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Multi-criteria feasibility of real use of self-compacting concrete with sustainable aggregate, binder and powder

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ABSTRACT

Replacing natural raw materials with industrial by-products can increase the sustainability of Self-Compacting Concrete (SCC), although its fresh and hardened behavior will usually worsen. The benefits of increased sustainability must therefore outweigh any reduction in concrete flowability and strength. These aspects can be analyzed through Multi-Criteria Decision-Making (MCDM) algorithms. In all, 19 SCC mixes were studied. One reproduced commercial SCC (limestone filler and conventional cement), the others were produced with more sustainable materials: 100% coarse Recycled Concrete Aggregate (RCA); 0%, 50% or 100% fine RCA; 45% Ground Granulated Blast-furnace Slag (GGBS); and sustainable aggregate powders such as limestone fines 0/0.5 mm and RCA powder 0/0.5 mm. Decreased flowability at 15 and at 60 min, compressive strength, modulus of elasticity, carbon footprint, and cost of mix were all studied. Both the carbon footprint and the cost were calculated considering only the composition of the SCC, without including aspects that depend on each particular case study, such as transport distances. These aspects constituted the decision-making criteria of the MCDM analysis, under which 14 scenarios were evaluated with different requirements for SCC, using 3 different algorithms (TOPSIS, AHP, and PROMETHEE). The results suggested that the ideal choice for fast concreting is a combination of GGBS, 100% coarse RCA and limestone fines, although if SCC has to be transported to the concreting point, then conventional cement should be used. Strength and stiffness can be maximized by limiting the fine RCA content to 50%. Finally, considering a versatile choice, only SCC with coarse RCA, limestone fines, GGBS and 0% fine RCA could compete with conventional SCC. Adapting the design to minimize the detrimental effects of by-products is therefore essential to promote sustainable SCC that is also commercially competitive.

1. Introduction

The construction sector is of great social importance. It provides varied infrastructure in response to the basic human right to housing and shelter and basic needs such as mobility, hygiene and social fulfilment, among many others. However, this sector also faces other important issues, among which the major environmental impact of concrete and asphalt mixtures is widely known (Mhatre et al., 2021). On the one hand, the extraction of Natural Aggregates (NA) used in the manufacture of these materials degrades the local natural ecosystem (quarries and gravel pits), affecting watercourses and the landscape (Hossain et al., 2016). On the other hand, both the manufacture of the cement used in concrete and the bitumen of asphalt mixtures generate high greenhouse gas emissions, so any construction activity with those materials will have a high carbon footprint (Yang et al., 2015). Moreover, the footprint largely depends on the amount of cement or bitumen added to the concrete or the asphalt mixture, respectively; so a construction material with a more demanding performance usually implies a higher environmental impact (Reis et al., 2020).

Among the strategies to reduce this impact, the replacement of natural raw materials with industrial by-products addresses the source of the problem (Mohd Hasan et al., 2019), by reducing the extraction of raw materials (Rodríguez-Fernández et al., 2019). At the same time, it valorizes waste materials that are otherwise deposited in landfill sites, which in turn addresses land degradation, another significant environmental impact (Lederer et al., 2021). Although the reuse of industrial

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Abbreviations: GGBS, ground granulated blast-furnace slag; ITZ, interfacial transition zones; LCA, life cycle assessment; MCDM, multi-criteria decision-making; NA, natural aggregate; RCA, recycled concrete aggregate; SCC, self-compacting concrete; w/b, water-to-binder.

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by-products has obvious environmental advantages, their addition generally worsens the performance of construction materials. Regarding concrete, the use of any industrial by-product generally has a negative effect on either its workability, or its strength and stiffness, or both (Sandanayake et al., 2020).

Recycled Concrete Aggregate (RCA) is manufactured by crushing pre-cast concrete elements with manufacturing defects. It can be defined as NA with adhered mortar, which reduces its density and increases its water absorption (Gonzalez-Corominas et al., 2017). Those properties, along with its angular shape, reduces the workability of concrete (Silva et al., 2018). The presence of adhered mortar also increases concrete porosity and creates Interfacial Transition Zones (ITZ) with reduced adhesion (Zhang et al., 2019). These two aspects mean that the mechanical properties of concrete will decrease as its RCA content increases (Verian et al., 2018).

Ground Granulated Blast-furnace Slag (GGBS) is a powdery material with binder properties, obtained after abrupt cooling and milling of ironmaking blast furnace slag. It can partially replace cement in concrete as long as its disadvantages are considered (Collivignarelli et al., 2021). On the one hand, GGBS decreases the workability of concrete, as it hinders the dragging of the coarse aggregate, due to its higher fineness. On the other, its strength and stiffness development is lower and is delayed over time (Prusty and Pradhan, 2020).

Besides the use of industrial by-products, the sustainability of construction materials has also been increased through their design. Self-Compacting Concrete (SCC) requires no vibration, which reduces energy consumption and, likewise, the carbon footprint of concreting (Reddy et al., 2020). Apart from adding superplasticizer, and defining a correct coarse-to-fine aggregate ratio to achieve self-compactability, a high content of particles less than 0.25 mm is necessary, which creates a compact cementitious paste that successfully drags the larger aggregate particles (Nepomuceno et al., 2016). This high amount of extra-fine particles is generally achieved by adding limestone filler (Lagerblad and Vogt, 2004), which has a particle size under 0.063 mm. Limestone filler is a natural aggregate that, in addition to the aforementioned issues regarding its extraction, is manufactured through grinding, sieving, flocculation, and air separation; processes that consume high amounts of energy and that all contribute a high carbon footprint (Rebello et al., 2019). In this way, the use of limestone filler outweighs the environmental benefits of the absence of energetic vibration during placement of SCC.

SCC is particularly sensitive to the proportion of the different components and therefore to the effects of adding by-products (Revilla-Cuesta et al., 2020b). For instance, the addition of RCA can reduce the slump flow by around 17% for full coarse NA replacement (Fiol et al., 2018), and 20% for full fine NA replacement (Carro-López et al., 2015). The effect of RCA on the strength and the elastic modulus of SCC is also quite negative, as any reductions can be up to as much as 15% and 35%, for 100% coarse or fine RCA, respectively (Santos et al., 2019). The use of GGBS also notably reduces flowability and strength of SCC (Reddy et al., 2020).

However, if the SCC composition is adapted to the new features, some of these problems can be mitigated, although that may amplify some others. Thus, increasing the water-to-binder (w/b) ratio to compensate for the higher water absorption of RCA minimizes the decreased flowability of SCC, but at the same time causes an additional decrease of strength, due to the higher dilution of cement (Mohammed et al., 2021). On the other hand, the reduction of the coarse aggregate content when using GGBS maintains the flowability of the SCC, although the strength of the SCC decreases (Djelloul et al., 2018).

Multi-Criteria Decision-Making (MCDM) is a programming subdiscipline whose purpose is to help decide between a finite set of alternatives. Through the use of different algorithms, it is possible to obtain an ordered ranking of the alternatives according to previously established criteria and to choose the best option (Rashid et al., 2020). The use of these algorithms is increasingly common and extends to numerous disciplines, from politics to both medicine and energy (Siksnelyte-Butkiene et al., 2020). MCDM algorithms can also successfully be used to maximize the sustainability of manufacturing processes, while considering the other characteristics of the process, such as cost or time (Pagone et al., 2021; Saxena et al., 2021).

In the field of construction materials, MCDM has clear lines of application, as it can be used to balance sustainability, costs and performance, among others (Schramm et al., 2020). Regarding concrete, MCDM can help to decide whether the decrease of workability and strength when incorporating any waste is worth the increase in sustainability that is achieved (Hafez et al., 2020). Whether the use of an alternative material in a concrete is appropriate can therefore be determined, considering all aspects of concrete behavior (Hafez et al., 2021a; Kurda et al., 2019a). Going a step further, MCDM frameworks especially dedicated to this type of analysis in concrete could even be designed (Hafez et al., 2021b; Kurda et al., 2019b). Nevertheless, this type of analysis applied to SCC manufactured with by-products is practically non-existent in the available literature, as the focus of most studies is usually on only one of the aspects: the behavior of SCC or the evaluation of its environmental impact by means of Life Cycle Assessment (LCA).

This study aims to evaluate if the use of SCC produced with different wastes is advantageous, considering not only its sustainability, but also its behavior in the fresh and the hardened state, as well as its manufacturing costs. For this purpose, in addition to the reference mix, which simulated the commercially available SCC, 18 sustainable SCC mixes were also produced. All the sustainable SCC mixes incorporated 100% coarse RCA and different fine RCA contents (0, 50% or 100%). Half of them incorporated 45% GGBS. Furthermore, limestone filler was replaced by more sustainable aggregate powders, such as limestone fines or RCA powder, in two thirds of the mixes. After the evaluation of their flowability, strength and stiffness, carbon footprint, and cost, a comprehensive MCDM analysis (3 different algorithms and 14 scenarios of analysis), focusing on different decision-making criteria (flowability, hardened behavior, carbon footprint, and cost), was performed. The results obtained provide a solid basis for optimizing the use of sustainable concrete mixes in real applications.

2. Materials, methodology, and calculations

2.1. Materials

2.1.1. Binders, water and admixtures

Two different binders were used: CEM I 52.5 R ordinary Portland cement according to EN 197-1 (2011), and GGBS. CEM I 52.5 R had a specific weight of 3.11 Mg/m^3 and a Blaine specific surface of 365 m^2/kg. Its clinker content was 95–98%. GGBS had a specific weight of 2.90 Mg/m^3 and a Blaine specific surface of 460 m^2/kg. Drinking water was taken from the supply network of Burgos, Spain. It contained no product that could affect the fresh or hardened behavior of SCC.

A plasticizer, which provided mix self-compactability, and a viscosity regulator, which reduced the water retention of SCC and contributed to the long-term conservation of self-compactability, were both added. The admixtures amounted to 2.6% and 1.8% of the binder mass in the mixes with CEM I and GGBS, respectively.

2.1.2. Aggregates

Siliceous gravel with minimum and maximum aggregate sizes of 4 mm and 12.5 mm, respectively (4/12.5 mm), and siliceous sand 0/4 mm extracted from a nearby gravel pit were used. The rounded form of these materials means that they are easily dragged within the cement paste and they are therefore commonly employed in the precast industry for SCC production (Fiol et al., 2018). Their physical properties, experimentally measured by the authors, presented typical values (Table 1) and their continuous granulometry meant that they were suitable for concrete production (Fig. 1).

Table 1
Physical properties of the aggregates.

Property	Coarse NA # Coarse RCA	Fine NA # Fine RCA	Limestone filler # Limestone fines # RCA powder
Saturated-surface-dry density (Mg/m^3)	2.61 # 2.41	2.59 # 2.38	2.78 # 2.59 # 2.32
24-h water absorption (%)	0.84 # 6.25	0.25 # 7.36	0.54 # 2.57 # 7.95
15-min water absorption without oven drying (%)	0.71 # 4.90	0.18 # 5.77	0.37 # 1.95 # 6.32

The RCA was supplied from a local waste-management company. Defective precast concrete elements were crushed to produce it. RCA was sieved to obtain coarse RCA 4/12.5 mm and fine RCA 0/4 mm. As shown in Table 1, the RCA had a slightly lower density than NA, while its water absorption was notably higher. In addition, like NA, RCA presented a continuous gradation (Fig. 1).

Traditional limestone filler with particle sizes lower than 0.063 mm and a $CaCO_3$ content of 98% was used. Furthermore, two sustainable alternatives were also considered. On the one hand, limestone fines 0/0.5 mm, with the same origin as limestone filler, although with lower energy consumption during manufacturing, which only includes grinding and sieving (Rebello et al., 2019). On the other, RCA powder 0/0.5 mm, which was obtained from crushing and sieving fine RCA 0/4 mm. This material not only has lower energy consumption during its manufacturing, but also a recycled origin, which provides greater sustainability (Hossain et al., 2016). Density and water absorption of these materials were experimentally determined, and the results are shown in Table 1. RCA powder had the lowest density and the highest water absorption, as the smaller the RCA size, the higher its water absorption, and the lower its density, due to its higher content of mortar particles (Nedeljković et al., 2021).

2.2. *Mix design*

The mix design was intended to achieve an initial SF3 class (slump flow from 750 mm to 850 mm), according to EFNARC (2002) recommendations, and to have the highest possible strength. Thus, no sustainability criteria were considered in their design beyond the introduction of the sustainable materials. The objective was to perform an MCDM analysis of a sustainable SCC with a fresh and hardened performance as good as possible, to demonstrate its validity for use in building and civil works.

The mix-design process was sequential, and all materials were added under normal atmospheric conditions:

- First, the reference mix was produced with 100% NA, CEM I 52.5 R, and limestone filler. The guidelines of Eurocode 2 (EC-2, 2010) were followed, and subsequently the SCC composition was empirically adjusted. The mix composition was typical of a commercial SCC (EFNARC, 2002). In this mix, an effective w/b ratio of 0.50, calculated from the 15-min water absorption (mixing time), was established. The effective w/b ratio (w/b_{eff}) was calculated according to Equation (1), in which w is the mixing water; apa the aggregate powder amount; $waap_{15}$ the water absorption in 15 min of the aggregate powder; aa_i the amount of every added coarse and fine aggregate; $waa_{15,i}$ the 15-min water absorption of every added coarse and fine aggregate; c the added amount of CEM I; and g the added amount of GGBS. All these data for each mix and material are shown in Tables 1 and 2.

$$w\Big/b_{eff} = \frac{w - apa \times waap_{15} - \sum_i aa_i \times waa_{15,i}}{c + g} \tag{1}$$

- Subsequently, 100% coarse NA was replaced by volume with RCA, and 0%, 50%, and 100% siliceous sand, by fine RCA. These RCA replacement percentages were proposed according to a previous study (Revilla-Cuesta et al., 2020a). The water amount was balanced to keep the effective w/b ratio, calculated according to Equation (1), constant.
- Then, the limestone filler was replaced with either limestone fines or RCA powder. Their lower proportion of particles less than 0.25 mm (Fig. 1) meant that the fine aggregate had to be partly replaced with powder to reach a SF3 class (slump flow between 750 mm and 850 mm) according to EFNARC (2002) recommendations. The effective w/b ratio (Equation (1)) was maintained constant.
- Finally, GGBS replaced 45% by mass of CEM I, which is the maximum permissible content to obtain an SF3 class without segregation in the slump-flow test. Furthermore, the amount of binder in these mixes was increased, to limit any decrease in strength, keeping the proportion between CEM I and GGBS constant.

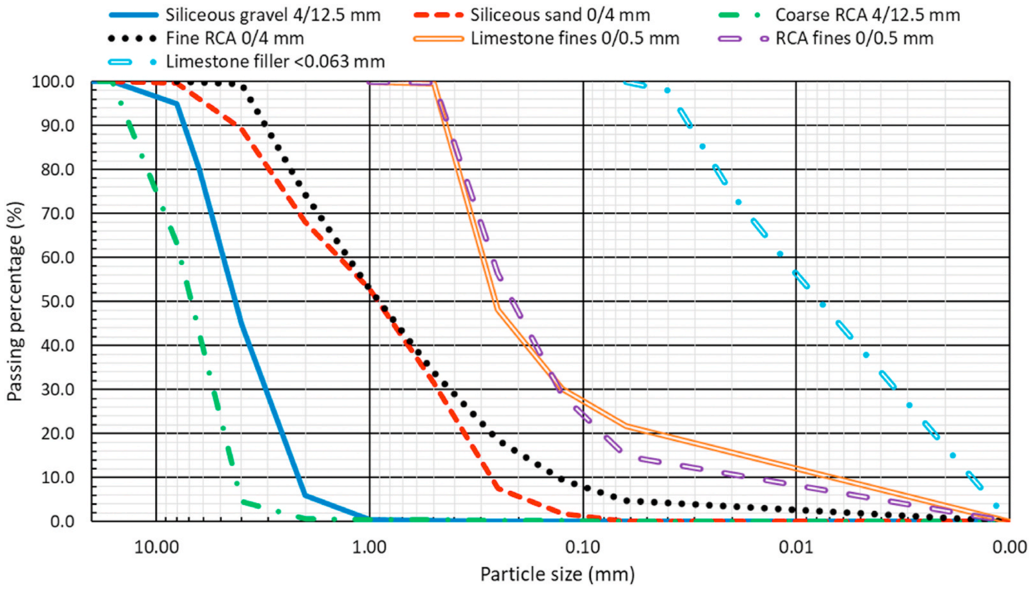

Fig. 1. Gradation of aggregate powders, NA, and RCA.

Table 2
Composition of the SCC mixes (kg/m^3).

	CEM I # GGBS	Water	Coarse RCA	Fine NA # Fine RCA	Limestone filler # Limestone fines # RCA powder
RSCC	300 # 0	165	0[a]	1100 # 0	165 # 0 # 0
C–F-0	300 # 0	185	530	1100 # 0	165 # 0 # 0
C–F-50	300 # 0	210	530	550 # 505	165 # 0 # 0
C–F-100	300 # 0	235	530	0 # 1010	165 # 0 # 0
G-F-0	235 # 190	185	430	1100 # 0	165 # 0 # 0
G-F-50	235 # 190	210	430	550 # 505	165 # 0 # 0
G-F-100	235 # 190	235	430	0 # 1010	165 # 0 # 0
C-L-0	300 # 0	185	530	940 # 0	0 # 355 # 0
C-L-50	300 # 0	210	530	475 # 435	0 # 355 # 0
C-L-100	300 # 0	235	530	0 # 865	0 # 355 # 0
G-L-0	235 # 190	185	430	940 # 0	0 # 355 # 0
G-L-50	235 # 190	210	430	475 # 435	0 # 355 # 0
G-L-100	235 # 190	235	430	0 # 865	0 # 355 # 0
C-R-0	300 # 0	200	530	940 # 0	0 # 0 # 305
C-R-50	300 # 0	220	530	475 # 435	0 # 0 # 305
C-R-100	300 # 0	245	530	0 # 865	0 # 0 # 305
G-R-0	235 # 190	200	430	940 # 0	0 # 0 # 305
G-R-50	235 # 190	220	430	475 # 435	0 # 0 # 305
G-R-100	235 # 190	245	430	0 # 865	0 # 0 # 305

In all mixtures, 5.50 kg/m^3 of plasticizer and 2.30 kg/m^3 of viscosity regulator were added to achieve self-compactability.

[a] RSCC mix incorporated 575 kg/m^3 of coarse NA (siliceous gravel 4/12.5 mm).

As the water content of these mixes was the same as for the 100%-CEM I mixes, their effective w/b ratio (Equation (1)) was 0.40.

The composition of all the mixes is shown in Table 2. Regarding the SCC designation, the reference mix was labelled RSCC, while the other 18 mixes were labelled according to the B-A-P code, where:

- B refers to the binder: C (100% CEM I 52.5 R) and G (45% GGBS and 55% CEM I 52.5 R).
- A refers to the additions of aggregate powder: R (RCA powder), L (limestone fines), or F (limestone filler).
- P refers to the percentage of fine RCA: 0%, 50%, or 100%.

2.3. Mixing process and experimental tests

Concrete self-compactability was not only optimized in its design, but also in the staged mixing process, which maximized both the absorption of water by the aggregates and the cement hydration process (Rajhans et al., 2019). Therefore, the components were added in three phases. First, aggregate powder, coarse and fine aggregate, and half the water were added. Then, the binder was included along with the remaining water. Finally, the admixtures were poured. After each phase, the SCC was mixed and left to rest for 3 and 2 min, respectively. These optimum times were empirically determined.

After the mixing process, the evaluation of fresh and hardened behavior of SCC for the MCDM analysis was performed through three tests:

- The main characteristic of SCC is its flowability in the fresh state, which must be properly conserved over time (Santos et al., 2019). Flowability was measured through the slump-flow test, according to EN 12350-8 (2020), performed immediately after the mixing, 15 min later (simulating fast concreting), and 60 min later (simulating transportation from the concrete plant to a distant concreting site: long-distance concreting). The SCC was kept in an operating concrete mixer for 60 min to perform these tests. On the other hand, the mixes also fulfilled the other requirements (viscosity, passing ability and sieve segregation) for SCC. Complete analyses of these SCC mixtures and their fresh behavior (slump-flow, V-funnel, 2-bar L-box and sieve-segregation tests) can be found in other articles by the authors (Revilla-Cuesta et al., 2021).
- The compressive strength, as per EN 12390-3 (2020), and the modulus of elasticity, following EN 12390-13 (2014), were evaluated at 28 days. In both cases, two 10x20-cm cylindrical specimens were used.

2.4. Environmental analysis: carbon footprint

SCC sustainability was assessed through the carbon footprint of the mixes. Since these values were intended for comparative purposes, it was assumed that both the transportation (of both raw materials and concrete) and the manufacturing processes were identical for all mixes. This simplification means that the exclusive effect of the industrial by-products on the carbon footprint of the concrete was evaluated, disregarding other factors (Rashid et al., 2020).

According to the above, to calculate the carbon footprint of each SCC mixture per m^3 (CF_{SCC}, kg CO_2 eq/m^3), it is necessary to know the unitary carbon footprint per kg (CF_u, kg CO_2 eq/kg) of its components (binders, coarse and fine aggregate, aggregate powder, water and admixtures). Subsequently, the unitary carbon footprints are multiplied by the amount of each component per m^3 (ca, kg/m^3) in the SCC mix, and, finally, the values obtained are summed. Accordingly, the carbon footprint of SCC can be calculated through Equation (2).

$$CF_{SCC} = \sum_i CF_{u,i} \times ca_i \tag{2}$$

Table 3 shows the average unitary carbon footprint calculated in the literature through LCA for both coarse and fine NA and RCA (Hossain et al., 2016), aggregate powders (Rebello et al., 2019), binders, water and admixtures (Yang et al., 2015). These papers were considered because they analyzed the carbon footprint of materials with similar characteristics to those used in this study. The values of Table 3 show the great environmental advantage of alternative binders, since the carbon footprint of GGBS is 3% of Portland cement. Moreover, the carbon footprint of RCA is about 60% lower than NA, by saving the extraction processes. And, finally, limestone filler has a carbon footprint that is approximately twice as high as the carbon footprint of limestone fines.

2.5. Cost analysis

The cost of each SCC mix was also calculated, considering only the costs of its component. Other variables such as transport and landfill fees were considered invariant (Rashid et al., 2020). The cost of each SCC mix per m^3 ($COST_{SCC}$, USD/m^3) was then obtained by adding the cost of each component to manufacture a cubic meter of SCC (Equation (3)), which was obtained by multiplying the quantity of each component (ca, kg/m^3) by its unitary cost ($COST_u$, USD/kg). These calculations are suitable for the MCDM algorithms due to their comparative nature.

$$COST_{SCC} = \sum_i COST_{u,i} \times ca_i \tag{3}$$

The unitary costs of the raw materials, shown in Table 3, were obtained from the official price database of the Spanish Ministry of Public Works and Transport (2016) and the Government of Extremadura (2019), Spain, except for the cost of the RCA, which was obtained from a private supplier. The unitary costs of industrial by-products are lower than those of natural materials, due to the absence of extraction processes, so waste management companies can purchase them at low cost (Varadharajan et al., 2020). In addition, the high cost of cement and limestone filler can also be appreciated, mainly caused by the high energy-consumption levels during manufacturing (Rebello et al., 2019).

Table 3
Unitary carbon footprint and cost of raw materials.

Property	CEM I # GGBS	Plasticizer # Viscosity regulator	Water	Coarse NA # Coarse RCA	Fine NA # Fine RCA	Limestone filler # Limestone fines # RCA powder
Carbon footprint (kg CO_2 eq/kg)	0.9310 # 0.0265	0.0005	0.0002	0.0075 # 0.0030	0.0026 # 0.0011	0.0157 # 0.0069 # 0.0033
Cost (USD/kg)	0.1320 # 0.0747	1.4612	0.0007	0.0079 # 0.0042	0.0093 # 0.0054	0.0461 # 0.0184 # 0.0115

3. Multi-Criteria Decision-Making (MCDM) framework

Selecting any product, in this case SCC, on the basis of a single property or characteristic is not recommended. The decision-maker should consider the different dimensions of the product, which is why MCDM analyses are essential (Schramm et al., 2020). In this study, a comprehensive MCDM analysis was performed, in which 4 decision-making criteria, 3 different algorithms, whose implementation processes are described in the supplementary data, and 14 analysis scenarios were considered.

3.1. Decision-making criteria

Four different decision-making criteria were considered, which define the four main aspects of SCC mixes incorporating industrial by-products: decreased flowability, hardened performance, carbon footprint, and cost.

- The distinctive property of SCC is its high flowability in the fresh state and its conservation over time (Okamura, 1997). Thus, the first decision-making criterion was decreased flowability at either 15 min or 60 min, depending on the scenario under consideration (see section 3.3). The value of the flowability decrease was directly introduced in the MCDM algorithms.
- Compressive strength (*CS*) and modulus of elasticity (*ME*) at 28 days are basic properties of any concrete for a correct hardened behavior (EC-2, 2010). In this case, both properties were considered equally important because of their relevance to the strength (De Domenico et al., 2018) and in-service (Lanti and Martínez, 2020) behavior of real structures. Thus, the indicator *"Hardened State (HS)"*, Equation (4), was defined, with no physical sense, but to simplify the MCDM analysis, rather than considering both properties separately. This indicator was the second decision-making criterion.

$$HS = \frac{CS\ (MPa) + ME(GPa)}{2} \tag{4}$$

- The other two decision-making criteria were carbon footprint and cost, whose values (kg CO_2 eq/m^3 or USD/m^3) were directly considered in the MCDM analysis.

3.2. MCDM algorithms

3.2.1. TOPSIS algorithm

The TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) algorithm belongs to the group of MCDM algorithms based on rankings. It is suitable for making decisions based on quantitative criteria, as in this study. The decision-makers only adjust the weight (relative importance as a percentage of 1) of each criterion.

3.2.2. AHP algorithm

The AHP (Analytic Hierarchy Process) algorithm is an MCDM ranking-based algorithm. The decision-makers are required to define several comparison matrices based on the qualitative or quantitative value that each criterion has for each alternative. One of these matrices indicates the importance of each criterion in relation to the others (pairwise comparison matrix), while the other matrices indicate how good each alternative is in relation to the others for each criterion (criterion comparison matrices). There are as many criterion comparison matrices as there are decision-making criteria. The values of the comparison matrices can be obtained from various standardized scales, the most common of which is the Saaty scale. The influence of the decision-makers is very high, but valid for qualitative criteria.

As all criteria were quantitative, the values of the Saaty scale in the criterion comparison matrices were assigned at intervals of 5% of the criterion value, so that the algorithm generated systematic results. Thus, an improvement in a value of a criterion ranging from 0% to 5% was assigned a value of 1, an improvement between 5% and 10% was assigned a value of 2, and so on up to an improvement of more than 40% that was assigned a value of 9. Negative variations (worsening) of the values were assigned the inverse values of those indicated.

3.2.3. PROMETHEE algorithm

The PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation) algorithm is an MCDM algorithm based on overranking. Like the TOPSIS algorithm, it is only valid for quantitative criteria, and the decision-makers only define the weight of each criterion.

3.3. Scenarios for analysis

The definitions of the 14 scenarios for analysis, shown in Table 4, cover the different conditions when selecting an SCC: best-possible flowability, best-possible hardened behavior, best-possible balance between fresh and hardened behavior, lowest-possible carbon footprint, lowest-possible cost, and multi-purpose. Each condition was analyzed considering either short- or long-term flowability (different concreting conditions), as shown in the second column of Table 4. In some applications (precast industry, for instance), concreting is performed immediately after the mixing process (fast concreting), so the short-term flowability must be considered. In other cases, concreting is performed at a great distance from the manufacturing plant (long-distance concreting), so long-term flowability is the key property (Carro-López et al., 2015). The scenarios for analysis were coded with an *H* followed by a number from 1 to 14, as shown in the third column of Table 4.

The terms "best-possible" and "lowest-possible" refer to the fact that, in each scenario, the SCC mixture with the best or lowest value of a property (flowability, hardened behavior, balance between fresh and hardened behavior, carbon footprint or cost) was sought (Table 4), but considering at the same time the value of the other properties, operations that MCDM algorithms can perform (Schramm et al., 2020). Accordingly, the property for which the best- or lowest-possible value was sought in each scenario was defined as the main criterion of that scenario, which are shown in the fourth column of Table 4. The main criteria of each scenario defined the weights of the TOPSIS and PROMETHEE algorithms, as well as the Saaty-scale values of the AHP algorithm:

- In the TOPSIS and PROMETHEE algorithms, the main criteria had twice the weight of the non-main criteria. In each scenario, all criteria in the same category (main and non-main) had the same

Table 4
Scenarios for analysis.

Condition	Scenario [a]	Code	Main criterion/criteria	TOPSIS/PROMETHEE weight of main criteria
Best-possible flowability	Concrete with best-possible short-term flowability	**H-1**	Decreased flowability at 15 min	0.400
	Concrete with best-possible long-term flowability	**H-2**	Decreased flowability at 60 min	0.400
	Concrete with best-possible balance between short- and long-term flowability	**H-3**	Decreased flowability at 15 min Decreased flowability at 60 min	0.286
Best-possible hardened behavior	Concrete with best-possible hardened behavior considering the short-term flowability	**H-4**	Hardened state (HS) indicator	0.400
	Concrete with best-possible hardened behavior considering the long-term flowability	**H-5**	Hardened state (HS) indicator	0.400
Best-possible balance between fresh and hardened behavior	Concrete with best-possible balance between short-term flowability and hardened behavior	**H-6**	Decreased flowability at 15 min Hardened state (HS) indicator	0.333
	Concrete with best-possible balance between long-term flowability and hardened behavior	**H-7**	Decreased flowability at 60 min Hardened state (HS) indicator	0.333
Lowest-possible carbon footprint	Concrete with lowest-possible carbon footprint considering its short-term flowability	**H-8**	Carbon footprint	0.400
	Concrete with lowest-possible carbon footprint considering its long-term flowability	**H-9**	Carbon footprint	0.400
Lowest-possible cost	Concrete with lowest-possible cost considering the short-term flowability	**H-10**	Cost	0.400
	Concrete with lowest-possible cost considering the long-term flowability	**H-11**	Cost	0.400
Multi-purpose	Multi-purpose considering the short-term flowability	**H-12**	All criteria equally important	0.250
	Multi-purpose considering the long-term flowability	**H-13**	All criteria equally important	0.250
	Multi-purpose considering both short-term and long-term flowability	**H-14**	All criteria equally important	0.200

[a] In all scenarios, 4 decision-making criteria were considered (decreased flowability at either 15 or 60 min, HS indicator, carbon footprint and cost) except in scenarios H-3 and H-14, in which decreased flowability both at 15 and at 60 min was considered (5 criteria).

weight. The weights of the main decision-making criteria are shown in the last column of Table 4.

- In the AHP algorithm, the values of the Saaty scale of the pairwise comparison matrix were defined on the basis of two rules. First, all the main criteria were of medium importance (value 5) compared to the non-main criteria. Second, all criteria in the same category were equally important (value 1).

4. Results and discussion: decision-making criteria

Each change in the composition of the mixtures affected the value of the four decision-making criteria under consideration. Table 5 shows the values of the decision-making criteria for each mix, whose behavior and trends are explained in the following sections.

4.1. Decreased flowability over time

Fig. 2 and Fig. 3 show the percentage decrease of flowability at 15 and at 60 min, respectively, for the mixes with increasing contents of fine RCA and different aggregate powders. The percentage decrease of flowability was directly introduced in the MCDM analysis. As defined in section 2.2, all mixes had an initial SF3 class (slump flow from 750 mm to 850 mm). After 60 min, all mixes were at least class SF1 (slump flow from 550 mm to 650 mm), except for the RCA-powder mixes.

The flowability was reduced when adding RCA regardless of the point in time (Figs. 2a and 3a). The more angular shape of RCA compared to siliceous aggregate, and its higher water absorption over time, explained the negative impact of this by-product (Silva et al., 2018).

The mixes incorporating GGBS showed smaller decreases of slump flow at 15 min, due to their lower coarse aggregate content. However, their decreased flowability at 60 min was greater. The higher fineness of GGBS appears to lead to a progressive agglutination of the cement paste that hinders particle dragging, as has been observed with other alternative binders (Pedro et al., 2017). Furthermore, the addition of fine RCA had a softer negative effect (lower slopes in absolute value of the trend lines, Figs. 2a and 3a) after 15 min in the mixes with GGBS, while the 60-min flowability preservation was better in the mixes with 100% conventional clinker. These results are linked to the conservation of flowability of each binder, as discussed above.

The mixes with limestone fines showed the best temporal conservation of flowability (Figs. 2b and 3b). The limestone-fines mixes with little fine RCA showed smaller flowability decreases at 15 min than the reference mix, manufactured with limestone filler. In other words, the use of limestone fines compensated the negative effect of the coarse RCA. The larger particle size of limestone fines appeared to create a denser cementitious paste within which the coarse aggregate were more efficiently dragged, as reported in other studies of SCC with steel slag (Santamaría et al., 2020). RCA powder resulted in greater flowability decreases, because of their greater deferred absorption of water (Silva et al., 2018).

4.2. Hardened behavior

4.2.1. Compressive strength

As shown in Fig. 4a, the use of coarse RCA reduced the compressive strength, following the appearance of weaker ITZ (Verian et al., 2018). Substitution of siliceous sand with fine RCA also decreased the strength

Table 5
Value of decision-making criteria for the SCC mixes.

Mix	Decreased flowability (%): in 15 min # in 60 min	Compressive strength (MPa)	Modulus of elasticity (GPa)	Indicator *HS*, Equation 4	Carbon footprint (kg CO_2 eq/m^3)	Cost (USD/m^3)
RSCC	−1.1 # −13.8	56.7	46.4	51.55	289.10	73.49
C–F-0	−2.4 # −19.9	44.9	41.6	43.25	286.38	71.19
C–F-50	−4.3 # −20.4	40.8	29.5	35.15	285.51	68.82
C–F-100	−4.5 # −23.7	27.8	23.2	25.50	284.64	66.45
G-F-0	−1.8 # −26.1	50.7	49.3	50.00	230.60	76.38
G-F-50	−2.1 # −29.9	44.5	34.3	39.40	229.73	74.01
G-F-100	−4.2 # −32.5	32.7	25.8	29.25	228.86	71.64
C-L-0	+0.7 # −13.1	45.6	36.4	41.00	285.82	68.63
C-L-50	−1.3 # −15.9	42.4	26.7	34.55	285.10	66.67
C-L-100	−1.9 # −22.7	54.6	22.1	38.35	284.34	64.59
G-L-0	+1.2 # −21.3	51.4	45.3	48.35	230.04	73.82
G-L-50	+0.4 # −25.7	36.9	31.4	34.15	229.32	71.86
G-L-100	−1.3 # −32.8	54.6	22.5	38.55	228.56	69.78
C-R-0	−6.0 # −22.0	36.0	25.9	30.95	284.38	65.61
C-R-50	−6.9 # −23.4	29.0	22.8	25.90	283.66	63.65
C-R-100	−9.4 # −31.1	15.4	15.2	15.30	282.90	61.57
G-R-0	−3.8 # −30.0	41.8	29.3	35.55	228.60	70.81
G-R-50	−4.5 # −33.5	31.5	27.1	29.30	227.88	68.84
G-R-100	−7.1 # −39.7	27.3	16.1	21.70	227.12	66.77

in a linear way. This strength loss was attributed to the presence of mortar particles in the fine RCA, and to the increased adhesion problems in the ITZ, also noted in other studies with increasing contents of this RCA fraction (Revilla-Cuesta et al., 2020a). Nevertheless, the use of 50% fine RCA generally resulted in higher compressive strengths than expected according to the trend lines. The negative effect of RCA was amplified as its content increased.

In general, the use of GGBS in the same amount as conventional cement causes concrete to develop lower compressive strengths (Djelloul et al., 2018). However, in the mixes that incorporated GGBS, the binder content was increased to enhance flowability and strength. As a result, the mixes with GGBS had 10–30% higher compressive strength than their counterparts manufactured with CEM I.

Concerning the effects of the aggregate powder (Fig. 4b), the limestone-fines mixes had the highest strength. The beneficial effect was especially noticeable when limestone fines and GGBS were simultaneously used. Limestone fines supplemented GGBS and created a high-quality cementitious matrix with improved compressive strength (Santamaría et al., 2020). The smaller the fraction that is used, the greater the detrimental effect of RCA on the mechanical behavior of the concrete, which meant that the RCA-powder mixes showed very low strengths (Nedeljković et al., 2021). In fact, the C-R-100 mix did not reach the minimum compressive strength of 25 MPa required for structural concrete (Cabrera et al., 2020).

The decreased compressive strength following the addition of fine RCA content (Fig. 4a) was similar regardless of the type of binder or aggregate powder under consideration, *i.e.*, all the trend lines presented similar slopes. The use of RCA powder and CEM I increase this loss of strength, possibly due to a notable porosity increase when large quantities of the finer RCA fractions were added (Nedeljković et al., 2021).

4.2.2. *Modulus of elasticity*

The modulus of elasticity of the mixes is shown in Fig. 5. The effect of RCA and GGBS on the elastic stiffness of SCC was similar to their effect on compressive strength (Fig. 5a):

- 100% coarse RCA reduced the modulus of elasticity by 7%, due to the lower stiffness of RCA compared to NA (Fiol et al., 2018). The lower stiffness and the increased porosity of fine RCA compared to siliceous sand, caused the modulus of elasticity to decrease in an approximately linear way in proportion with the fine RCA content (Santos et al., 2019). Furthermore, in general, the modulus of elasticity was lower than predicted by the trend lines for a fine RCA proportion of 50%, so the harmful effect of fine RCA on the stiffness of SCC was clearer for low contents.
- GGBS has lower stiffness than conventional cement clinker (Prusty and Pradhan, 2020). However, this effect was compensated by the higher binder content of that mixes, which led to higher elastic stiffness results (*e.g.*, the G-F-0 mix had a modulus of elasticity 6% higher than that of the RSCC mix).

A synergistic effect between the GGBS and the fine RCA was also observed (Fig. 5a), as the reduction in the modulus of elasticity with increasing percentages of fine RCA was more pronounced in the mixes with GGBS. While the slag-based mixes had higher moduli of elasticity than the CEM I mixes with 0% fine RCA, the moduli of elasticity for 100% fine RCA were similar for both binders.

In contrast to strength, limestone-filler mixes presented the highest stiffness (Fig. 5b). The smaller size of the limestone filler may have led to a more compact and stiffer cementitious matrix (Khan et al., 2019). RCA powder was associated with the lowest modulus of elasticity. The effect of RCA was so negative, that its addition decreased the sensitivity to the fine RCA rate (trend lines with a lower slope, Fig. 5a).

4.2.3. *Indicator "hardened state" (HS)*

The hardened state behavior of the SCC was introduced in the MDCM analysis by means of the indicator *"Hardened State (HS)"*, as defined in Equation (4), which consists of performing the arithmetic mean of the compressive strength and the modulus of elasticity of the SCC mix. The fifth column of Table 5 shows the value of this indicator for each mix.

4.3. *Carbon footprint*

The carbon footprints of the SCC mixes are shown in Fig. 6. In their calculation, only the composition of the SCC was considered. The manufacturing processes, the mixing, and the laying were considered identical in all the mixes. As an example, and for clarity, Table 6 shows the calculation of the carbon footprint of the RSCC reference mix using Equation (2) and the data in Tables 2 and 3. The values obtained through these calculations were directly introduced in the MCDM analysis.

The use of RCA had a minor impact on the carbon footprint of SCC (Fig. 6a). Thus, the mix with 100% RCA in both its coarse and its fine fractions only reduced the carbon footprint by around 4 kg CO_2 eq/m^3. The environmental benefits of using RCA in SCC are mainly linked to the reduction of the landscape impacts caused by aggregate extraction (Hossain et al., 2016).

The effect of suppressing the limestone filler also had a minor effect

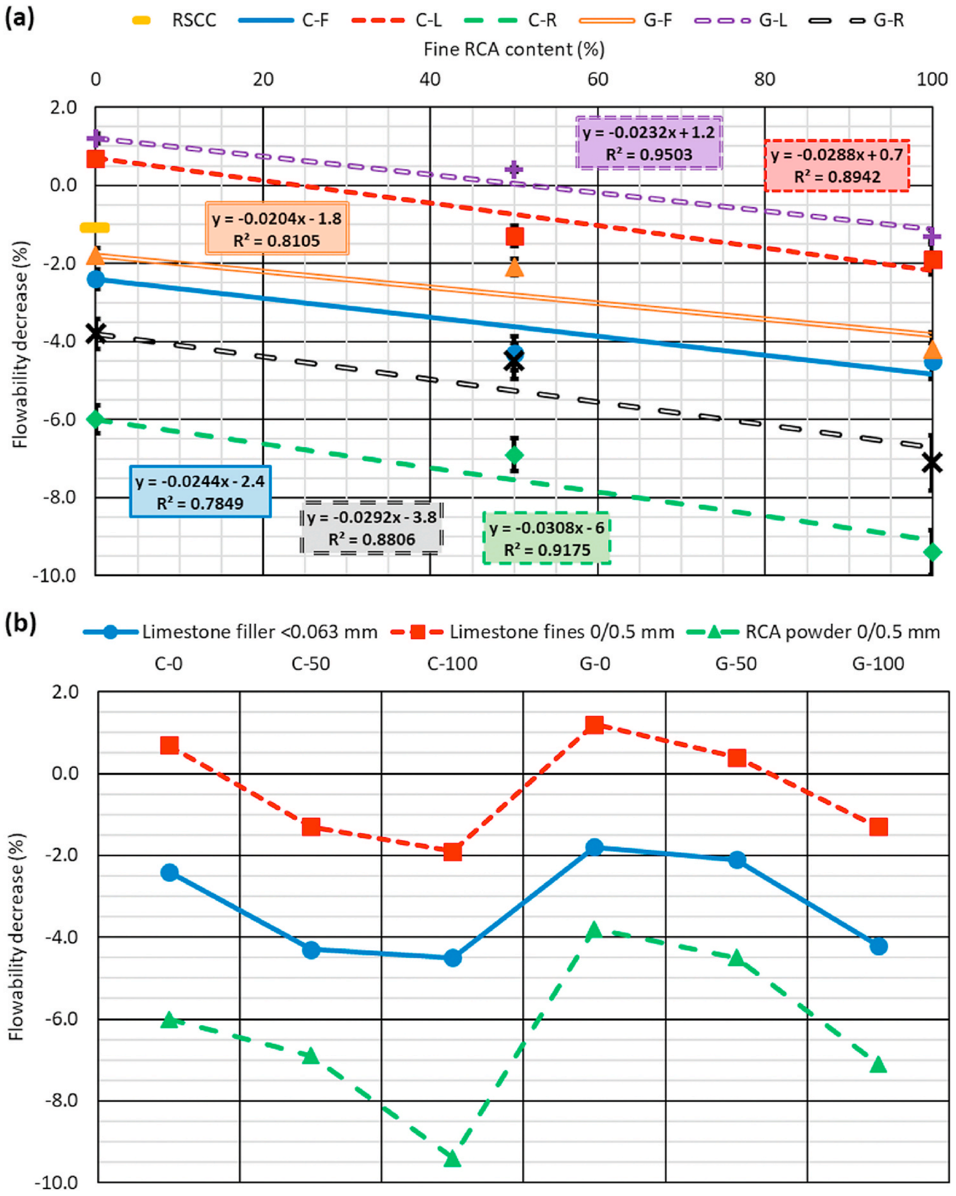

Fig. 2. Flowability decrease in 15 min: (a) effect of fine RCA content; (b) effect of aggregate powder and binder.

(decrease of around 1–2 kg CO_2 eq/m^3), as shown in Fig. 6b. As explained in section 2.2, when alternative aggregate powders were used, their amount had to be increased, which almost completely counteracted the desired decrease of the carbon footprint, due to the lower energy consumption during manufacturing (Ameri et al., 2020). Therefore, achieving adequate fresh behavior of SCC diminished its environmental benefit. However, using RCA powder once again reduced the damage related to extraction from quarries or gravel pits (Nedeljković et al., 2021).

Cement is the concrete component that usually contributes most to its carbon footprint, so decreasing its content will significantly reduce its associated environmental damage (Hafez et al., 2021b). This observation is also corroborated in the present study, as the use of significant amounts of GGBS (45% of the total binder content) reduced the carbon footprint of SCC by 20% (Fig. 6a). Positive results were obtained even though the binder content was increased when using GGBS, to compensate for its lower dragging capacity and lower strength than conventional cement.

4.4. Cost

The cost of the mixes (Fig. 7) was also calculated by only comparing their composition. As the use of wastes is generally cheaper than conventional materials, due to the lower cost of acquisition and manufacturing for the companies (Varadharajan et al., 2020), the higher the amount of RCA, the cheaper the SCC. So, the cost of the RSCC mix, whose calculation according to Equation (3) is shown in Table 7 as an example, was 73.5 USD/m^3, while the cost of the same SCC with 100% coarse and fine RCA was 66.4 USD/m^3. The cost values were directly included as calculated in the MCDM algorithms.

The use of aggregate powders with larger particle sizes further reduced that cost to 64.6 USD/m^3 and 61.6 USD/m^3 for limestone fines and RCA powder, respectively (Fig. 7b). Lower energy consumption during the manufacture of these aggregate powders and the recycled origin of RCA powder both explain these lower costs (Rebello et al., 2019).

It was previously shown that GGBS has a 43% lower unitary cost than conventional Portland cement. However, Fig. 7a shows that the mixes with GGBS were more expensive than their conventional counterparts.

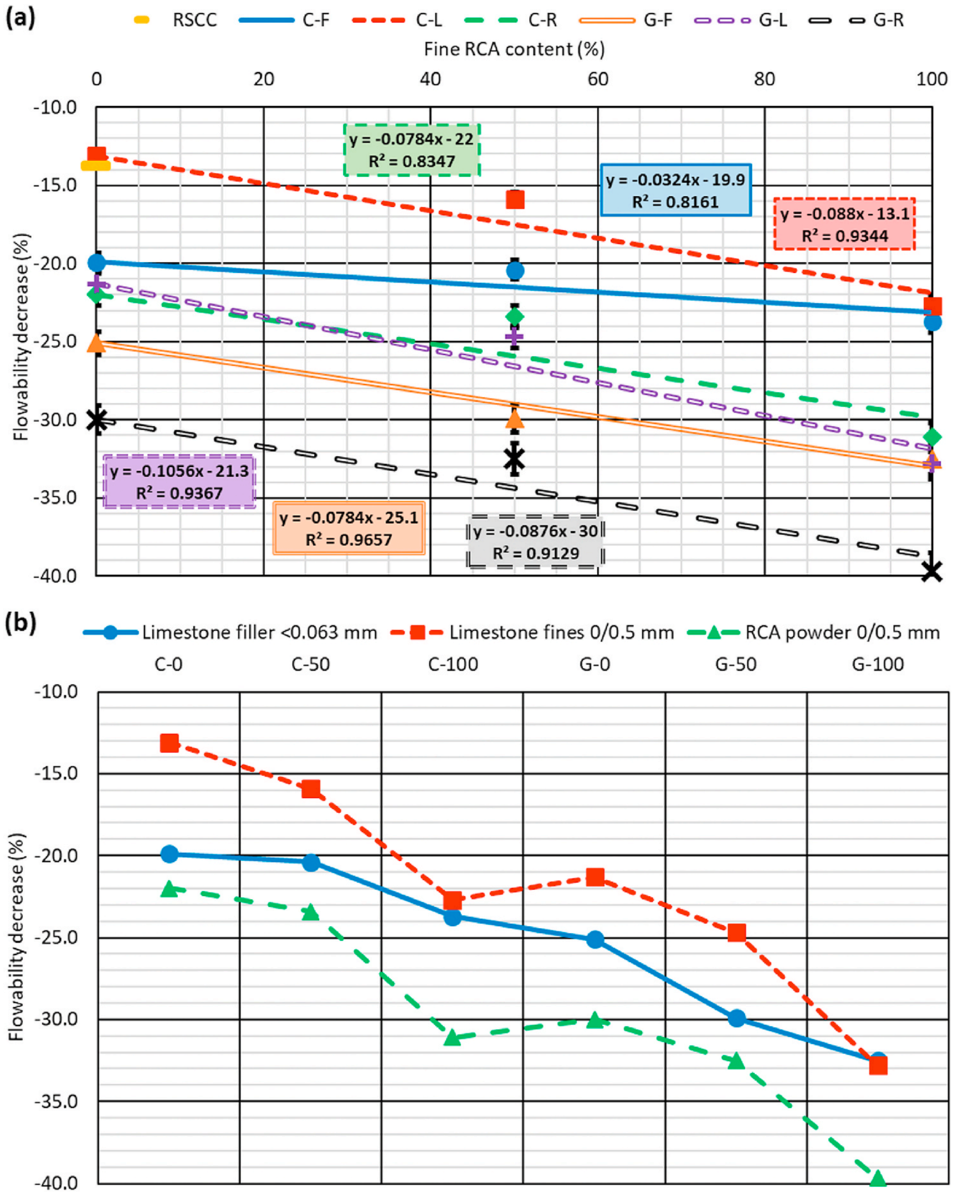

Fig. 3. Decreased flowability in 60 min: (a) effect of fine RCA content; (b) effect of aggregate powder.

The higher binder content of these mixes increased the cost of the SCC. Large quantities of RCA have to be added, to obtain a slag-based SCC of adequate strength and flowability and, at the same time, cheaper than conventional SCC.

5. Results and discussion: MCDM analysis

The results of the MCDM analysis are presented and discussed in this section. The ranking of each mix and scenario according to each algorithm (TOPSIS, AHP, and PROMETHEE) is shown alongside the average ranking obtained from the joint results of the three algorithms, upon which the discussion of the results is based.

5.1. *SCC with best-possible flowability*

From the point of view of short-term flowability (scenario H-1), the best mixes were made with limestone fines and, preferably, GGBS, as shown in Fig. 8a. Their joint use, together with 100% coarse and fine RCA would also be adequate, since the G-L-100 mix was the fifth best mix. The use of CEM I and limestone fines is undoubtedly the preferred option for long-term flowability (scenario H-2, Fig. 8b), along with the fine RCA content limited to 50%.

Although a sustainable mix was ranked first in both scenarios, the RSCC mix was the third best option for fast concreting and the second for long-distance concreting. These results prove that if high flowability were a priority, employing large amounts of wastes might not be as worthwhile as seeking a balance between sustainability and fresh behavior. The balance between short- and long-term flowability (scenario H-3, Fig. 8c) showed similar results. So, if the main requirement of SCC is its flowability, the combination of limestone fines, CEM I or GGBS, 100% coarse RCA and up to 50% fine RCA could compete with commercial SCC.

The worst options of these three scenarios were linked to the use of RCA powder. The lower carbon footprint and cost of this material could not compensate the decrease in flowability. If high flowability is the priority, RCA powder cannot be recommended. The use of limestone filler was also detrimental when combined with both GGBS and fine RCA, so limestone fines are a better option to achieve a sustainable SCC with the best temporal flowability.

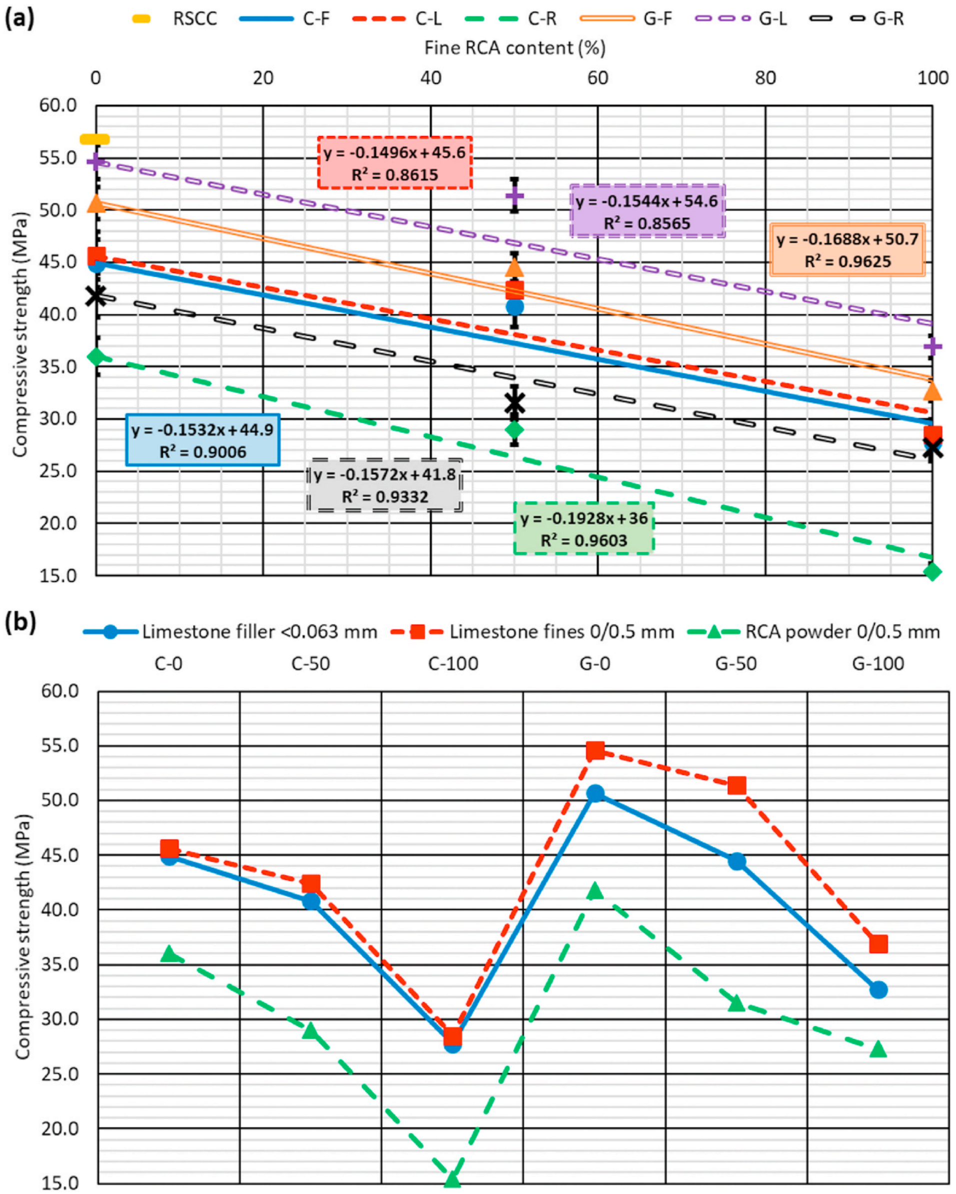

Fig. 4. Compressive strength of the mixes: (a) effect of fine RCA content; (b) effect of aggregate powder.

5.2. *SCC with best-possible hardened behavior*

As Fig. 9 shows, the best options when designing an SCC with best-possible hardened performance were those that incorporated low amounts of recycled industrial by-products. The mixes containing GGBS were the exception, due to their increased binder content. So, if the design of SCC has been adjusted to compensate the expected worsening of mechanical behavior when the highest-possible strength and stiffness is required, then the use of industrial by-products can be advantageous. No major variations were observed between the hypothetical situation of fast concreting (scenario H-4, Fig. 9a) or long-distance concreting (scenario H-5, Fig. 9b). Hence, mixes G-L-0, C-L-0, and G-F-0, all with 100% coarse RCA, apart from mix RSCC, were the best options for a high-strength SCC. They also supported the preference for limestone fines rather than limestone filler.

In general, the use of fine RCA would not be recommended here, especially if high long-term flowability is demanded. Using large amounts of fine RCA or RCA powder led to large strength and stiffness decreases that were not compensated by their environmental advantages or economic savings. Nevertheless, in some cases of fast concreting, it may be reasonable to use an intermediate content, *e.g.*, 50% fine RCA, as the G-L-50 mix was the third best mix in the scenario H-4.

5.3. *Best-possible balance between fresh and hardened behavior of SCC*

The ranking of the mixes is shown in Fig. 10, considering both short-term (scenario H-6, Fig. 10a) and long-term (scenario H-7, Fig. 10b) flowability, in the search for an SCC that balances both fresh and hardened behavior. The findings are a combination of the two previous sections:

- The joint use of GGBS and limestone fines provided the best results in the scenario of fast concreting. In this case, up to 50% fine RCA combined with these materials would be adequate (the G-L-50 mix was the third best option).
- In the case of long-distance concreting, the best option for the maximization of flowability and mechanical properties is to reduce the fine RCA content. Its environmental advantage cannot of course counteract its problems in the performance of SCC (Nedeljković

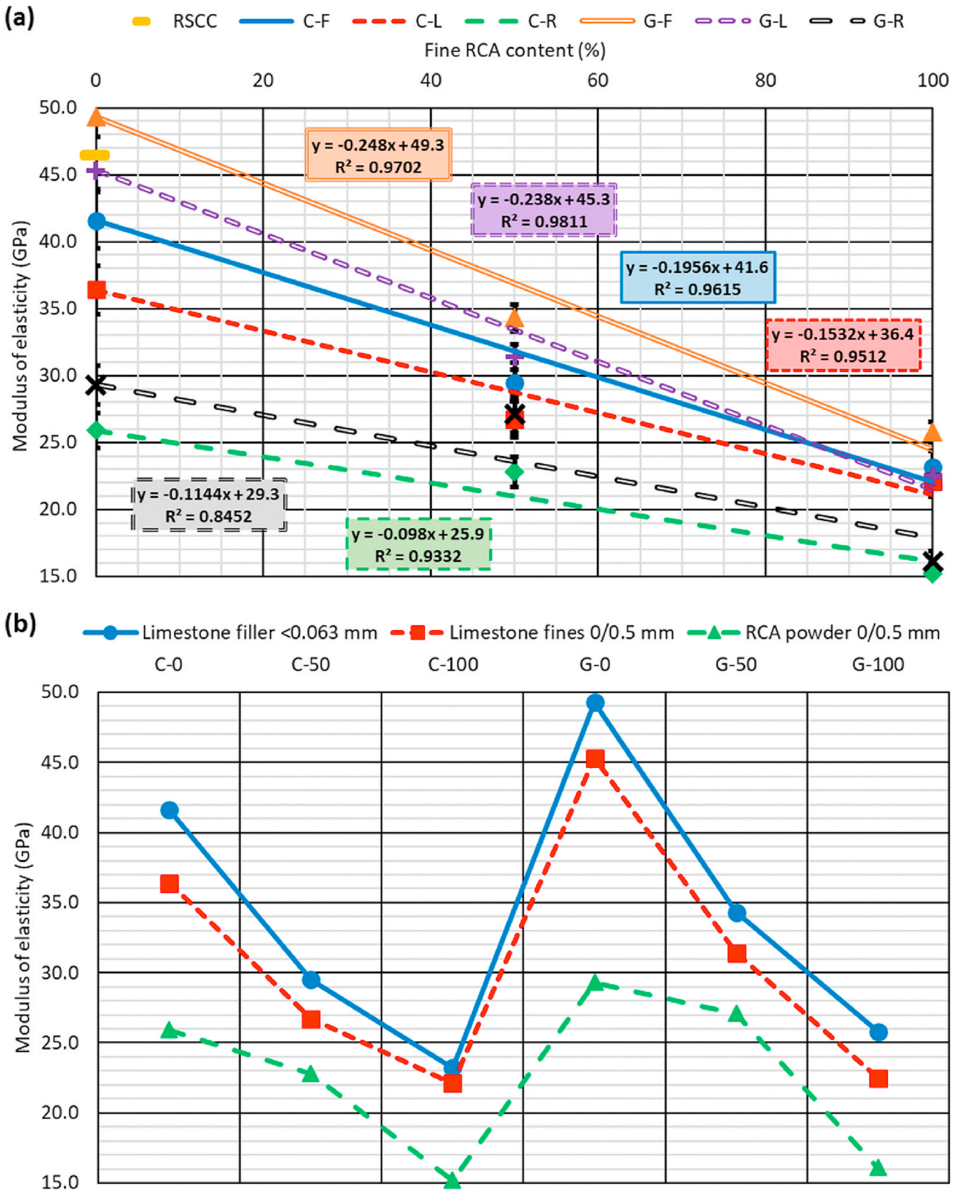

Fig. 5. Modulus of elasticity of the mixes: (a) effect of fine RCA content; (b) effect of aggregate powder.

et al., 2021). The use of limestone fines as a sustainable powder was once again the best option.

- In any case, the use of 100% coarse RCA is advisable, as it has no adverse effects on SCC performance. However, the use of RCA powder should be avoided.

Despite all the above, the RSCC mix, produced without any industrial by-products, was the highest one in the ranking. So, if fresh and hardened behavior is prioritized, then the MCDM analysis showed that its higher costs and emissions were no obstacle to its use. This result demonstrated the need for further optimization of the SCC mix design when introducing sustainable raw materials.

5.4. *SCC with lowest-possible carbon footprint*

Considering the carbon footprint as the priority when defining the concrete composition for a specific application is not a common situation, because both the fresh and the hardened requirements are usually imperative from a technical point of view (Revilla-Cuesta et al., 2020b). Furthermore, although intuitively the higher the content of industrial by-products, the lower the carbon footprint, the conventional RSCC mix was not the worst option (Fig. 11), which proves that not only sustainability, but also SCC performance, has to be considered in the frameset of the decision.

Based on the results of the MCDM, some proposals for an optimal carbon footprint (scenarios H-8 and H-9, Fig. 11) are as follows:

- The use of GGBS is preferable to conventional cement clinker. Its lower unitary carbon footprint significantly decreased the resulting footprint of SCC, even despite the increase in binder content that was required to improve the mechanical behavior.
- Regarding the aggregate powder, the use of limestone fines is the best choice. Otherwise, the use of either limestone filler or RCA powder presents few perceptible differences. If a low-carbon-footprint SCC is preferential, then the greater sustainability of RCA powder will compensate the loss of flowability and the lower strength that they produce.
- Finally, the amount of fine RCA added should be 50% or lower. Using 100% coarse RCA is an adequate option.

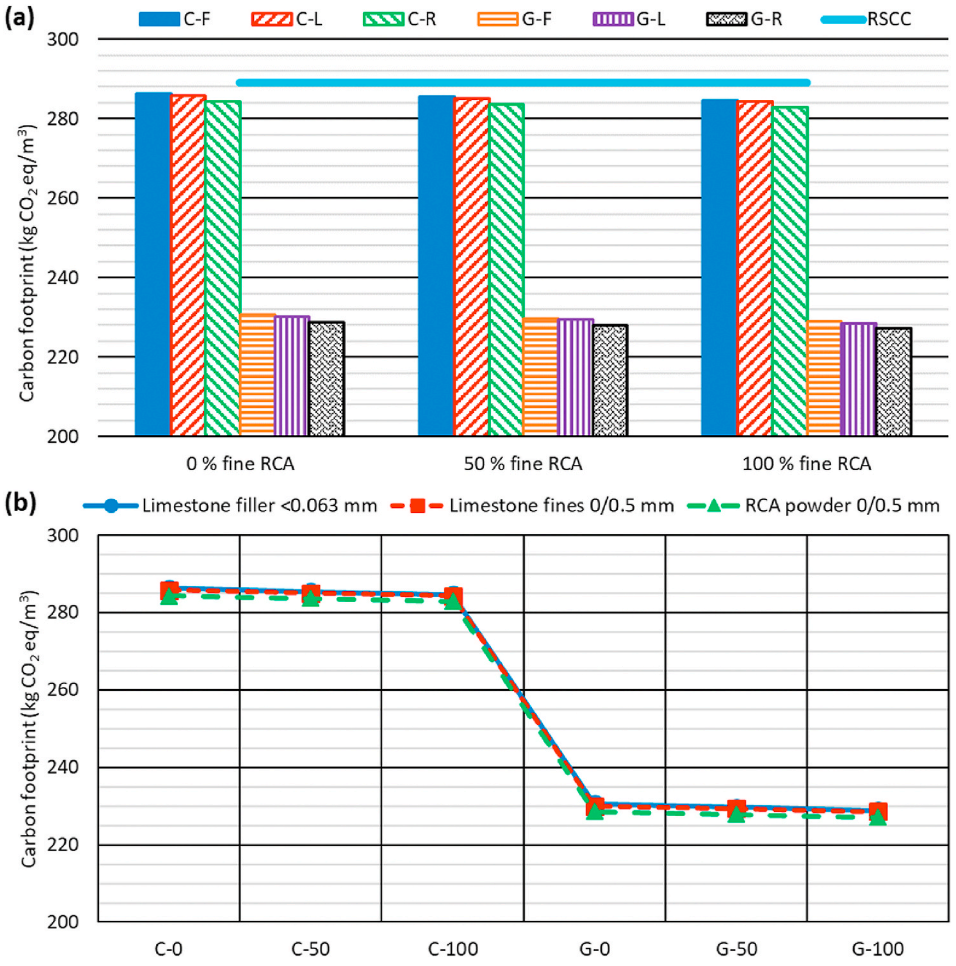

Fig. 6. Carbon footprint of the mixes: (a) effect of fine RCA content; (b) effect of aggregate powder.

Table 6
Calculation of the carbon footprint of the RSCC mix (notation according to Equation (2)).

Material	Unitary carbon footprint ($CF_{u,i}$, kg CO$_2$ eq/kg)	Component amount (ca_i, kg/m^3)	Carbon footprint of the component in 1 m^3 of RSCC mix ($CF_{u,i} \times ca_i$)	Total carbon footprint of mix RSCC (CF_{SCC}, kg CO$_2$ eq/m^3)
CEM I	0.9310	300	279.300	289.10
Plasticizer	0.0005	5.50	0.002	
Viscosity regulator	0.0005	2.30	0.001	
Water	0.0002	165	0.033	
Coarse aggregate (siliceous gravel 4/12.5 mm)	0.0075	575	4.313	
Fine aggregate (siliceous sand 0/4 mm)	0.0026	1100	2.860	
Aggregate powder (limestone filler <0.063 mm)	0.0157	165	2.591	

5.5. *SCC with lowest-possible cost*

A lowest-possible-cost SCC may be preferential in low-demanding applications, such as the manufacture of non-structural elements or urban furniture. Nevertheless, the SCC must meet minimum requirements of flowability and strength (Rashid et al., 2020). In this situation, notable differences arise depending on the concreting moment under consideration:

- For fast concreting (scenario H-10, Fig. 12a), the optimal choice is undoubtedly to use limestone fines and 100% coarse RCA, regardless of the type of binder and fine RCA content. In addition, the use of RCA powder might be appropriate when combined with CEM I. The addition of limestone filler cannot be recommended, due to its high cost, large carbon footprint, and reduction of short-term flowability.
- For long-distance concreting (scenario H-11, Fig. 12b), ordinary Portland cement should be used, because it produces economical SCC with better conservation of flowability. Whether it is used in combination with limestone fines or RCA powder is practically irrelevant. The fine RCA content should be limited to 50% to ensure adequate placement.

5.6. *Multi-purpose SCC*

The “multi-purpose” scenario could be interesting for a company that intends to manufacture a versatile SCC. The manufactured SCC could never be the ideal choice for specific applications, but its composition will be close to the optimal one. It could be used in a wide range of

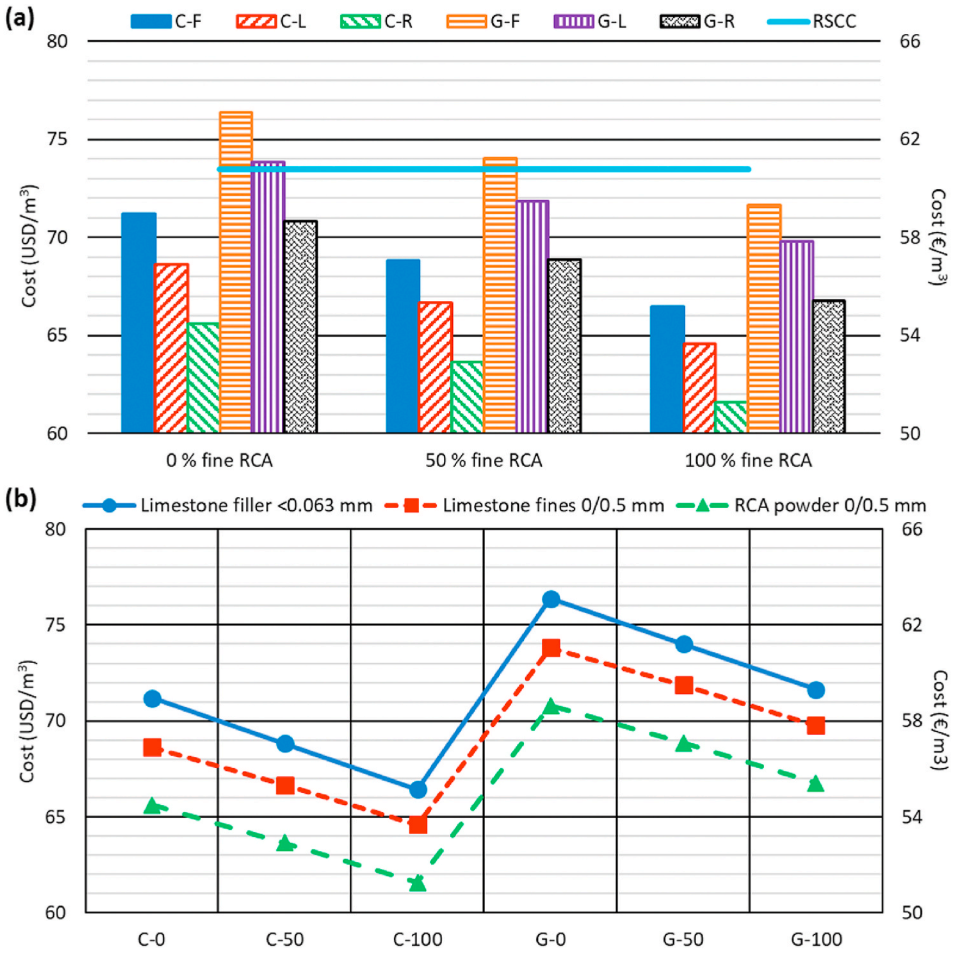

Fig. 7. Cost of the mixes: (a) effect of fine RCA content; (b) effect of aggregate powder.

Table 7
Calculation of the cost of the RSCC mix (notation according to Equation (3)).

Material	Unitary cost ($COST_{u,i}$, USD/kg)	Component amount (ca_i, kg/m^3)	Cost of the component in 1 m^3 of RSCC mix ($COST_{u,i} \times ca_i$ USD/m^3)	Total carbon footprint of mix RSCC ($COST_{SCC}$, USD/m^3)
CEM I	0.1320	300	39.60	73.50
Plasticizer	1.4612	5.50	8.04	
Viscosity regulator	1.4612	2.30	3.36	
Water	0.0007	165	0.12	
Coarse aggregate (siliceous gravel 4/12.5 mm)	0.0079	575	4.54	
Fine aggregate (siliceous sand 0/4 mm)	0.0093	1100	10.23	
Aggregate powder (limestone filler <0.063 mm)	0.0461	165	7.61	

situations, bringing beneficial economic profit for the producer (Hafez et al., 2021b).

Notwithstanding the above, the concreting moment conditions the choice of the composition, except regarding the use of coarse RCA, which is always recommendable:

- If high short-term flowability is sought (scenario H-12, Fig. 13a), GGBS and limestone fines should be used, while the fine RCA content is to some extent irrelevant. In the absence of the joint use of GGBS and limestone fines, the use of GGBS and limestone filler, or CEM I with limestone fines will be equally suitable.
- Limestone fines should be used, to produce SCC with high long-term flowability (scenario H-13, Fig. 13b) and the content of fine RCA should be limited to 50%. The type of binder is irrelevant. If limestone fines are not available, any combination of binder (CEM I or GGBS) and aggregate powder (limestone filler or RCA powder) could be used, provided that the fine RCA content is limited to 50%. Conventional SCC is the third best option.

This “multi-purpose” choice could even be more generalized, designing a concrete suitable for all applications regardless of the concreting distance (scenario H-14, Fig. 13c). In this case, the recommendations given for scenario H-13 (multi-purpose with adequate long-term flowability) should be followed. The flowability of SCC is detrimentally affected by the addition of industrial by-products, an effect that becomes more noticeable as the time between the manufacture (mixing) of concrete and its placement lengthens (Santos et al., 2019).

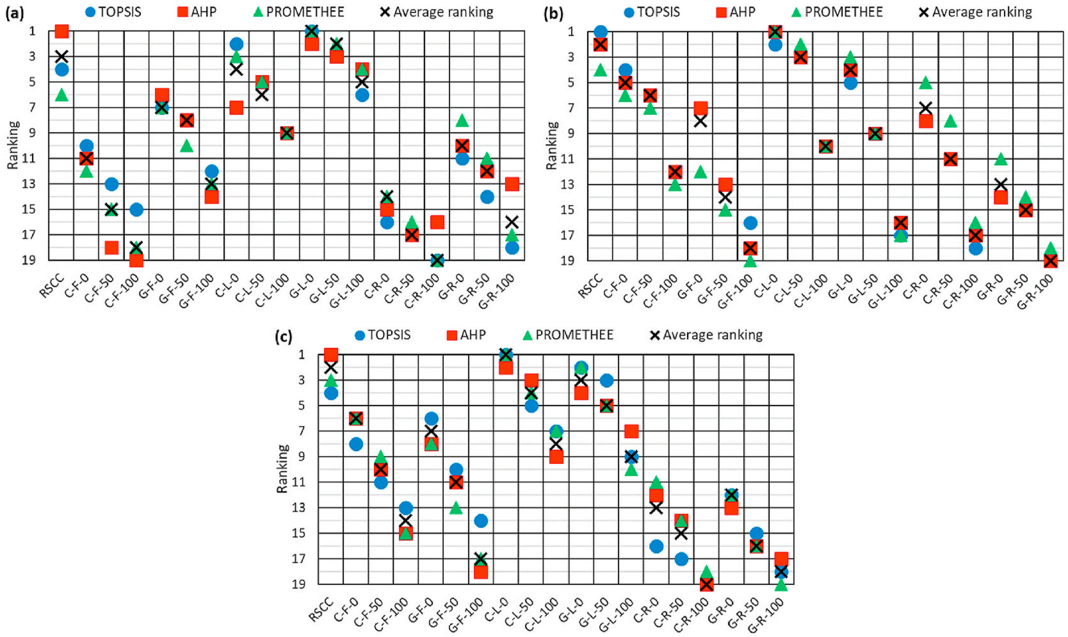

Fig. 8. Selection of SCC with best-possible flowability: (a) scenario H-1; (b) scenario H-2; (c) scenario H-3.

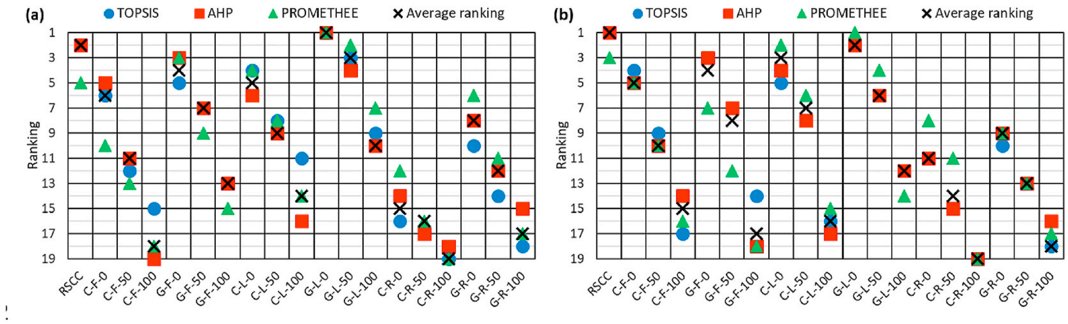

Fig. 9. Selection of SCC with best-possible hardened behavior: (a) scenario H-4; (b) scenario H-5.

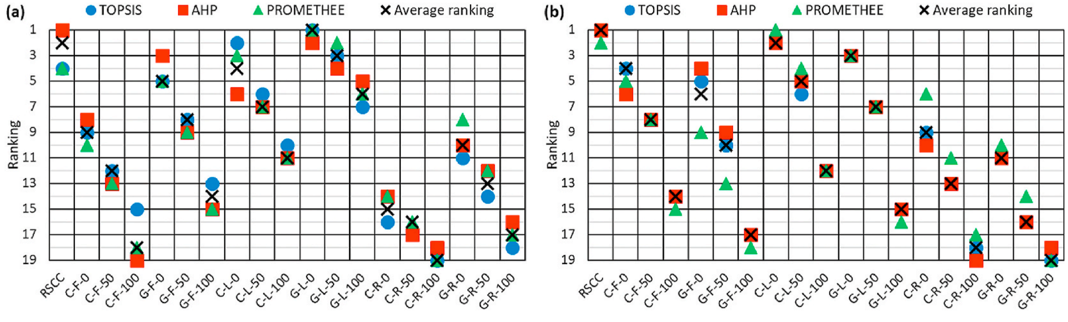

Fig. 10. Selection of SCC with a best-possible balance between fresh and hardened behavior: (a) scenario H-6; (b) scenario H-7.

5.7. Robustness of the analysis

The implications of modifying the weights up to ±20% were evaluated for each scenario, except for scenarios H-12, H-13 and H-14 (multi-purpose SCC), in which the weights of all criteria had to be the same. The aim was to check the robustness of the MCDM analysis and evaluate the possible changes in the average ranking calculated from the results of the three MCDM algorithms under consideration. Changes in the average ranking were all of little relevance, as shown in the robustness-analysis cases included in the supplementary data. In fact, the fourth best mixes for each scenario, shown in Table 8, remained unchanged, so this robustness analysis can be said to confirm the validity and the reliability of the results.

6. Conclusions

The feasibility of using Self-Compacting Concrete (SCC) with large amounts of industrial by-products has been studied in this paper through a Multi-Criteria Decision-Making (MCDM) analysis. This type of analysis, novel in the available literature, has been used to determine

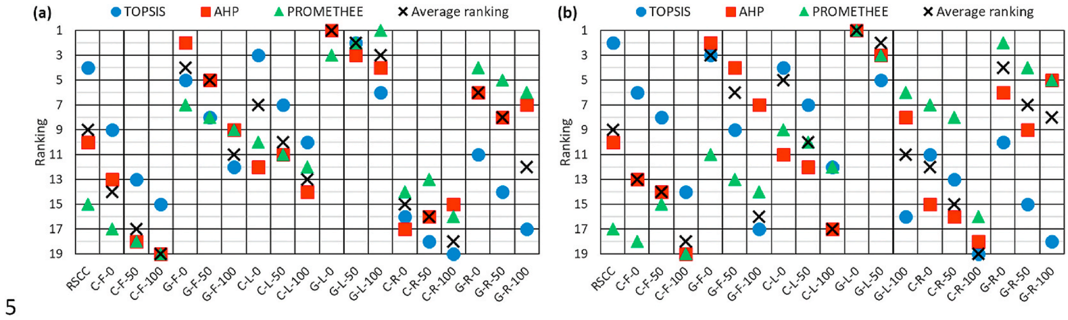

Fig. 11. Selection of SCC with lowest-possible carbon footprint: (a) scenario H-8; (b) scenario H-9.

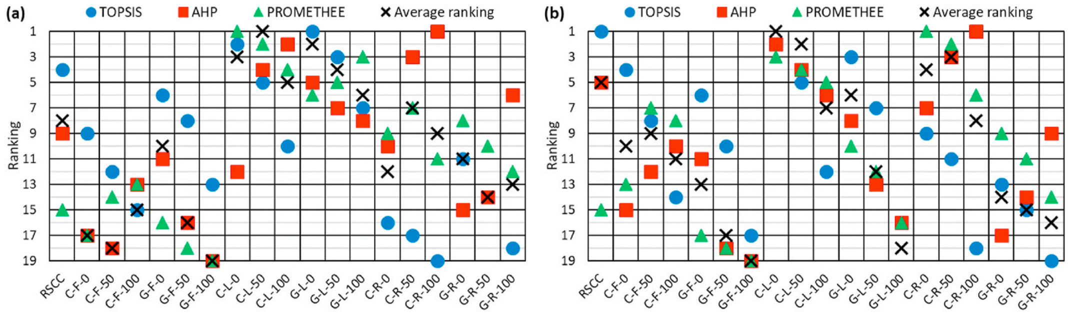

Fig. 12. Selection of SCC with lowest-possible cost: (a) scenario H-10; (b) scenario H-11.

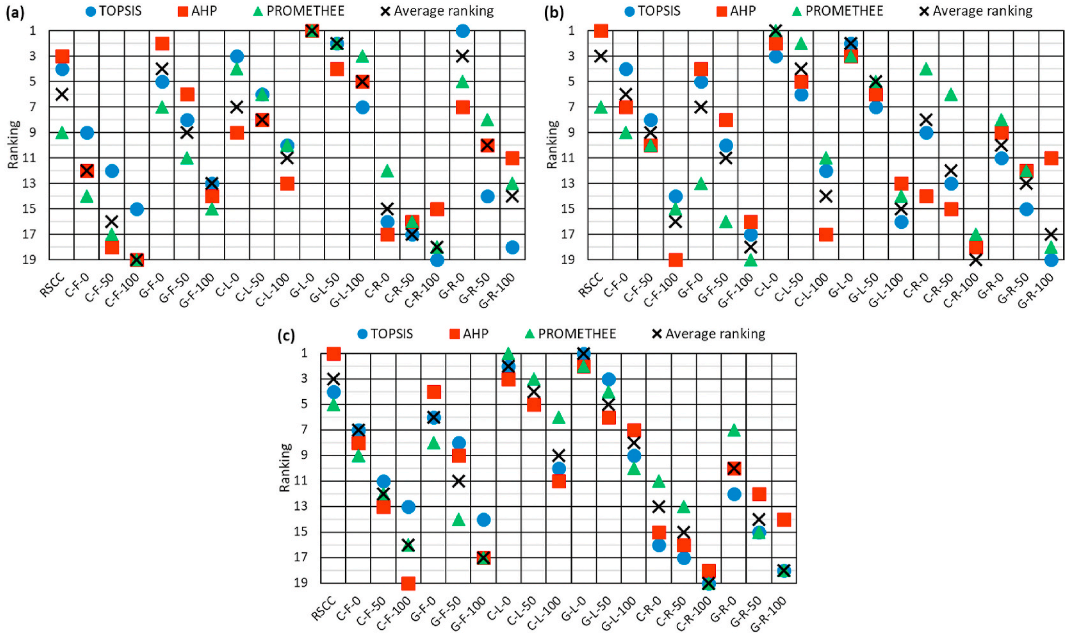

Fig. 13. Multi-purpose selection of SCC: (a) scenario H-12; (b) scenario H-13; (c) scenario H-14.

whether the use of SCC with industrial by-products is worthwhile, considering the different dimensions that define SCC: flowability, hardened behavior, sustainability, and cost.

In all, 19 SCC mixes were first produced to perform this analysis. One of them reproduced the commercially available SCC (ordinary Portland cement, 100% NA, and limestone filler). The other mixes incorporated different by-products or more sustainable raw materials than the conventional ones: 100% coarse RCA; 0%, 50%, or 100% fine RCA; 45% Ground Granulated Blast-furnace Slag (GGBS); and limestone fines 0/0.5 mm or RCA powder 0/0.5 mm. All the mixes were designed to obtain the best possible fresh and hardened performance. They were all tested for decreased flowability at 15 and at 60 min, 28-day compressive strength, 28-day modulus of elasticity, carbon footprint, and cost. Carbon footprint and cost were calculated on the basis of SCC composition alone and aspects that may vary from one case study to another, such as the transportation distances, were overlooked. The test results showed that:

- Increasing GGBS content and reducing the amount of coarse aggregate compensated for the lower dragging capacity and strength of this binder. Thus, slag-based mixes showed higher short-term slump flow, strength and elastic stiffness than mixes made with

Table 8
Best mixes for each scenario.

Scenario	Best mix	Second best mix	Third best mix	Fourth best mix
H-1	G-L-0	G-L-50	RSCC	C-L-0
H-2	C-L-0	RSCC	C-L-50	G-L-0
H-3	C-L-0	RSCC	G-L-0	C-L-50
H-4	G-L-0	RSCC	G-L-50	G-F-0
H-5	RSCC	G-L-0	C-L-0	G-F-0
H-6	G-L-0	RSCC	G-L-50	C-L-0
H-7	RSCC	C-L-0	G-L-0	C–F-0
H-8	G-L-0	G-L-50	G-L-100	G-F-0
H-9	G-L-0	G-L-50	G-F-0	G-R-0
H-10	C-L-50	G-L-0	C-L-0	G-L-50
H-11	C-L-0	C-L-50	C-R-50	C-R-0
H-12	G-L-0	G-L-50	G-R-0	G-F-0
H-13	C-L-0	G-L-0	RSCC	C-L-50
H-14	G-L-0	C-L-0	RSCC	C-L-50

conventional cement clinker. They also had a lower carbon footprint, but the increased binder content led to higher costs.

- Limestone fines resulted in cheaper, stronger and more flowable mixes than limestone filler, but increased the amount of aggregate powder needed, which led to a minimal decrease of the carbon footprint. RCA powder only showed advantages in terms of carbon footprint and cost.
- Adding 100% coarse RCA to SCC produced suitable fresh and hardened properties. Increasing the fine RCA content slightly reduced the carbon footprint and cost. However, it also led to a notable linear decrease of the fresh and hardened properties of SCC with RCA content. Overall, its interaction with GGBS was worse than with ordinary Portland cement.

The MCDM analysis was comprehensive. In all, 14 scenarios for analysis, depending on the aspect of the SCC to be optimized, 3 algorithms (TOPSIS, AHP, and PROMETHEE), whose implementation process is described in the supplementary data, and 4-or-5 decision-making criteria (short-term and/or long-term flowability, hardened behavior, carbon footprint, and cost) were considered. The optimal compositions of SCC in different situations (Table 8) were defined from this analysis:

- For fast concreting, GGBS and limestone fines should be used. In principle, the fine RCA content is irrelevant, but from a conservative approach, its content should be limited to 50%.
- If SCC placement had to be performed at a great distance from the manufacturing plant, SSC with limestone fines might be the best option. If in this situation the main requirement is high flowability, ordinary Portland cement should be used. However, if maximum strength is required, GGBS would be a better choice. It would be indispensable not to exceed a content of fine RCA of 50% in both cases. The MCDM analysis of a versatile SCC led to similar recommendations.
- Minimizing the carbon footprint of SCC in no way justifies excessive use of industrial by-products. The best option is to use GGBS as binder and limestone fines as aggregate powder.
- Obtaining an SCC of optimal cost is linked to the addition of limestone fines. The type of binder would be irrelevant, and the fine RCA should be limited to 50%, especially if the SCC is to be transported over a long distance.
- In general, the full replacement of coarse NA with RCA would always imply improving the multi-dimensional behavior (flowability decrease, strength and stiffness, sustainability and cost) of SCC.

This MCDM analysis has demonstrated the convenience of adding industrial by-products to SCC. However, conventional SCC was ranked between first and sixth in almost all scenarios. Therefore, it is fundamental to adapt the SCC composition to the particular properties of each by-product in use, to moderate any negative effects, even though that might mean renouncing some of the sustainability improvements for SCC that might otherwise be achieved.

CRediT authorship contribution statement

Víctor Revilla-Cuesta: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Software, Writing – original draft. **Marta Skaf:** Conceptualization, Investigation, Formal analysis, Project administration, Writing – review & editing. **Ana B. Espinosa:** Investigation, Software, Formal analysis, Visualization, Validation. **Vanesa Ortega-López:** Conceptualization, Methodology, Project administration, Funding acquisition, Resources, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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