for all mixtures.
- Each SCC mixture's cost was determined based on the costs of its constituent parts.

The multi-criteria decision-making analysis was performed based in 4 decision-making criteria and 5 different scenarios by means of three different algorithms. The criteria used were: decreased flowability, hardened performance by means of CS and ME at 28 days, carbon footprint, and cost.

Three different algorithms were used: TOPSIS, AHP and PROMETHEE. Then, a series of scenarios were defined that could be significant of the different situations or sensitivities for the use of the product. In each scenario, the property given priority had a double weight compared to the other three.

- In scenario 1, priority is given to SCC´s flowability.
- In scenario 2, priority is given to the hardened behavior of SCC, *i.e.*, the combination of CS and MS.
- In scenario 3, sustainability prevails over the other criteria.
- In scenario 4, greater weight is given to product cost.
- Finally, in scenario 5, a "multi-purpose" product is proposed, in which all criteria are given equal weight.

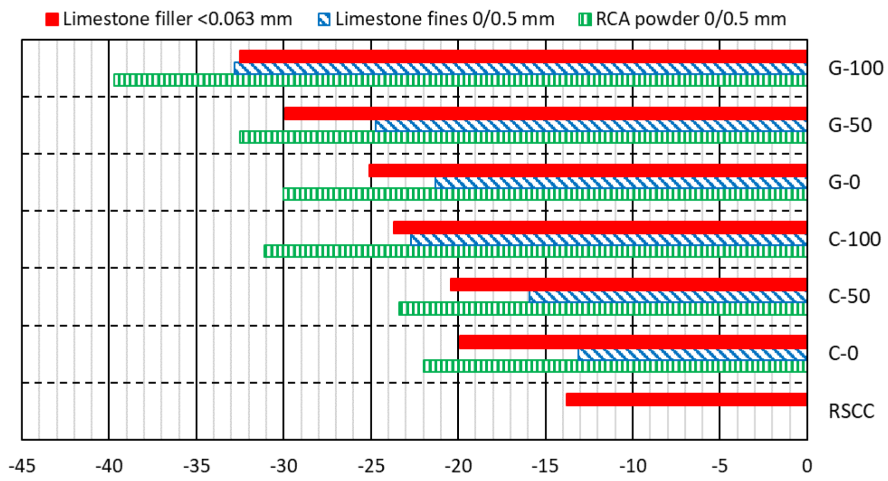
3 Results and discussion of input data

3.1 Flowability

In Figure 1, the percentage decrease of the flowability after 60 minutes can be observed. The mixes presented initially a slump flow of 750-850 mm (SF3 class) and after 60 minutes, nearly all mixes achieved a slump flow of 550-650 mm (SF1 class).

The general analysis of this property alone shows that the flowability was worsened when adding RCA in any size, which is attributed to its angular shape and higher water absorption [10]. Moreover, the mixes with GGBFS showed greater fluidity losses, which has also been observed by others [11]. The mixes that incorporated limestone fines had the best temporal slump-flow preservation, even overcoming the adverse effect of the coarse recycled aggregates.

Fig. 1. Decreased flowability of the mixes at 60 minutes (%).

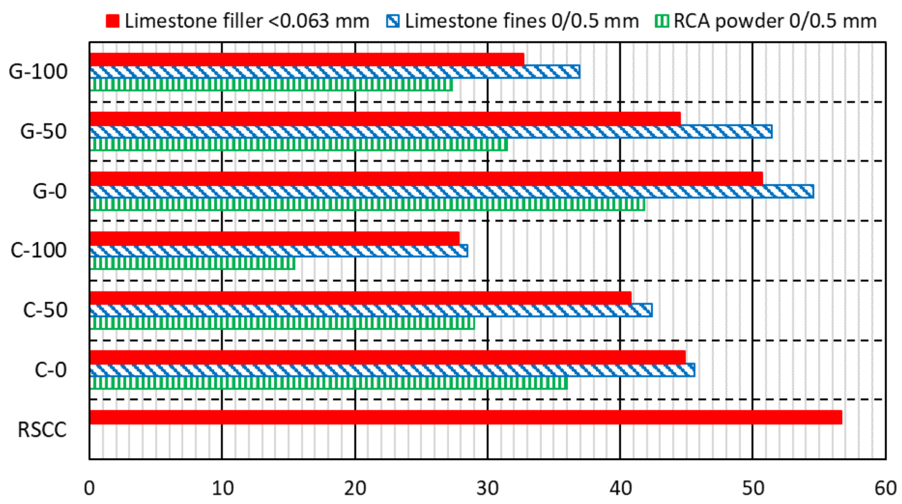


3.2 Compressive strength

Compressive strength was significantly reduced when RCA was used (Figure 2). This residue appears to weaken the interfacial transition zone, an effect that is more noteworthy in the finer fractions, due to the appearance of mortar particles [12].

The expected reduction in CS due to the use of GGBFS was counterweighed by the increase in the binder content of the G-mixes, to achieve an adequate flowability.

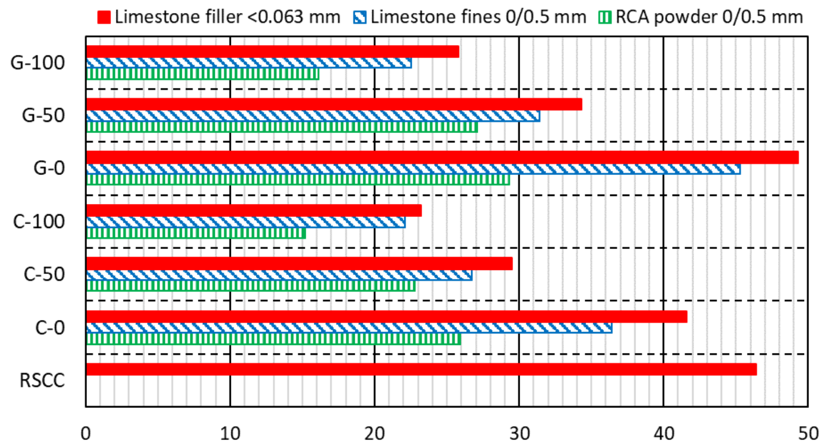
Fig. 2. Compressive strength of the mixes at 28 days (MPa).



3.3 Modulus of elasticity

The impact of both RCA and GGBFS on the elastic stiffness of the mixtures was parallel to the one described for the CS in the previous section (Figure 3).

Fig. 3. Modulus of elasticity of the mixes at 28 days (GPa).

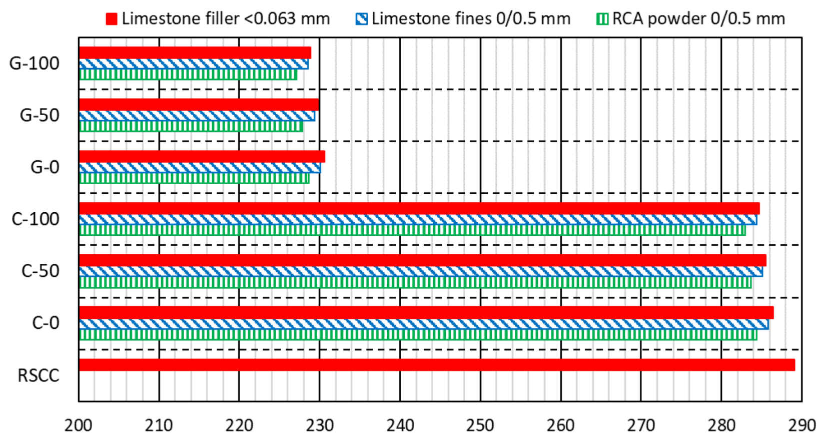


3.4 Carbon Footprint

The use of RCA and eliminating the limestone filler had a minimal influence on the resulting carbon footprint of the final SCC, although the environmental benefits in the reduction of quarrying should be highlighted [13].

The most outstanding feature is the effect on cement substitution (Figure 4). In SCC with GGBFS (45%), the reduction of the carbon footprint of SCC was up to 20%, despite the mix design required a higher binder content.

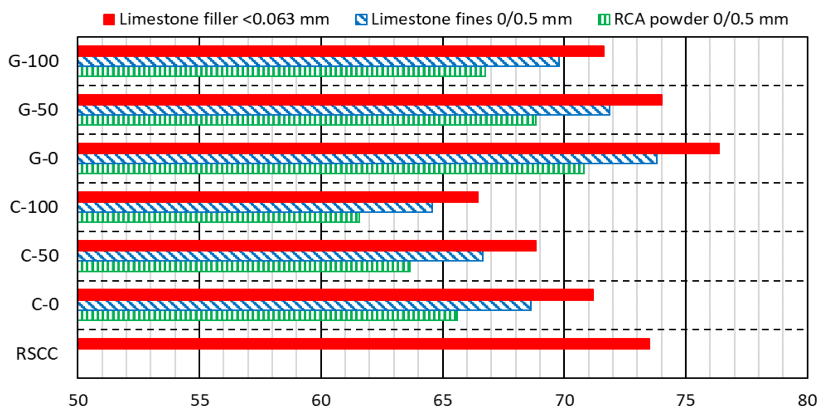
Fig. 4. Carbon footprint of the mixes (kg CO_2 eq/m^3).



3.5 Cost

The lower cost of acquiring the residues is appreciable, as well as the reduction in manufacturing costs of the less fine powders (Figure 5). However, although the price of GGBFS is lower than Portland cement, the increase in binder amounts lead to a higher resulting cost. All these factors resulted in the cheapest mix being C-100-R.

Fig. 5. Cost of the mixes (USD/m^3).



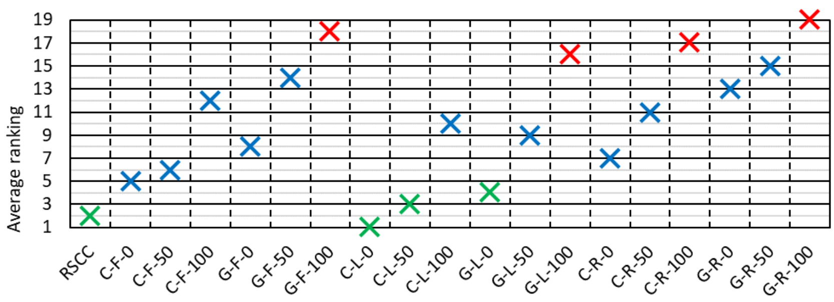
4 Results and discussion of multi-criteria analysis.

In this section, the average results of the three algorithms are shown, based on the five scenarios previously defined. The worst options are drawn in red and the best ones in green.

4.1 Scenario 1: SCC with optimum flowability

From the flowability perspective, the optimum mixes were manufactured with CEMI and limestone fines, with the fine RCA content restricted to 50%. The worst options were associated with the use of RCA powder (Figure 6).

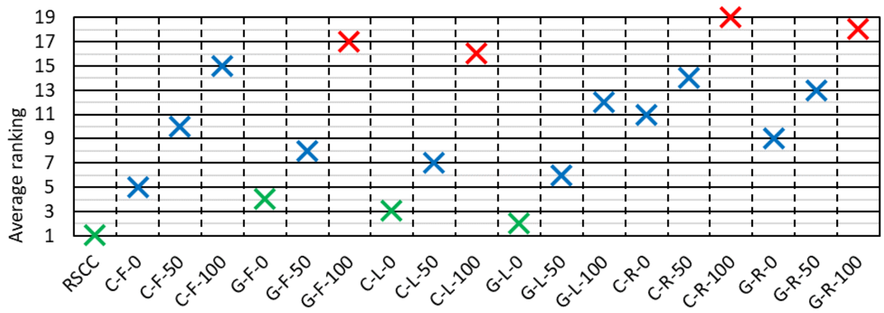
Fig. 6. Selection of SCC with optimum flowability.



4.2 Scenario 2: SCC with optimum hardened behavior

As Figure 7 shows, the least amount of residues was the best choice when searching an SCC with the best hardened performance.

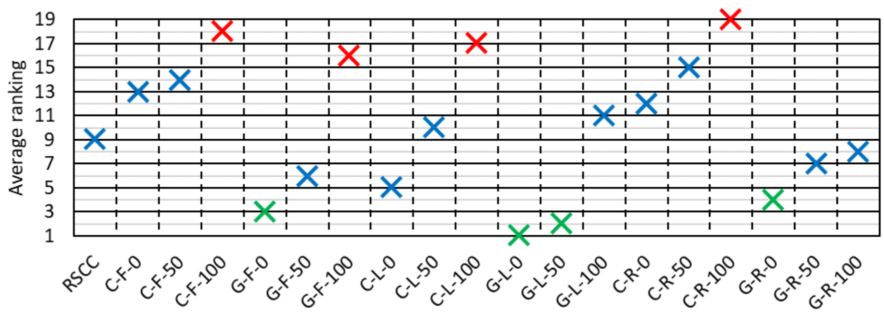
Fig. 7. Selection of SCC with optimum hardened performance.



4.3 Scenario 3: most sustainable SCC

For a minimal carbon footprint, the suggestion would be: to use GGBFS instead of conventional cement clinker, limestone fines as aggregate powder, and finally, the volume of fine RCA could not be higher than 50% (Figure 8).

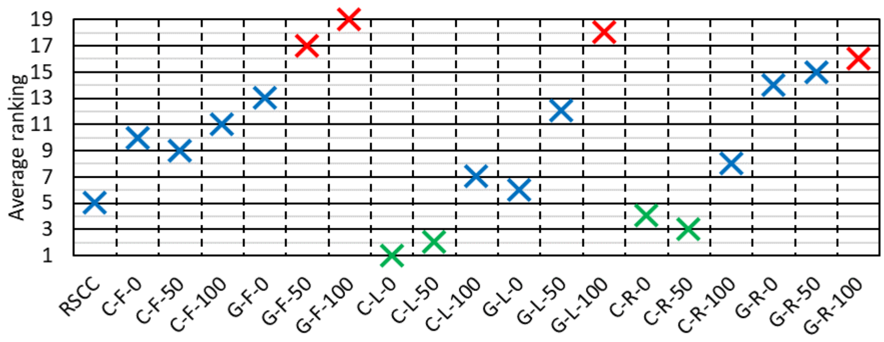
Fig. 8. Selection of SCC with minimum carbon footprint.



4.4 Scenario 4: SCC with minimum cost

In low-demanding uses, like the production of non-structural elements or urban furniture, a cheaper SCC may be preferred. From the analysis of the algorithms, in these cases, the recommendation is to use ordinary Portland cement (Figure 9).

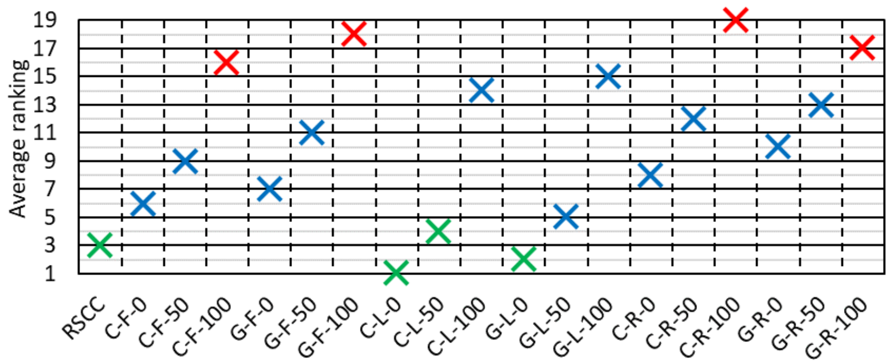
Fig. 9. Selection of SCC with optimum cost.



4.5 Scenario 5: Multi-purpose SCC

This design can be attractive for companies seeking to produce a versatile SCC, not designed for a specific application, but close to the optimal for a wide range of uses. The recommendation in this case is to use coarse RCA, limestone fines and fine RCA limited to a substitution of 50%, being irrelevant the type of binder (Figure 10).

Fig. 10. Multi-purpose selection of SCC.



5 Conclusions

Main conclusions of the investigation are as follows:

- Regarding the powder used, limestone fines performed great in most scenarios, being a relevant sustainable option to the limestone filler.
- The use of RCA coarse aggregate was generally positive in all the dimensions studied (flowability, strength, sustainability, and cost). However, RCA fines should be limited to 50% replacement.

- If high flowability preservation is required, then the use of Portland cement is especially advisable. It also improves the cost of the mixes, but when prioritizing sustainability, it cannot compete with the use of GGBFS.

The overall conclusion is that proper design can incorporate a multi-dimensional study of versatile products combining cost, engineering efficiency and sustainability.

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