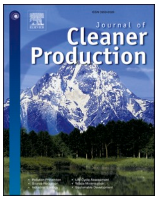
Journal of Cleaner Production 373 (2022) 133873

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Using recycled aggregate concrete at a precast-concrete plant: A multi-criteria company-oriented feasibility study

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ARTICLE INFO

Handling editor, Prof. Jiri Jaromir Klemeš

Keywords:
Recycled aggregate
Self-compacting concrete
Industrial-scale mixes
Precast-concrete company
Multi-criteria analysis
Company-oriented approach

ABSTRACT

Numerous test results at laboratory scale confirm the utility of Recycled Aggregate (RA) for the development of concrete that demonstrates durability and adequate in-fresh and mechanical behavior. However, feasibility evaluations of the use of RA in real industrial applications are necessary, before any large-scale industrial application of these products can begin. In this research, the feasibility of producing precast-concrete components containing large amounts of coarse RA at a precast-concrete plant is analyzed. Two Self-Compacting Concretes (SCC) were produced incorporating 0% and 100% coarse RA, respectively, at both laboratory scale ($0.08\ m^3$) and industrial scale ($2\ m^3$). Work took place at the industrial-scale facilities of a precast-concrete company that was collaborating in this study. Flowability and mechanical behavior were maintained as concrete production volumes increased, and concrete strength even increased after adding coarse RA, due to a careful mix design. However, the durability performance worsened by around 20% when produced at industrial scale, being this worsening higher whether coarse RA was used. A Multi-Criteria Decision-Making (MCDM) analysis, in which the criteria of the precast-concrete company defined the relative importance of each concrete property, showed the feasibility of manufacturing precast-SCC components containing coarse RA for interior usage, whose fundamental requirement is adequate mechanical strength. The results of the MCDM analysis also underlined the lower cost of coarse RA, making its use in SCC components cast with large concrete volumes advisable. Overall, the addition of coarse RA in the precast-concrete industry is recommended in the interests of a greener construction sector.

1. Introduction

The construction sector is one of various industrial sectors with some of the highest environmental impacts (Joensuu et al., 2020). On the one hand, large-scale civil works alter the landscape, orography, water flows, flora, and fauna, *etc*. The environmental impact of a civil work project must therefore be carefully studied, proposing all necessary measures to mitigate environmental harm (Xing et al., 2018). On the other hand, the sustainability levels of traditional construction materials are very low. Concrete, mainly composed of aggregate and cement, is a clear example. On the one hand, the extraction of Natural Aggregate (NA) from quarries and gravel pits causes serious orographic and hydro-geological and therefore environmental damage (Skaf et al., 2017). On the other hand, 0.9 tons of CO_2 per ton of manufactured cement are emitted (Habert et al., 2020). The trend towards the use of wastes and by-products in replacement of conventional raw materials are largely due to the environmental problems that have been outlined above (Faleschini et al., 2021; Orsini and Marrone, 2019). The feasibility of including sustainable aggregates within concrete, such as slag or Recycled Aggregate (RA), and alternative binders, such as fly ash or ground granulated blast furnace slag, has therefore been the subject of various proposals, many of which are currently under study (Anastasiades et al., 2021; Bravo et al., 2020).

RA is a by-product obtained by crushing and sieving demolished, rejected or out-of-use concrete elements (Silva et al., 2019). If properly conducted, a granular material is produced with a suitable aggregate gradation for use in concrete. RA is composed of NA, limestone or siliceous, and adhered fragments of mortar from the cementitious matrix of crushed concrete (Sainz-Aja et al., 2022), although particles exclusively

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https://doi.org/10.1016/j.jclepro.2022.133873
Received 18 May 2022; Received in revised form 27 July 2022; Accepted 25 August 2022

Acronyms

multi-criteria decision-making	(MCDM)
natural aggregate	(NA)
recycled aggregate	(RA)
self-compacting concrete	(SCC)

composed of mortar can be found in the finest fractions (Evangelista and De Brito, 2014). Its higher water absorption than NA, as well as the very irregular geometry of its particles, means that its use in concrete reduces workability (Silva et al., 2018), which leads to the need to increase the water content of the mix for constant workability (Amara et al., 2021). The presence of mortar fragments reduces aggregate adhesion within the cementitious matrix and increases porosity levels of concrete (Revilla-Cuesta et al., 2021a). Their presence therefore worsens all the mechanical and the durability properties of the concrete (Li et al., 2022; Mahmood et al., 2022) and reduces the peak strain of concrete under compressive loading (Tang et al., 2022b), besides the fact that concrete made with RA exhibits a more brittle behavior (Xiao et al., 2022). Nevertheless, a lower water content partially compensates those effects (Fiol et al., 2021). The design of RA concrete therefore involves a very precise adjustment of the amount of water, seeking the optimum balance between workability, strength, and durability (Villagrán-Zaccardi et al., 2022). With this concrete-design strategy, RA can be successfully employed in concrete structures (Xiao, 2018) and pavements (Tang et al., 2022a). It may be added that coarse RA has demonstrated better behavior in concrete, yielding higher-quality concretes than fine RA (Etxeberria et al., 2022).

The use of RA has even been extended to special concretes, such as Self-Compacting Concrete (SCC) (Revilla-Cuesta et al., 2020). Characterized by its extremely-high workability, this type of concrete performs in a very similar way to a liquid, filling the formwork with no need for vibration (Sevim et al., 2021), demonstrating optimal in-fresh behavior, which has many advantages. First of all, concreting can almost take place anywhere using any method, even pumping upwards to high levels. In addition, heavily reinforced components are easily concreted using SCC (Santamaría et al., 2017). Secondly, concreting time is reduced, as no time is needed for vibration, which yields a higher output and greater industrial benefit (Faraj et al., 2020). Finally, it saves money and energy, as no vibration is required during concreting, which in turn attaches a lower carbon footprint to the concrete (Iures et al., 2010). The use of RA within SCC has the same effects as within vibrated concrete, with the coarse fraction of this alternative aggregate showing the best performance (Santos et al., 2019). However, the mix design assumes greater importance as the flowability of SCC is very sensitive to variations in water content, the adjustment of which is a key criterion for the good behavior of an SCC containing RA (Bir Singh and Singh, 2021).

Multi-Criteria Decision-Making (MCDM) analysis is an objective decision-making method to select the optimal option among a finite set of alternatives considering the aspects that the decision-maker finds most important and the characteristics of each alternative. Often considered a sub-discipline of programming, successful implementations of MCDM require the use of sophisticated algorithms (Schramm et al., 2020). It is widely used in the energy sector, in political strategy, and in industrial processes (Saxena et al., 2021). In the concrete sector, MCDM is used to select the most suitable mix by weighing up both performance factors and carbon footprint or sustainability factors, as well as costings (Hafez et al., 2020). To that end, MCDM approaches have even been specifically developed for concrete produced with sustainable raw materials (Hafez et al., 2021; Kurda et al., 2019), such as RA. In fact, MCDM analyses have shown that proper concrete dosages, together with the environmental and the economic advantages of RA, lower carbon footprint and costs than NA, make the use of RA in both vibrated concrete and SCC preferable to NA (Rashid et al., 2020; Revilla-Cuesta et al., 2021b). However, these analyses have so far been limited to laboratory-scale mixes, *i.e.*, small volumes of up to 0.1 m^3.

The precast-concrete industry is gaining ground. It has much simpler, faster and more cost-effective construction techniques than concreting *in situ*, which are increasingly recognized within the construction sector where precast components are set in place to assemble buildings or bridges, for example (Jiménez, 2020). For this purpose, beams, columns, panels, and other necessary concrete pieces are manufactured at an industrial plant and then transported to the construction site where they are placed (Fang et al., 2021). The manufacturing of these concrete components at the plant is carried out with SCC to increase output and to reduce costs (Singh and Venkatanarayanan, 2020), as well as to guarantee optimum concreting, due to the large amounts of both passive and active reinforcements that are used (Anaya et al., 2020). Moreover, sourcing RA for this industry is in principal quite simple, as this alternative aggregate can be obtained from the crushing of surplus SCC or rejected concrete components, due to excess production or geometric defects at the plant (Fiol et al., 2018). Clearly, it is therefore very relevant to study the feasibility of using SCC containing coarse RA in the precast-concrete industry through MCDM approaches, in order to promote the use of this sustainable material, thus moving towards a greener construction sector.

1.1. Research scope

The research described in this paper was conducted in collaboration with a precast-concrete company that manufactures beams, columns, panels, slabs, *etc*. for building applications. This company uses SCC with a minimum compressive strength of 45 MPa to manufacture its concrete components and has appropriate machinery to crush and to sieve reject precast components for producing coarse RA. Its agreement to participation in this study was therefore a good starting point for the development of this research.

Two mixes were designed with 0% and 100% coarse RA, respectively, which fulfilled the flowability and strength requirements of the company. Both mixes were produced at the precast-concrete plant at laboratory scale (volume of 0.08 m^3) and at industrial scale (volume of 2 m^3). Accordingly, this research work pursued two fundamental objectives:

- The first objective was to verify whether the durability and the in-fresh and mechanical behavior found in design volumes of concrete, usually produced in the laboratory and reported in the scientific literature, were also applicable to large volumes of coarse-RA concrete. Furthermore, the question of whether this kind of concrete mix fulfilled the performance and the cost requirements for the manufacture of real components at a precast-concrete plant was also answered.
- The second objective was to conduct a multi-criteria feasibility evaluation of using SCC containing coarse RA to produce concrete elements at a precast-concrete plant. The concrete properties under study, and the relevance of each one when choosing the right SCC for a precast-concrete application were defined in collaboration with the collaborating company. Based on this aspect, the feasibility of using an SCC containing large amounts of coarse RA in different precast-concrete components was evaluated from an MCDM approach.

The aim of the present study was therefore to evaluate whether the use of SCC with large amounts of coarse RA can be successfully extended to the industrial context and, specifically, to the precast-concrete industry.

2. Materials and methods

2.1. Raw materials

In this study, all the mixes were produced with the raw materials that are normally used to manufacture the commercial products of the collaborating precast-concrete manufacturer. The raw materials that are detailed below were supplied as part of its agreement to participate in this research.

2.1.1. Cement, water, and admixtures

All the SCC mixes were produced with CEM I 52.5 R cement as per EN 197-1 (2011), which has a density of 3.11 Mg/m^3 and a specific Blaine surface of 370 m^2/kg. This type of cement provides high initial strengths to SCC, which speeds up the manufacturing process of concrete components at the precast-concrete plant.

The water was taken from the local water supply at Aranda de Duero, a town in the province of Burgos, Spain. The chemical analyses regularly performed by the precast-concrete company showed no presence of any compounds with detrimental effects on the behavior of SCC.

Two superplasticizing admixtures supplied by SIKA® were simultaneously added to the SCC. Their purpose was to provide self-compactability to the mixes, while reducing the water demand of SCC, thus allowing an adequate water-to-cement ratio to reach the required compressive strength (45 MPa). Both admixtures were added in proportions of 0.5–1.5% by weight of cement.

2.1.2. Natural aggregate (NA)

Two different types of NA were used to dose the SCC:

- Limestone filler <0.063 mm, with a $CaCO_3$ content of 96.5% and a density of 2.75 Mg/m^3, regularly used at the precast-concrete plant to provide the necessary content of aggregate fines to SCC to improve flowability and, at the same time, to increase mechanical strength (Fiol et al., 2018).
- Rounded siliceous aggregate, extracted from a gravel pit managed by the precast-concrete company. Two fractions were used, 2/12.5 mm and 0/2 mm, both commonly used at the precast-concrete plant. The values of their main physical properties are shown in Table 1, while their continuous gradations are depicted in Fig. 1.

2.1.3. Recycled aggregate (RA)

The RA used in this study was obtained by crushing rejected components, mainly beams and columns with geometrical defects, manufactured at the precast-concrete company. The strength of the concrete components was at least 45 MPa, so a good-quality RA was obtained (Fiol et al., 2021). The production process of coarse RA included the three steps listed below, which should be complemented with others such as magnetic separation or water washing, procedures of proven usefulness in the literature (Carriço et al., 2021; Sousa and Bogas, 2021). These processes were not applied in this study due to the lack of the necessary machinery for their implementation.

- First, the steel reinforcements were removed by hydraulic clamping, obtaining concrete fragments up to 300 mm in size.
- Subsequently, those concrete fragments were subjected to a primary crushing process by means of a jaw crusher, yielding a preliminary RA with a maximum aggregate size of 80 mm.
- Finally, a secondary crushing process employing an impact crusher produced an RA of 0/25 mm in size, suitable for the manufacture of concrete.

In this study, only the coarse fraction of RA of an adequate size for SCC was used, so the RA 0/25 mm was sieved and the larger sized fraction (12.5/25 mm) was re-crushed and sieved again to obtain coarse RA 4/12.5 mm. Table 1 shows the most relevant physical properties of this RA fraction where its lower density, abrasion resistance, and its higher water absorption may be seen compared to those same values for NA. The initial moisture of the coarse RA used in the laboratory-scale mixes was 0.29%, which was measured by oven drying (EN 1097-5, 2009). The moisture of the coarse RA for the industrial-scale mixes, measured by a moisture probe inside the aggregate storage silos of the precast-concrete plant, ranged from 0.25% to 0.36% depending on the moment of the day. The continuous gradation of coarse RA is shown in Fig. 1.

It is also worth noting that the coarse fractions of NA and RA used to manufacture the SCC were of different sizes, which was due to the manufacturing conditions at the plant where siliceous aggregate 2/12.5 mm is usually employed, and to the desire to limit this study to the coarse RA fraction (RA 4/12.5 mm), leaving the fine fraction 0/4 mm for future research. Thus, the replacement of NA 2/12.5 mm by RA 4/12.5 mm implied the simultaneous adjustment of the content of NA 0/2 mm, as detailed below in the mix-design section.

Table 1
Physical properties of the aggregates.

Property	Standard	Siliceous aggregate 0/2 mm	Siliceous aggregate 2/12.5 mm	Recycled aggregate 4/12.5 mm
Saturated-surface-dry density (Mg/m^3)	EN 1097-6 (2014)	2.64	2.63	2.41
24-h water absorption (% wt.)	EN 1097-6 (2014)	0.26	1.16	4.15
Los Angeles loss (% wt.)	EN 1097-2 (2010)	–	31	37

2.2. Mix design

Two mixes were proposed to analyze the feasibility of using coarse RA at the precast-concrete plant: a reference mix with 100% coarse NA 2/12.5 mm (mix C) and another with 100% coarse RA 4/12.5 mm (mix CR). A replacement ratio for the coarse RA of 100% was considered, to test the feasibility of using large amounts of coarse RA in the plant, thereby maximizing the sustainability of SCC. The mix compositions are shown in Table 2.

First, the composition of mix C was defined, so as to obtain acceptable self-compactability (at least a slump-flow class SF1 and a slump-flow-viscosity class VS2 as per EN 206 (2013)) and strength (minimum of 45 MPa) values required for its use in the concrete components manufactured at the precast-concrete plant. For this purpose, the usual formulation of the SCC used in the plant was considered. The joint aggregate gradation of the mix was adjusted to the Fuller curve (Fig. 2).

Subsequently, the mix CR was designed. The following aspects were considered:

- The replacement of coarse NA with coarse RA was completed by volume correction, due to the different density of the two aggregates (Table 1). Batches were easily weighed with the concrete weighbridge system at the plant.
- As indicated in the previous section, the NA 2/12.5 mm was replaced by coarse RA 4/12.5 mm. Therefore, the content of NA 0/2 mm was increased, in order not to modify the aggregate content of size 0/4 mm. In this way, the joint gradation of both mixes was similar (Fig. 2).
- The water content of the SCC was held constant when the coarse RA was added, despite its significantly higher water absorption than NA (Table 1), thereby compensating for the habitual strength decrease after adding coarse RA, thus achieving adequate strengths (Fiol et al., 2018). The admixture content was then increased from 0.6% to 1.0%

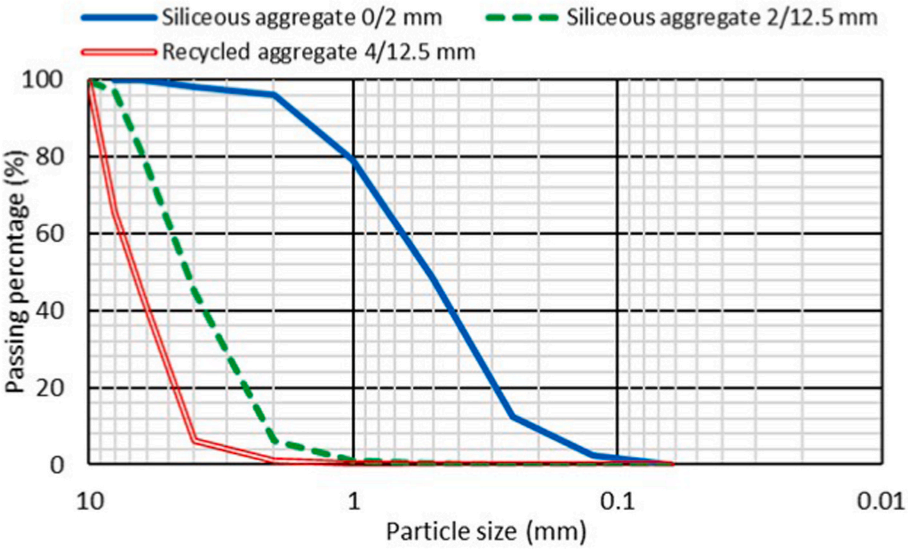

Fig. 1. Gradation of the aggregates.

Table 2
Mix compositions (kg/m^3).

Component	Laboratory mixes		Industrial mixes	
	C	CR	C	CR
Cement CEM I 52.5 R	320	320	320	320
Water	112	112	112	112
Admixture 1	0.50	0.85	0.55	0.90
Admixture 2	1.30	2.00	1.32	2.20
Limestone filler	280	280	280	280
Siliceous aggregate 0/2 mm	650	720	650	720
Siliceous aggregate 2/12.5 mm	1150	0	1150	0
Coarse RA 4/12.5 mm	0	1040	0	1040

by weight of cement, in compensation for the flowability decrease, due to the high water absorption levels of coarse RA and its irregular shape.

Mixes C and CR were produced both at laboratory scale, producing a volume of 0.08 m^3 of SCC in a portable concrete mixer, and at industrial scale at the precast-concrete plant, producing a volume of 2 m^3 in an industrial concrete mixer. The composition in both cases was identical, except for the amount of admixture, which was slightly increased in the case of the industrial mixes to ensure the required flowability (Table 2).

2.3. *Mix production*

The fundamental objective during the preparation of the mixes was to ensure that all the mixes were fully comparable to each other. To that end, regardless of the scale of the mix (laboratory or industrial), all the mixes were prepared in vertical-axis concrete mixers, as shown in Fig. 3, the only difference between them being their size. The facilities at the precast-concrete company were used for production at an industrial scale. In all cases, the mixing was carried out following the production procedure of the precast-concrete plant, as per ASTM C192 (2018):

- First, the concrete mixer was slightly dampened and then the coarse aggregate, fine aggregate and half of the water were added. The SCC was mixed for 3 min.
- The cement, the filler, and the remaining water were then added, followed by mixing for 5 min, after which the fresh-state tests were performed.

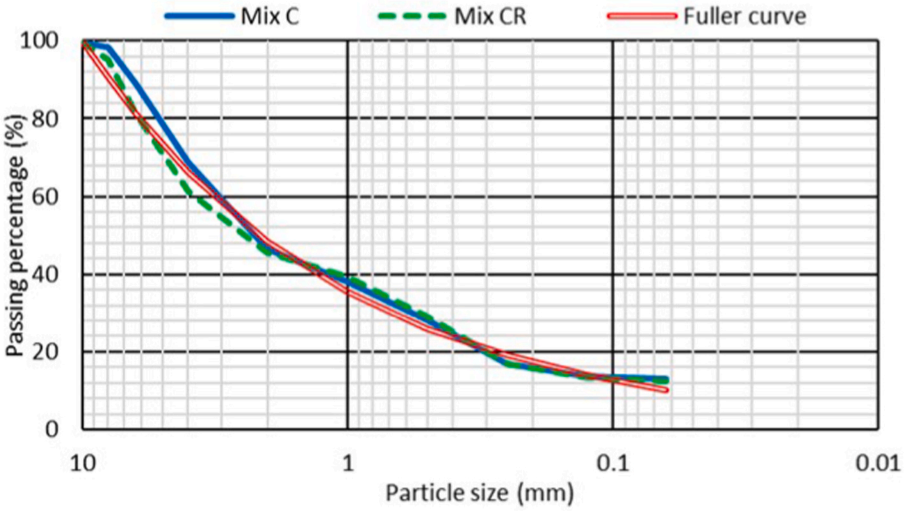

Fig. 2. Joint gradation of the mixes.

Fig. 3. Concrete mixers for mixes at laboratory scale (left) and at industrial scale (right).

2.4. *Characterization of the mixes*

The first objective of this study was to verify that the behavior of the SCC in the laboratory-scale mixes was similar to its behavior in the industrial-scale mixtures, as well as to check that the SCC met the necessary performance and cost requirements for industrial use. Its characterization met this first objective and, by doing so, the inputs for the MCDM-feasibility analysis were obtained.

2.4.1. *Experimental tests*

The tests performed on the mixes were defined in collaboration with the precast-concrete company. The standard tests of the company were therefore conducted for characterizing mix behavior and for validating the use of each mix for the manufacture of its concrete components.

The first test performed was the slump-flow test according to EN 12350-8 (2020) at the end of the mixing process, so that the filling ability and viscosity of the SCC could be evaluated. The specimens required for the mechanical and durability tests were then prepared, which are detailed in Table 3 together with the test standards, the test ages, and the type of specimens used. Each property was determined as the arithmetic mean of the results of 3 specimens. All specimens were stored in a humid chamber (95 ± 5% humidity and 20 ± 2 °C temperature) until the test age, except for the shrinkage specimens, which were stored in a dry chamber (humidity of 45 ± 5% and temperature of 20 ± 2 °C).

Table 3
Hardened-state tests.

Test type	Test	Standard	Test age (days)	Specimen type
Mechanical tests	Compressive strength	EN 12390-3 (2009)	1, 7, 28, 180	15 × 30-cm cylindrical specimens
	Splitting tensile strength	EN 12390-6 (2010)	28	15 × 30-cm cylindrical specimens
Durability tests	Full-immersion water absorption	ASTM C 642 (2006)	28	10 × 10 × 10-cm cubic specimens
	Porosity			
	Water penetration under pressure	EN 12390-8 (2020)	28	15 × 30-cm cylindrical specimens
	Shrinkage	UNE 83318 (1994)	1–360	7.5 × 7.5 × 27.5-cm prismatic specimens

2.4.2. *Economic analysis*

The economic analysis consisted of determining the unit price of both SCC mixes. For this purpose, the simple unit prices that the precast-concrete company usually pays for the acquisition of the cement, water, limestone filler and admixtures; the production of NA, which included the costs of workforce and energy consumption, as it was obtained from gravel pit managed by the precast-concrete company; and the production of coarse RA were considered. Furthermore, the energy consumption by the concrete mixer and the salary costs for the workforce during SCC production were also taken into consideration.

The simple unit price of the coarse RA 4/12.5 mm was estimated on the basis of the electrical consumption and workforce due to machinery use; machinery depreciation costs; income from the sale of recycled scrap steel reinforcements disentangled from the concrete components; and partial savings of dumping fees otherwise applicable to the reject concrete components. The simple unit price of coarse RA, shown in Table 4, was calculated at a final value of 11.75 €/t (13.70 USD/t). This price was slightly higher than the cost of coarse RA from a waste-management company (Rashid et al., 2020), although it may in the long-term imply a saving for the precast-concrete company after paying off the purchase costs of the machinery.

Once all the simple unit prices had been fixed (Table 5), multiplying each item by the quantity needed to produce one cubic meter of SCC yielded the unit price (€/m^3 or USD/m^3) of the SCC.

2.5. *Multi-criteria decision-making framework*

The characterization of the mixes described in the previous section provided the inputs for the MCDM analysis of SCC containing coarse RA in the production of common precast-concrete components. The key aspects of this analysis are discussed in this section.

2.5.1. *Decision criteria*

According to the precast-concrete company, five criteria were defined, based on the characteristics of the mixes, so that a MCDM analysis could be used to select the most suitable mix for each type of concrete component to be manufactured (scenario). These criteria were:

- Variation of the mechanical behavior of the mixture due to the scale effect. The properties of the mix produced at an industrial scale were

Table 4
Calculation of the simple unit price of coarse RA.

Unit	Designation	Price (€/unit) [a]	Price (USD/unit) [a]	Amount (unit)	Cost (€)	Cost (USD)
h	Hydraulic clamp	45.00	51.17	0.65 [b]	29.25	33.26
t	Jaw crusher	0.50	0.57	1 [c]	0.50	0.57
t	Impact crusher	2.00	2.27	1 [c]	2.00	2.27
t	Sieving machine	4.00	4.55	1 [c]	4.00	4.55
t	Landfill transport (50 km in distance, tax included)	10.00	11.37	0.3 [d]	3.00 [d]	3.42 [d]
				1 [e]	−10.00 [e]	−11.37 [e]
kg	Recyclable steel rebar	0.2125	0.2375	80 [f]	−17.00 [f]	−19.00 [f]
t	**Simple unit price of coarse recycled aggregate 4/12.5 mm (€/t or USD/t)**				**11.75**	**13.70**

[a] Prices set by the precast-concrete company already considering that each ton of crushed concrete yields 0.7 tons of coarse RA 4/12.5 mm.

[b] The hydraulic crushing clamp crushes 1 ton of concrete in 0.65 h (source: machine operators' estimation at the precast-concrete plant).

[c] Crushing and sieving of 1 ton of RA as per section 2.1.3.

[d] According to the trials and considering re-crushing of RA 12.5/25 mm, 70% of the RA in weight could be reduced to 4/12.5 mm in size, making it appropriate for SCC production. It will therefore be necessary to transport only the fine fraction of RA (30% in weight of all RA) to the landfill site, which in this study is not considered for use in concrete manufacturing.

[e] No transport of reject concrete components to landfill sites is considered, which represents a (negative opportunity cost) saving for the precast-concrete company compared to the situation of not using coarse RA.

[f] It is estimated that 80 kg of recyclable steel reinforcements can be extracted from each ton of crushed concrete, which can then be sold on to recycling plants, representing a (negative opportunity cost) saving for the precast-concrete company.

Table 5
Simple unit prices.

Unit	Designation	Price (€/unit)	Price (USD/unit)
t	Cement CEM I 52.5 R	100.82	114.29
t	Siliceous aggregate 0/2 mm	13.90	15.76
t	Siliceous aggregate 2/12.5 mm	18.00	20.40
t	Recycled aggregate 4/12.5 mm	11.75	13.70
t	Limestone filler	29.00	32.87
kg	Admixture 1	2.00	2.27
kg	Admixture 2	2.00	2.27
m^3	Water	0.36	0.41
h	Ordinary laborer	12.95	14.68
h	Concrete mixer 3 m^3	3.89	4.41

therefore compared with the results at laboratory scale, yielding an indicator of mix reliability and mechanical properties under both conditions. The variation was calculated using Equation (1) (*MV*, percentile mechanical variation; CS_i, industrial-scale compressive strength, in MPa; CS_l, laboratory-scale compressive strength, in MPa; STS_i, industrial-scale splitting tensile strength, in MPa; STS_l, laboratory-scale splitting tensile strength, in MPa). A positive *MV* value implied better SCC properties in the industrial production, and conversely, worse properties when negative.

$$MV = \frac{1}{2} \times \left(\frac{CS_i - CS_l}{CS_l} + \frac{STS_i - STS_l}{STS_l} \right) \times 100 \tag{1}$$

- Variation of SCC durability due to the scale effect. Identical to the previous criterion, yet referring to durability behavior. The durability variation (*DV*, in percentage) was determined by Equation (2), so that, in analogy to Equation (1), a positive sign implied better durability properties when the SCC had been mixed at an industrial scale, and a negative sign, a worsening. In this equation, *P* is the porosity of the concrete, in percentage terms; *WP*, the water penetration under pressure, in mm; and *S*, the shrinkage, in mm/m. The subscripts *l* and *i* refer to the laboratory and industrial scale, respectively.

$$DV = \frac{1}{3} \times \left(\frac{P_l - P_i}{P_l} + \frac{WP_l - WP_i}{STS_l} + \frac{S_l - S_i}{S_l} \right) \times 100 \tag{2}$$

- Mechanical behavior. Measured in terms of the compressive strength and the splitting tensile strength of the industrial-scale mixture. The weight assigned to this criterion in the MCDM algorithms was split between the compressive strength and the splitting tensile strength. This distribution (percentage) was set together with the collaborating company according to the strength requirements for each particular concrete component.
- Durability behavior. The industrial-scale values of the three durability properties under evaluation were directly considered. The weight assigned to this criterion was divided between 360-day shrinkage, porosity, and depth of water penetration under pressure as per the durability requirements for each type of precast-concrete component that was analyzed. Water penetration under pressure is an indirect measurement of concrete porosity (Matar and Barhoun, 2020), so its weight was always the same as the weight attached to porosity in the MCDM algorithms.
- Cost. Finally, mix costs at an industrial scale were directly considered. This measure was complementary to the mechanical and durability performance of each concrete.

It may be noted that neither the fresh performance nor the environmental benefits of the coarse-RA mixes were considered in the selection criteria. In consequence, only the two fundamental aspects considered by any concrete company in the analysis, concrete behavior and cost, were taken into account (Fiol et al., 2018). The reason for this approach regarding the fresh behavior, according to the precast-concrete company, was that it made no difference whether the fresh behavior had a lower or a higher flowability, as long as it complied with the in-fresh requirements of the company, *i.e.*, a slump-flow class SF1 and a slump-flow-viscosity class VS2 as per EN 206 (2013), which usually guarantee correct concreting in the plant. Furthermore, any sudden and unexpected loss of SCC flowability during concreting could be solved by the self-vibrating system that the formworks of the precast-concrete plant incorporated. On the other hand, it was also decided, in agreement with the company, to disregard the environmental benefits of using the mix with 100% coarse RA, which were categorized as "added value". The environmental benefits of using coarse RA are the main advantages of RA concrete (Tang et al., 2022a), but giving no direct consideration of it in the MCDM analysis allowed for a more demanding MCDM analysis regarding the use of coarse RA. In this way, any SCC mix containing coarse RA that is found to be optimal in the MCDM analysis will have good mechanical behavior and durability, as well as adequate costs, in the absence of any advantages related to "added value" for the environment. Thus, it is intended to show that the use of coarse RA in SCC is also advisable for a precast-concrete plant from the point of view of the performance and costs of the concrete that this alternative aggregate allows obtaining without considering its sustainability-related advantages.

2.5.2. MCDM algorithms

Two different algorithms were considered when selecting the optimum alternative, to make the analysis robust and to guarantee that the results were valid:

- Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). This is an MCDM algorithm suitable for quantitative criteria. The optimal choice is determined by the closeness of each alternative to the ideal optimal solution, which shows the best possible values for each criterion.
- Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE). It is also an MCDM algorithm used for quantitative criteria. In this case, the most suitable option is determined from the positive and negative flows calculated through the preference indexes obtained for each alternative of election.

2.5.3. Scenarios for MCDM analysis

The objective of the MCDM analysis was to analyze the feasibility of using an SCC with 100% coarse RA in different types of precast-concrete components produced at the precast-concrete plant. Five scenarios for analysis were therefore defined, each corresponding to a different type of precast-concrete components. Those scenarios are shown in Fig. 4:

- Scenario 1 consists of a reinforced precast cladding panel with latticework that can be placed both vertically and horizontally. There are two fundamental aspects to the technique for manufacturing these panels. On the one hand, durability and its variability, due mainly, to shrinkage cracking and to the entry of external aggressive agents, which have to be minimized when the panels are used in an outdoor environment. On the other hand, costs, which must be reduced in view of the large concrete volumes that are required. Compressive and tensile strengths are equally important, whenever the component may be subject to transversal stress.
- An alveolar plate is analyzed in Scenario 2. This structural component is used for the production of interior floor slabs, so durability is less important than when exposed to the external environment. Uniform mechanical behavior and adequate tensile strength (as the slab has no transverse reinforcements) are the most relevant aspects. This type of plate usually has a depth of 30–40 cm and is manufactured with concrete extrusion machines at minimum lengths of 25 m, which are then cut to size. As large concrete volumes are needed, any reductions in concrete costs are encouraged.
- In Scenario 3, it is considered a T or an L beam used for floor slabs, to support the alveolar plates for example. The durability of the concrete is relatively important, as beams of that sort can be exposed to the external environment. However, the compressive strength and minimal variations are the most important aspects. The tensile-strength requirements of the concrete are not very demanding, as it is a longitudinal component with longitudinal reinforcements, subjected to almost zero transversal stress. The cost of the concrete is less relevant, as the most expensive beam materials are the rebars.
- Scenario 4 covers an ARTWIN beam, which is a prestressed deck beam cast in forms. Although it is usually waterproofed on placement, durability and its uniformity are the most important aspects of the concrete used in its production, as deck beams are exposed to the outdoor environment and both the penetration of external agents and shrinkage cracking must therefore be minimized. The mechanical behavior, although it must be adequate, is of minor importance. It is a minimum-thickness piece without transverse reinforcement, so concrete tensile strength must also be considered. Finally, the cost should also be controlled.
- Finally, Scenario 5 consists of a precast column. Compressive strength is the most important production-related aspect of the concrete and, more specifically, a mechanical behavior that is not highly variable, so that all the columns show similar behavior. The cost is of intermediate importance, as a high number of columns usually need to be produced for a conventional building, which implies high concrete volumes at all times. Although these columns are usually protected from the external environment, minimal consideration must be given to durability, due to the contact zone with the ground at the column footings where they intersect with the foundation.

In accordance with the above aspects, the weights considered for each scenario were jointly defined with the precast-concrete company and are detailed in Table 6. In addition to using two different MCDM algorithms, the weights were also varied ±20% to ensure the robustness of the MCDM analysis and to test whether the same results could be obtained with little weight variations.

3. Results and discussion: experimental tests

This section reports the results of the different experimental tests on the SCC mixes. They were used to compare laboratory- and industrial-scale behavior. In addition, 4 of the 5 selection criteria used in the MCDM analysis were determined: mechanical variation, durability variation, mechanical behavior, and durability behavior.

3.1. Fresh performance

The fresh behavior of the mixes was evaluated with the slump-flow test, according to EN 12350-8 (2020). The precast-concrete company thresholds for adequate SCC concreting were as follows: slump-flow class SF1, *i.e.*, slump flow between 550 mm and 650 mm, and

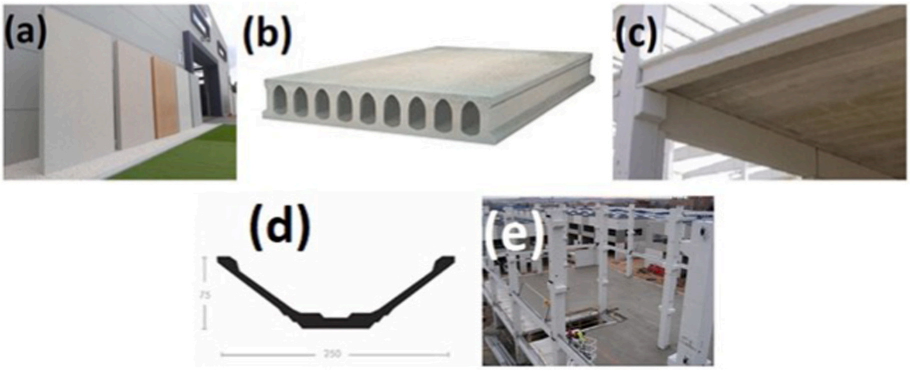

Fig. 4. MCDM-analysis scenarios (images provided by the collaborating company): (a) Scenario 1, precast panel; (b) Scenario 2, alveolar plate; (c) Scenario 3, double-T or L beam for floor slab; (d) Scenario 4, ARTWIN beam; (e) Scenario 5, precast column.

Table 6
Weights of each scenario for the MCDM analysis.

Scenario		1 (precast panel)	2 (alveolar plate)	3 (double-T or L beam for floor slab)	4 (ARTWIN beam)	5 (precast column)
Mechanical variation (*MV*, Equation (1))		0.100	0.250	0.300	0.150	0.400
Durability variation (*DV*, Equation (2))		0.200	0.100	0.200	0.300	0.100
Mechanical behavior	Compressive strength	0.050	0.150	0.210	0.075	0.270
	Splitting tensile strength	0.050	0.150	0.090	0.075	0.030
Durability behavior	Porosity	0.060	0.035	0.025	0.105	0.035
	Depth of water penetration under pressure	0.060	0.035	0.025	0.105	0.035
	Shrinkage	0.280	0.030	0.050	0.090	0.030
Cost		0.200	0.250	0.100	0.150	0.200

viscosity class VS2, that is, t_{500} between 2 s and 5 s, as per EN 206 (2013). The results obtained for both mixes at both laboratory and industrial scale are shown in Table 7.

The addition of 100% coarse RA decreased the flowability of the SCC, due both to the irregular, angular shape of this alternative aggregate (Silva et al., 2018) and to the fact that its higher water absorption was not compensated, in order to maintain adequate strength (Revilla-Cuesta et al., 2020), as discussed in the mix-design section. This aspect was partially compensated by increasing the admixture content. In relation to the scale effect, the production of concrete volumes of 2 m^3 appeared to produce a more homogeneous SCC and to improve flowability, a property that was also favored by the increase in the amount of admixture. Furthermore, the greatest difficulty to maintain aggregate moisture constant due to the high amount of aggregate needed and, therefore, to perform a precise control over the water content when producing large-scale concrete could also explain those results (Fiol et al., 2021). All the mixes met the flowability requirements of the collaborating company, so their fresh behavior was no obstacle to the use of coarse RA.

3.2. Compressive strength

Compressive strength was measured at 1, 7, 28, and 180 days as per EN 12390-3 (2009), for the evaluation of the long-term strength development of the SCC, as shown in Fig. 5. Taking the compressive strength value at 180 days as a reference:

- The compressive strength of mix CR, with 100% coarse RA, was higher than that of mix C, with 0% coarse RA (69.7 MPa vs. 65.0 MPa). The non-adjustment of the water content (maintaining water content constant when adding coarse RA, as shown in Table 2) led to a reduction of the effective water-to-cement ratio. This, combined with the use of a quality coarse RA from precast-concrete elements, compensated for the expected decrease in strength that the use of coarse RA usually causes, due to its lower strength than NA and its lower adhesion to the cementitious matrix (Santos et al., 2019). Adequate mix flowability was likewise achieved by adjusting the content of the plasticizing admixture.
- The production of the mixes at an industrial scale decreased their strength at 180-days by an almost negligible 3–5%. A difference that may have been due to the small increase in admixture content without modifying the amount of water, which may have caused a slight increase in porosity, as found in other studies (Barbudo et al., 2013). Another aspect is less precise controls over aggregate moisture levels when producing large industrial volumes of concrete.
- The strength development of SCC was always similar, regardless of the presence of coarse RA or the scale at which the mix was produced. Thus, at 7 and 28 days, all of them developed around 85% and 95% of the 180-day compressive strength. This fast development of strength guarantees the good performance of SCC with 100% coarse RA when used at an industrial scale (Benmokrane et al., 2020).

Table 7
Slump-flow behavior of SCC as per EN 206 (2013).

Scale	Magnitude	Mix C	Mix CR
Laboratory scale	Slump flow (mm)	750 ± 15	650 ± 20
	Slump-flow class	SF2	SF1
	t_{500} (s)	3 ± 0.2	5 ± 0.2
	Viscosity class	VS2	VS2
Industrial scale	Slump flow (mm)	765 ± 10	680 ± 15
	Slump-flow class	SF3	SF2
	t_{500} (s)	2.5 ± 0.2	4 ± 0.1
	Viscosity class	VS2	VS2

In terms of the precast-concrete plant, it is important to note that the compressive strength of the two mixes at an industrial scale was within the margins of the compressive-strength self-monitoring performed at the plant according to ISO 9001 (2015), as shown in Fig. 6. In other words, the compressive strengths of mixes C and CR when produced at an industrial scale were suitable for the production of precast-concrete components, based on standard quality controls and monitoring of the manufactured concrete components on the premises of the precast-concrete company.

3.3. Splitting tensile strength

The splitting tensile strength at 28 days of each mix (EN 12390-6, 2010) is shown in Table 8. The addition of 100% coarse RA decreased the splitting tensile strength, as reported in the bibliography (Tam et al., 2021a). However, this decrease was minimal, around 5%, which shows the suitability of using large amounts of coarse RA to produce this type of concrete mixes. The production of industrial-scale concrete volumes led to an increase in splitting tensile strength, which in turn also led to a lesser reduction in splitting tensile strength when adding 100% coarse RA. This behavior was contrary to the compressive strength trends, which is attributed to the lower dependence of the splitting tensile strength on concrete porosity (Revilla-Cuesta et al., 2021a). Both aspects caused the SCC mix produced at industrial scale with 100% coarse RA to show higher splitting tensile strengths than the SCC mix produced at laboratory scale with 0% coarse RA. This confirms the validity of the mechanical behavior of SCC with 100% coarse RA for use in the precast-concrete industry.

3.4. Full-immersion water absorption and porosity

Table 9 shows the results of full-immersion water absorption and porosity of the mixtures, determined at 28 days according to ASTM C 642 (2006). These properties were obtained from the oven-dried weight, the saturated weight, and the submerged weight of the test specimens. The results showed that:

- Both magnitudes increased with the addition of coarse RA, due to the higher porosity of the adhered mortar compared to the NA particles, which increased porosity within the interfacial transition zones

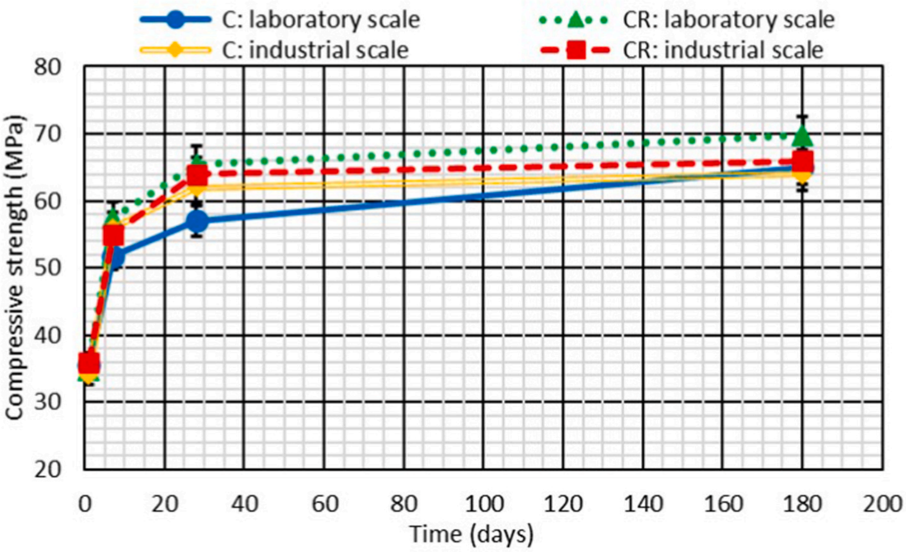

Fig. 5. Compressive strength.

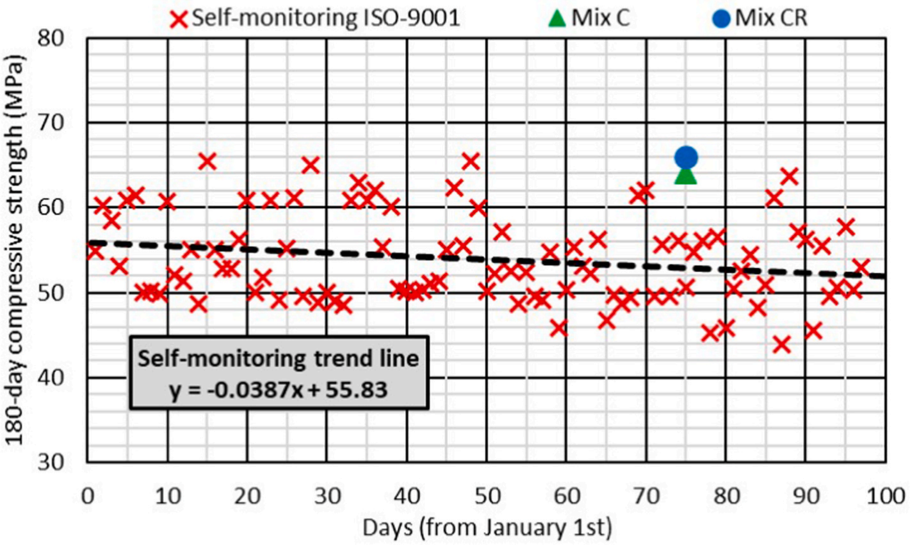

Fig. 6. Concrete compressive-strength self-monitoring in the precast-concrete plant.

Table 8
28-day splitting tensile strength.

Parameter	Laboratory scale		Industrial scale	
	C	CR	C	CR
Splitting tensile strength (MPa)	5.3 ± 0.1	5.0 ± 0.1	5.8 ± 0.0	5.6 ± 0.1
Variation due to 100% coarse RA addition (%)	–	−5.7	–	−3.6
Variation due to scale effect (%)	–	–	+9.4	+12.0

(Revilla-Cuesta et al., 2021a). However, this increase in porosity was much lower than in other studies (Santos et al., 2019), possibly because in the mix design the water content of the SCC was not increased when adding coarse RA. The mixes with 100% coarse RA therefore had higher compressive strengths, as detailed above.

- The increased production volume of the SCC caused an increase in both water absorption and porosity, although the variation of the latter was very small, around 2–7%. It is thought that the increased

Table 9
Full-immersion water absorption and porosity at 28 days.

Test	Test parameter	Laboratory scale		Industrial scale	
		C	CR	C	CR
Full-immersion water absorption	Water absorption (% wt.)	2.95 ± 0.06	3.20 ± 0.07	3.30 ± 0.12	3.82 ± 0.15
	Variation due to 100% coarse RA addition (%)	–	+8.5	–	+15.8
	Variation due to scale effect (%)	–	–	+11.9	+19.4
Porosity	Permeable-voids volume, porosity (% vol.)	5.15 ± 0.11	6.00 ± 0.12	5.50 ± 0.17	6.10 ± 0.13
	Variation due to 100% coarse RA addition (%)	–	+16.5	–	+10.9
	Variation due to scale effect (%)	–	–	+6.8	+1.7

content of plasticizer when preparing the industrial-scale mixes, with no change in the water content, might explain this slight increase in porosity (Barbudo et al., 2013). The less precise control of industrial-scale aggregate humidity and the higher variability of the RA rather than the NA properties might have also led to a higher porosity in the SCC mix (Fiol et al., 2018). No clear interaction between the scale factor and the effect of coarse RA was observed.

3.5. Water penetration under pressure

The water-penetration-under-pressure test (EN 12390-8, 2020), conducted at 28 days, yielded the results shown in Table 10. As expected, they followed the same trend as the porosity results shown in the previous section, due to the close relationship between both properties (Matar and Barhoun, 2020). Thus, the water-penetration depth increased with the addition of 100% coarse RA and with the production of industrial-scale SCC mixes. However, it should in all cases be noted that the depth of water penetration under pressure was lower than the usual concrete cover over the reinforcements, at around 25–30 mm as per European standard Eurocode 2 (EC-2, 2010). In the opinion of the employees at the precast-concrete company, these water penetration depths suggest that SCC with 100% coarse RA can be successfully used in the manufacture of precast-concrete components.

3.6. Shrinkage

The shrinkage of all the mixes was measured from 1 to 360 days in accordance with UNE 83318 (1994), initially quite frequently and then between lengthier time intervals. The results are shown in Fig. 7.

According to the results of the mixes produced at laboratory scale, the use of coarse RA slightly increased shrinkage, as 360-day shrinkage was −482 μm/m in mix C and −498 μm/m in mix CR as per the trend lines. The water content was not adjusted to compensate for the higher water absorption levels of coarse RA, so shrinkage increase was not as sharp as the results reported in other studies (Tam et al., 2021b). However, coarse RA was less resistant than coarse NA to cementitious-matrix contraction processes as its water content evaporated, thus increasing the shrinkage of the SCC containing coarse RA. Increased shrinkage was also due to the presence of adhered mortar fragments of the coarse RA, which in turn meant that the coarse RA in the matrix was of a lower stiffness than the coarse NA (Tam et al., 2021a).

The production of industrial-scale SCC mixes led to an increase in shrinkage, with 360-day shrinkage reaching −635 μm/m for mix C and −712 μm/m for mix CR. This increase was again explained by the not-so-precise control of aggregate moisture when producing large-scale concrete mixes (Fang et al., 2021). It is thought that this aspect, together with the increase in admixture content and the higher variability of the coarse-RA quality compared to NA (Agrela et al., 2011), might also explain the higher relative increase in shrinkage when adding 100% coarse RA, as these increases at an industrial and at a laboratory scale were 12.1% and only 3.3%, respectively.

Table 10
28-day water penetration under pressure.

Parameter	Laboratory scale		Industrial scale	
	C	CR	C	CR
Penetration depth (mm)	16 ± 0.3	18 ± 0.4	18 ± 0.2	21 ± 0.3
Variation due to 100% coarse RA addition (%)	–	+12.5	–	+16.7
Variation due to scale effect (%)	–	–	+12.5	+16.7

3.7. Overview: laboratory scale versus industrial scale

Table 11 summarizes both laboratory- and industrial-scale results, showing the different properties evaluated in the mixes. In addition, it also shows the variation of their mechanical behavior and durability, calculated according to Equation (1) and Equation (2), respectively. In line with what has been commented in previous sections, two aspects may be observed:

- Industrial-scale mix production caused minimal variations to the mechanical behavior of the SCC mixes. These variations even led to overall improvement of the mechanical behavior according to the mechanical variation *MV* (Equation (1)). The relative decrease in compressive strength was smaller than the relative increase in splitting tensile strength.
- On the other hand, durability performance was negatively affected as the volume of concrete production increased (durability variation *DV*, Equation (2)). Concrete durability depends to a large extent on concrete porosity, which is strongly conditioned by the water content of the mix (Hafez et al., 2020). Therefore, the poorer control at an industrial scale of the water content of the mix and the aggregate moisture levels might have provoked this performance (Fiol et al., 2018). It should be noted that the durability behavior worsened in both mixes: 17.0% in mix C and 20.4% in mix CR.

In general, as the durability variation was higher than the mechanical variation, the mix CR, with 100% coarse RA, showed greater variability in its overall behavior, possibly due to the greater dispersion of the properties of coarse RA compared to those of a certified NA such as the one used in the precast-concrete plant (Agrela et al., 2011). In addition, the greater range of possible moisture contents of coarse RA, due to its higher levels of water absorption, might have favored this behavior. However, regardless of the aggregate, the results underlined the need for a reasonable laboratory scale design of the SCC, so that adequate results may be obtained when the SCC is scaled-up for industrial production, especially in terms of durability.

4. Results and discussion: cost

The cost of concrete is a very relevant aspect for any precast-concrete company whose main objective is to produce concrete and concrete components that meet performance specifications at a reasonable price (Jiménez, 2020). Considering the simple unit prices indicated in section 2.4.2, the unit prices of the two mixes designed at industrial scale were calculated, as detailed in Table 12. The prices, at around 80–85 €/m^3 (90–95 USD/m^3), were similar to those reported in other studies, showing that the cost of these mixes was within the usual market values (Reddy et al., 2020). The use of 100% coarse RA resulted in savings of around 5.5%, due to the lower cost of RA compared to NA. The same point in favor of the use of RA as a raw material in concrete manufacturing has also been mentioned in other similar studies (Rashid et al., 2020).

5. Results and discussion: multi-criteria decision-making analysis

In this section, the MCDM analysis of the feasibility of using SCC containing 100% coarse RA is discussed in relation to the production of precast-concrete components manufactured by the company. The starting points for this analysis were detailed in section 2.5.

5.1. Decision matrix

As indicated in section 2.5.1, there were 5 decision criteria: mechanical variation (*MV*, Equation (1)); durability variation (*DV*, Equation (2)); mechanical behavior (compressive strength and splitting

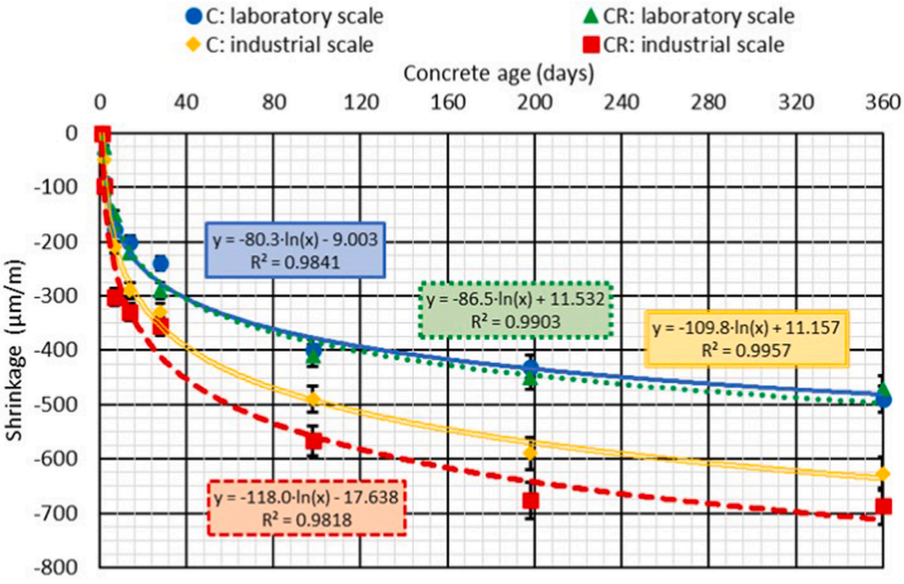

Fig. 7. Shrinkage.

Table 11
Laboratory scale versus industrial scale: average results and variation.

Property	Laboratory scale		Industrial scale	
	Mix C	Mix CR	Mix C	Mix CR
180-day compressive strength (MPa)	65.0	69.7	64.0	66.0
28-day splitting tensile strength (MPa)	5.3	5.0	5.8	5.6
Mechanical variation (*MV*, %, Equation (1))	–	–	+3.95	+3.35
Porosity (% vol.)	5.15	6.00	5.50	6.10
Depth of water penetration under pressure (mm)	16	18	18	21
360-day shrinkage (μm/m)	−482	−498	−635	−712
Durability variation (*DV*, %, Equation (2))	–	–	−17.01	−20.44

tensile strength); durability behavior (porosity, water penetration depth under pressure, and shrinkage); and cost. In illustration of this approach, Table 13 shows the decision matrix for the development of the TOPSIS and PROMETHEE algorithms, which were the ones considered in this research work, as indicated in section 2.5.2. The feasibility of using an SCC containing 100% coarse RA in different precast components (section 2.5.3) was determined on the basis of that matrix.

5.2. *Preference ranking*

Based on the decision matrix, and considering the different scenarios and weights described in section 2.5.3, jointly defined with the precast-concrete company, the preferred mix, C or CR, for the manufacture of different types of precast-concrete components was determined. The results of both algorithms are shown in Table 14. Both the TOPSIS and the PROMETHEE algorithms were considered, to guarantee the robustness of the MCDM analysis. Furthermore, weight variations of ±20% for

Table 12
Unit price of the industrial-scale SCC mixes (€/m^3 or USD/m^3).

Mix	Unit	Designation	Price (€/unit)	Price (USD/unit)	Amount (unit) [a]	Cost (€/m^3)	Cost (USD/m^3)
C	h	Ordinary laborer	12.95	14.68	0.80	10.36	11.74
	h	Concrete mixer 3 m^3	3.89	4.41	0.55	2.14	2.43
	t	Cement CEM I 52.5 R	100.82	114.29	0.32	32.26	36.57
	t	Siliceous aggregate 0/2 mm	13.90	15.76	0.65	9.04	10.24
	t	Siliceous aggregate 2/12.5 mm	18.00	20.40	1.15	20.70	23.46
	t	Recycled aggregate 4/12.5 mm	11.75	13.70	0.00	0.00	0.00
	t	Limestone filler	29.00	32.87	0.28	8.12	9.20
	kg	Admixture 1	2.00	2.27	0.50	1.00	1.14
	kg	Admixture 2	2.00	2.27	1.30	2.60	2.95
	m^3	Water	0.36	0.41	0.112	0.04	0.05
	m^3	**Unit price of mix C (€/m^3 or USD/m^3)**				**86.26**	**97.78**
CR	h	Ordinary laborer	12.95	14.68	0.80	10.36	11.74
	h	Concrete mixer 3 m^3	3.89	4.41	0.55	2.14	2.43
	t	Cement CEM I 52.5 R	100.82	114.29	0.32	32.26	36.57
	t	Siliceous aggregate 0/2 mm	13.90	15.76	0.72	10.01	11.35
	t	Siliceous aggregate 2/12.5 mm	18.00	20.40	0.00	0.00	0.00
	t	Recycled aggregate 4/12.5 mm	11.75	13.70	1.04	12.22	14.25
	t	Limestone filler	29.00	32.87	0.28	8.12	9.20
	kg	Admixture 1	2.00	2.27	0.90	1.80	2.04
	kg	Admixture 2	2.00	2.27	2.20	4.40	4.99
	m^3	Water	0.36	0.41	0.112	0.04	0.05
	m^3	**Unit price of mix CR (€/m^3 or USD/m^3)**				**81.35**	**92.62**

[a] Amounts needed per cubic meter of SCC. Hourly ordinary laborer wages and concrete mixer costs defined by the precast-concrete company. All others fixed according to the mix design.

Table 13
Decision matrix for MCDM algorithms.

Mix	Mechanical variation (*MV*, %, Equation (1))	Durability variation (*DV*, %, Equation (2))	Mechanical behavior		Durability behavior			Cost (€/m^3-USD/m^3)
			Compressive strength (MPa)	Splitting tensile strength (MPa)	Porosity (% vol.)	Depth of water penetration under pressure (mm)	Shrinkage (μm/m)	
C	+3.95	−17.01	64.0	5.8	5.50	18	−635	86.26–97.78
CR	+3.35	−20.44	66.0	5.6	6.10	21	−712	81.35–92.62

Table 14
MCDM analysis.

Scenario	Weights	Mix	TOPSIS algorithm		PROMETHEE algorithm	
			Relative closeness coefficient	Preferred mix	Net flow	Preferred mix
1 (precast panel)	Initial values (Table 6)	C	0.711	C	0.110	C
		CR	0.289		−0.110	
	+20%	C	0.745	C	0.206	C
		CR	0.255		−0.206	
	−20%	C	0.674	C	0.094	C
		CR	0.326		−0.094	
2 (alveolar plate)	Initial values (Table 6)	C	0.318	CR	−0.150	CR
		CR	0.682		0.150	
	+20%	C	0.276	CR	−0.200	CR
		CR	0.724		0.200	
	−20%	C	0.371	CR	−0.100	CR
		CR	0.629		0.100	
3 (double-T or L beam for floor slab)	Initial values (Table 6)	C	0.428	CR	−0.110	CR
		CR	0.572		0.110	
	+20%	C	0.386	CR	−0.110	CR
		CR	0.614		0.110	
	−20%	C	0.479	CR	−0.110	CR
		CR	0.521		0.110	
4 (ARTWIN beam)	Initial values (Table 6)	C	0.693	C	0.150	C
		CR	0.307		−0.150	
	+20%	C	0.768	C	0.210	C
		CR	0.232		−0.210	
	−20%	C	0.610	C	0.060	C
		CR	0.390		−0.060	
5 (precast column)	Initial values (Table 6)	C	0.227	CR	−0.320	CR
		CR	0.773		0.320	
	+20%	C	0.197	CR	−0.320	CR
		CR	0.803		0.320	
	−20%	C	0.263	CR	−0.320	CR
		CR	0.737		0.320	

each scenario were also implemented, to ensure that the results were not dependent on small variations of those weights. So, the preferred mix obtained in every scenario was reliable.

The MCDM-feasibility analysis showed that the use of SCC with 100% coarse RA, *i.e.*, mix CR, was preferable for the manufacture of alveolar plates, double-T and L beams for floor slabs and precast columns. On the other hand, mix C, with 100% coarse NA, was recommended for the manufacture of precast panels and ARTWIN beams. The concrete components in which the use of mix CR was preferable met two defining aspects:

- These were components in which good mechanical behavior was more important than good durability properties. Rather than being the cause of the usual decrease in strength (Orsini and Marrone, 2019), the mix design actually increased the strength of the mix. This trend was contrary to the durability results. Thus, the use of coarse RA is not necessarily a negative aspect in terms of strength development and its use in precast-concrete components that require good mechanical behavior is feasible.
- These components required large volumes of concrete, so low-cost concrete had to be used (Singh and Venkatanarayanan, 2020). Coarse RA implies less expensive SCC, as also reported in other studies (Rashid et al., 2020), which is one reason to recommend its use when producing large volumes of SCC.

According to the results of the MCDM analysis, precast-concrete components exposed to external aggressive agents should be made with SCC incorporating conventional coarse NA. Although the mix design was aimed at minimizing the negative effects caused by the use of coarse RA on concrete (Silva et al., 2019), those related to durability, such as increased porosity (Revilla-Cuesta et al., 2021a), could not be fully compensated. In addition, greater variability of concrete durability is associated with the use of coarse RA, which implies less certainty over this property when using this alternative aggregate.

6. Conclusions

The feasibility of producing Self-Compacting Concrete (SCC) containing coarse Recycled Aggregate (RA) has been studied at a precast-concrete plant some of whose employees were actively involved with this research. For this purpose, 2 mixes were designed, with 0% and 100% coarse RA respectively, which were produced at both laboratory scale (0.08 m^3) and industrial scale (2 m^3) at the precast-concrete plant. The mechanical and durability behavior at both scales has been compared, for an evaluation of the effect of coarse RA on the variability of SCC behavior when producing industrial volumes of concrete. In addition, the feasibility of using this type of mix in different precast-concrete components has been evaluated through a Multi-Criteria Decision-Making (MCDM) analysis, based on the results and the experience of employees at the precast-concrete plant. The following conclusions can be drawn:

- The production of large-scale SCC with the addition of 100% coarse RA at an industrial plant can be conducted in such a way that the SCC simultaneously shows adequate flowability (slump flow and viscosity) and compressive strength. To do so, the water content should not be increased when adding coarse RA, to compensate for the expected decrease in strength, which even improved the strength of the conventional SCC. The required flowability was achieved by increasing the admixture content. Both properties matched the concrete requirements of the collaborating company.
- Compared to the test results of the laboratory-scale mixes, the mechanical behavior of the industrial-scale mixes was maintained, even though durability worsened by 17% and 20% in the mixes with 0% coarse RA and 100% coarse RA, respectively. Industrial-scale concrete production implied less precise control of aggregate moisture and coarse RA showed greater variability of its properties, due to the large quantities of aggregate that were required. Both aspects favored these results.
- According to the estimations of the precast-concrete company and despite the necessary acquisition costs of specific machinery (hydraulic clamp, crushers and sieving machines), the use of a 100% coarse RA could lead to a 5% reduction in the cost of the SCC. This economic advantage may be weighed up against the cost of conventional SCC when producing large volumes of concrete.
- The MCDM-feasibility analysis showed that the use of 100% coarse RA could be recommendable when producing alveolar plates, double-T or L beams for floor slabs and precast columns. These components are not exposed to external aggressive agents, such that good mechanical behavior and low mechanical-property variability are the main features to be considered in concrete production. Together with the need to minimize costs, it makes the use of coarse RA feasible. It is not recommendable to use SCC containing coarse RA with a design similar to the one of this research for components exposed to an external environment, such as precast cladding panels and ARTWIN deck beams, due to the worse durability properties of those mixes than the durability of conventional SCC.

Coarse RA can be easily processed in a precast-concrete plant, due to the availability of surplus concrete and rejected concrete components that can be crushed and sieved to be used as aggregate in the concrete produced in the plant itself. Although the coarse RA obtained in this way is scarcer, it has a better quality than the coarse RA from construction and demolition waste, as it is not mixed with other components. This means that it can be successfully used to manufacture the concrete used in precast-concrete elements, as demonstrated in this paper. The authors of this study therefore hope that the results of this study will incentivize the use of this alternative aggregate within the precast-concrete sector and other areas of the construction industry.

The next steps in this research line may be (1) to analyze the use of coarse RA in a precast-concrete plant considering, in addition to the aspects covered in this paper, the environmental advantages of using this alternative aggregate; or (2) to improve the design of the SCC containing coarse RA to extend the recommended use of this type of mixes to precast-concrete elements with high durability requirements, such as precast panels or ARTWIN beams. Structural verification of precast components containing these sorts of concrete mixes could also be a promising development for future research within this field.

CRediT authorship contribution statement

Víctor Revilla-Cuesta: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review & editing. **Francisco Fiol:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Priyadharshini Perumal:** Methodology, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Vanesa Ortega-López:** Conceptualization, Supervision, Writing – review & editing, Project administration, Funding acquisition. **Juan M. Manso:** Conceptualization, Methodology, Writing – review & editing, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to express their gratitude for funding this research work to the Spanish Ministry of Universities, MICINN, AEI, EU, ERDF and NextGenerationEU/PRTR [PID2020-113837RB-I00; 10.13039/501100011033; TED2021-129715B-I00; FPU17/03374]; the Junta de Castilla y León (Regional Government) and ERDF [UIC-231]; and the University of Burgos [SUCONS, Y135.GI]. In addition, Priyadharshini Perumal acknowledges the financial support received from the project DeConcrete [grant # KO 4068: Eco-efficient Arctic technologies cooperation] funded by the Kolarctic CBC initiative of the European Union. Finally, the support and assistance of ARTEPREF S.A. for the development of this study is also highly appreciated.

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