Effect of fine recycled concrete aggregate on the mechanical behavior of self-compacting concrete

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Abstract

The high flowability of Self-Compacting Concrete (SCC) is achieved by adding large amounts of fine aggregate. Therefore, the addition of fine Recycled Concrete Aggregate (RCA) in this type of concrete can very noticeably change its behavior. SCCs with different percentages of fine RCA (0 %, 25 %, 50 %, 75 %, and 100 %) and 100 % coarse RCA were manufactured in this study, to evaluate their performance, and to analyze the effect of fine RCA in an SCC when a high amount of coarse RCA is also added. Both the fresh properties (flowability, density, and air content) and their mechanical behavior (strengths, non-destructive tests, stress-strain curves, and Poisson coefficient) at different curing ages were studied. These mechanical properties were compared with the values calculated using the formulas from two of the most common structural design standards. High values of strength and modulus of elasticity were obtained up to a fine RCA content of 50 %. Additionally, any increase in fine RCA increased flowability and elastic and plastic deformability of the SCC. The theoretical values overestimated the experimental ones by around 25 %. From the mechanical point of view, SCC with up to 50 % fine RCA could be used for structural applications, although service requirements regarding deformability recommend that its content should be limited to 25 %.

Keywords: Self-Compacting Concrete; Recycled Concrete Aggregate; flowability; mechanical performance at different curing ages; stress-strain curves; design values

1. Introduction

Construction sector activities are generally characterized as large-scale projects that consume vast amounts of natural resources, something that the production figures of the sector largely reflect. On average, within the European Union, around 2,700 Mt of Natural Aggregate (NA) are placed on the market each year, of which 120 million were consumed in Spain. Moreover, 16 Mt of bituminous concrete, and 22 Mm^3 of hydraulic concrete were produced, in 2018, in this country [1]. High levels of resource exploitation have continued over time, leading in some areas to significant scarcities [2].

Construction and Demolition Waste (CDW) represents 34.7 % of all building waste generated in Europe, over 800 Mt/year, where the countries with the highest production levels are France and Germany (227 and 207 Mt/year respectively) [3]. In Spain, with the upturn of the construction sector, CDW production exceeded 20 Mt in 2017 [3]. Demolition processes generated around 0.9 t of CDW per m^2 of demolished housing, reaching 1.2 t/m^2 in industrial buildings, 40 % of which was deposited in illegal landfill sites [4]. CDWs usually present a mixture of concrete with ceramic residues and glass and/or gypsum, which worsen their behavior as a raw material for other uses [5]. Recycled Concrete Aggregate (RCA), a particular type of CDW, is usually produced from the crushing of selected concrete elements, such as precast concrete rejects, and it demonstrates better mechanical behavior, because it contains fewer contaminants and its properties are less variable [6].

The two above-mentioned problems -scarcity of natural resources and abundance of waste- could be mitigated through a simple strategy: using waste as a raw material in different construction sector applications, in substitution of NA, among which the manufacture of hydraulic and bituminous concretes is notable [7-13]. This strategy would also help to reduce the ecological impact of quarrying as well as the carbon footprint of the construction sector [5; 14-16]. Among the various potential usages of RCA, this study is focused on its validation in the manufacture of Self-Compacting Concrete (SCC).

The total aggregate volume of concrete is 65-70 %, making RCA an ideal material for applying the above strategy. In fact, the literature contains several studies of conventional concretes made with proper dosages of coarse RCA that have demonstrated a good behavior [17; 18]. The addition of fine RCA has a more harmful effect, causing a very noticeable decrease in the mechanical properties of the concretes in which it is incorporated [19]. Although there are some studies on high-performance concretes, such as SCC [20], the available bibliography is scarce, fundamentally in relation to fine RCA, a remarkable aspect, considering the importance of the fine aggregate fractions within this type of concrete [21].

The aspects commented on above are due to the particular characteristics of RCA. The coarse fraction of RCA, which is larger than 4 mm, is mainly characterized by three interrelated aspects. Firstly, the mortar adhering to the surface of the RCA means that, in comparison with the NA, its density and hardness are lower [22; 23]. Secondly, RCA has a contact surface between the aggregate and the mortar, known as the Interfacial Transition Zone (ITZ) [24], which is weaker and less dense than the ITZ of NA [22; 25]. Finally, the high water absorption levels of RCA can be due to the unhydrated cement in the attached mortar [23; 25]. The behavior of the fine RCA, less than 4 mm in size, is strongly conditioned by the mortar particles, as well as some pollutants (clay, gypsum and mica), mainly introduced during the crushing process, which cause, among other aspects, higher levels of water absorption than in the coarse fraction [26].

The addition of RCA affects not only both the fresh and the hardened behavior of the concrete, but also the estimation of compressive strength through non-destructive testing, such as the hammer rebound index and Ultrasonic Pulse Velocity (UPV), mainly due to the presence of attached mortar [27]. However, the validity of these procedures has been demonstrated in vibrated concrete with high contents of coarse RCA [28; 29], even at early ages [30]. Despite the low coarse aggregate content of SCC, non-destructive tests are also valid for this type of concrete when NA is used [31].

The aim of this study is to evaluate the effect of adding different amounts of fine RCA in an SCC with a constant amount of coarse RCA. SCC requires a high proportion of fine aggregate to reach flowability, so it is more sensitive to the effects of fine RCA. In addition, the interaction between coarse and fine RCA can influence its performance. The coarse RCA content was defined in a preliminary analysis, involving tests on the compressive strengths and the elastic moduli of mixes with 0 %, 50 % and 100 % of coarse RCA. Based on this analysis, the amount of 100 % coarse RCA was chosen for the optimum sustainability of the product. Subsequently, five different SCCs with 100 % coarse RCA and fine RCA percentages of 0 %, 25 %, 50 %, 75 % and 100 % were manufactured and analyzed in this study.

Firstly, the evaluation of the fresh concrete behavior of these SSCs verified their compliance with all the recommendations of the European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC) [32]. Subsequently, the temporal evolution of the mechanical properties was evaluated. Additionally, the theoretical values of these mechanical properties, estimated from their compressive strengths, were calculated and compared with the experimental values, in order to validate the calculation methods. The validity of RCA as a material for manufacturing SCC for structural usage was therefore demonstrated, in accordance with its dosage (in particular, the percentage of fine RCA), which must be selected to meet the main purpose of the concrete design (self-compactability and/or strength).

2. Materials

The characteristics of the materials used in this study are described in this section. An analysis of the physical properties and the chemical composition of the RCA is also included, to evaluate its suitability for concrete manufacture.

2.1. Cement, water, filler and admixtures

A conventional Portland cement CEM I 52.5 R was used, with a density of 3.12 Mg/m^3 and a clinker content of around 98 %. Mix water that contained no chemical compounds with potentially adverse effects on concrete behavior was taken from the water supply of the city of Burgos, Spain.

The finest fraction of the granulometry (< 0.063 mm) was provided by the addition of limestone filler with a $CaCO_3$ content higher than 98 %. According to the manufacturer's specifications, this filler had a density of 2.77 Mg/m^3 and a water absorption rate of 0.54 % over 24 h (0.37 % in 10 minutes).

Two additives, fundamental components for providing the SCC with its characteristic self-compactability, were used, which had demonstrated good behavior in a similar study [33]. The first one, a plasticizer, enhanced concrete flowability. The second, a viscosity regulator, maintained SCC flowability over longer periods, improving the results of the in-fresh state tests. In all dosages, total additions of admixture amounted to 2.2 % by weight of cement.

2.2. Aggregates (RCA, siliceous gravel and siliceous sand)

The RCA was produced from concrete components with a characteristic strength of 45 MPa, manufactured with siliceous aggregate, which had subsequently been rejected by the prefabrication industry and crushed. Supplied in sizes between 0 and 31.5 mm from a local CDW management company, the RCA was sieved and separated into fine RCA (0/4 mm) and coarse RCA (4/12.5 mm) fractions, both of which were used in this study.

In Table 1, the main properties of the RCA are compared with the recommended limit values from the Spanish concrete standard EHE-08 [34]. The comparison shows that the RCA fulfilled most of the requirements, except for density and water absorption, which explains the limitation that is specified in the standard of a maximum content of 20 % total coarse RCA. The chemical composition of fine RCA obtained by X-ray fluorescence (XRF) spectrometry and the X-ray diffraction (XRD) pattern are shown in Table 2 and Figure 1, respectively. The predominance of silicon oxide and calcium carbonate can be observed in its composition. The hydrated cementitious components (CSH) are not visible in the XRD test results, although the content in both aluminum and iron oxides denotes the presence of old mortar in the fine RCA.

Siliceous gravel and sand were used to complete the coarse (preliminary analysis) and the fine aggregate fraction of each concrete mix. Their properties are also summarized in Table 1.

Test	Regulations [35]	Siliceous gravel	Siliceous sand	Coarse RCA	Fine RCA	EHE-08 limit [34]
Saturated-Surface-Dry (SSD) density (Mg/m³)	EN-1097-6	2.62	2.58	2.42	2.37	≈ 2.6 kg/dm³
Water absorption 24h (%)	EN-1097-6	0.84	0.25	6.25	7.36	Coarse RCA content < 20 %: <7 % Coarse RCA content > 20 %: Combination of RCA and NA coarse fractions: < 5 %
Water absorption 10 minutes (%)	-	0.66	0.18	5.28	6.03	If RCA content is lower than 20 %: <5.5 %
Fines content (%)	EN-933-1	0.11	1.82	0.17	4.83	< 1.50 % (coarse fraction)
Equivalent sand (%)	EN-933-8	-	-	-	83	> 75
Bulk density (Mg/m³)	EN-1097-3	-	-	1.26	1.23	-
Los Angeles coefficient (%) (size 10/14 mm)	EN-1097-2	-	-	35	-	< 40
Sand friability test (%) (size 0/4 mm)	UNE-146404	-	-	-	16	

Table 1. Aggregates' physical properties.

SiO_2	CaO	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	TiO_2	P_2O_5	Others (CO_2 …)
50.80	20.00	3.74	1.12	1.00	0.63	0.60	0.15	0.06	21.9

Table 2. Chemical composition (% in weight) of fine RCA trough XRF.

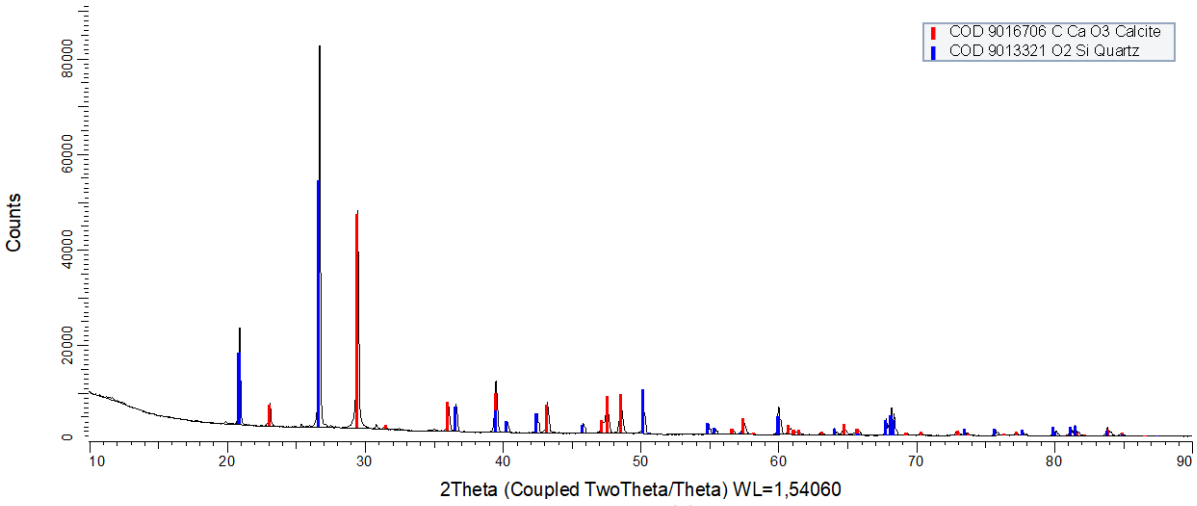

Figure 1. XRD of fine RCA

The granulometric curves of all aggregates are shown in Figure 2. It can be seen that the fine RCA shows higher percentages of fine particles than the siliceous sand.

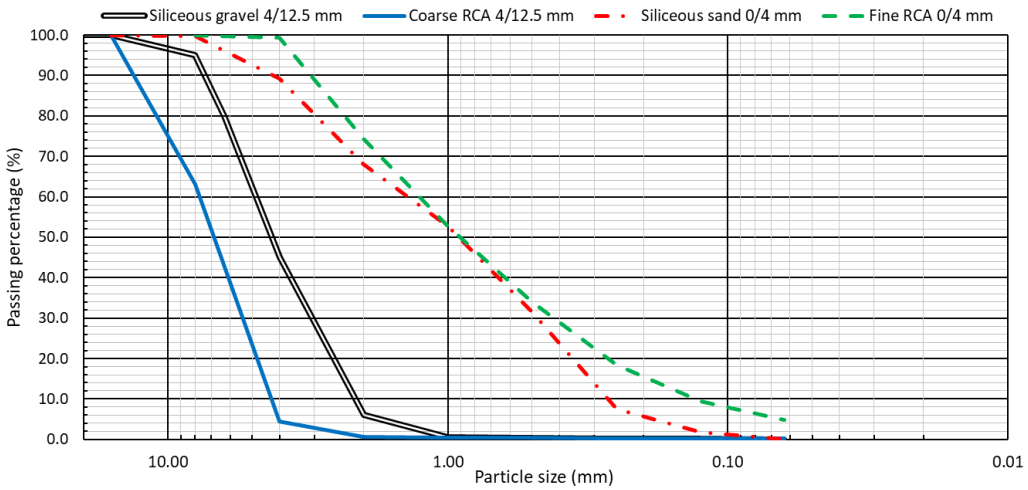

Figure 2. Granulometry of aggregates used

3. Methodology

In this section, the design of the experiment is explained. Firstly, a preliminary analysis is shown to define the coarse RCA content in the mixes. Secondly, the dosage of the SCCs with different percentages of fine RCA are defined. Thirdly, the set of tests performed on the mixes is discussed. Finally, the type of analysis of the experimental data is likewise explained.

3.1. Experiment design

Firstly, a preliminary analysis served to define the amount of coarse RCA to use in the mixes. Based on this analysis, it was decided to use 100 % coarse RCA (see section 3.2). Later, the fine RCA contents (25 %, 50 %, 75 % and 100 %), the set of tests to carry out and the number of samples in each test (application of the power method, with a significance level of 5 % and a power of 20 %) was defined by analyzing other similar research studies [36; 37]. In addition, testing ages were established according to the standards [34; 38; 39], in order to evaluate the effect of fine RCA over time. Therefore, age and fine RCA content were the two factors evaluated in this study.

3.2. Mix design

The dosage of all mixes was defined by the specifications of EHE-08 [34], based on EC2 [39]. The overall particle size was adjusted to the Fuller curve, using the granulometric modules of the aggregates. Rather than the addition of admixtures to the mix design, the water content in the mixtures was carefully increased to achieve a proper self-compactability. That decision was taken to avoid admixture segregation that occurred when its proportion in the mix exceeded 2.2 % of cement mass.

3.2.1. Preliminary analysis

The optimum amount of coarse RCA to be added to the mixtures was decided after a preliminary analysis. Three mixes with 0 %, 50 % and 100 % coarse RCA (labelled C0, C50 and C100 respectively) were used to mold 10x20-cm cylindrical samples (2 samples in each test). Their compositions are shown in Table 3. The compressive strength and the modulus of elasticity of the samples were tested at 7 and 28 days. The results were evaluated with a one-way ANOVA (5 % significance level), which showed no significant differences between the compressive strength and the modulus of elasticity of the mixes with 50 % and 100 % of coarse RCA (Table 4). So, an amount of 100 % of coarse RCA was used in the analysis of the fine RCA mix performance, in order to maximize the sustainability of the SCC designed.

Mix	C0	C50	C100
Cement	300	300	300
Filler	180	180	180
Water	140	155	165
Siliceous gravel 4/12.5 mm	570	285	0
Coarse RCA 0/12.5 mm	0	265	525
Siliceous sand 0/4 mm	1,150	1,150	1,150
Admixture 1	2.20	2.20	2.20
Admixture 2	4.40	4.40	4.40

Table 3. Mix design of the mixes of the preliminary analysis (kg)

		Mixes			One-way ANOVA. Factor analyzed: coarse RCA content	
Test	**Age (days)**	**C0**	**C50**	**C100**	**P-value**	**Homogeneous groups**
Compressive strength (MPa)	7	67.6	57.8	55.7	0.0002	C50 and C100
	28	69.8	61.5	59.3	0.0082	
Modulus of elasticity (GPa)	7	39.7	35.9	34.8	0.0001	
	28	43.4	40.0	39.1	0.0002	

Table 4. Hardened properties (average values) and one-way ANOVA of the preliminary analysis

3.2.2. Mixes with fine RCA

Having defined the reference dosage (100 % coarse RCA and 0 % fine RCA), the siliceous sand 0/4 mm was progressively replaced with fine RCA by volume, in percentages of 25 %, 50 %, 75 %, and finally 100 %. As indicated above, the water content was adjusted to each mix, thereby increasing the water-to-cement (w/c) ratio and the effective w/c ratio, calculated from the water absorption rate over 10 minutes. The values for these ratios and the mix design can be seen in Table 5. The mixes were labelled M0, M25, M50, M75, and M100 depending on the percentage of fine RCA. In this table, the dosage of the mixtures is shown in two different ways. Firstly, in a comparative way, by weight, with respect to the reference mix M0, so that any changes to the fine RCA and the water content may be easily observed. Secondly, the dosage of the mixtures adjusted to 1 m^3 is shown, so that they may be easily

reproduced. Figure 3 shows the overall particle size (corrected by volume) of mixes M0, M50, and M100, and their Fuller curve.

	Comparative dosage with mixture M0 (kg)					Dosage (kg/m^3)				
Mix	**M0**	**M25**	**M50**	**M75**	**M100**	**M0**	**M25**	**M50**	**M75**	**M100**
Cement	300	300	300	300	300	300	295	288	282	276
Filler	180	180	180	180	180	180	176	173	169	166
Water	165	187	205	230	250	165	183	198	215	232
Coarse RCA 0/12.5 mm	525	525	525	525	525	525	518	508	497	487
Fine RCA 0/4 mm	0	265	530	795	1,060	0	260	510	748	977
Siliceous sand 0/4 mm	1,150	865	575	290	0	1,150	850	555	272	0
Admixture 1	2.20	2.20	2.20	2.20	2.20	2.20	2.18	2.14	2.10	2.05
Admixture 2	4.40	4.40	4.40	4.40	4.40	4.40	4.32	4.24	4.15	4.06
Approximate volume (l)	1,000	1,018	1,038	1,060	1,083	1,000	1,000	1,000	1,000	1,000
Approximate weight (kg)	2,327	2,307	2,282	2,262	2,237	2,327	2,289	2,238	2,189	2,144
w/c	0.561	0.624	0.688	0.763	0.839	0.561	0.624	0.688	0.763	0.839
Effective w/c	0.459	0.470	0.482	0.506	0.530	0.459	0.470	0.482	0.506	0.530

Table 5. Mix design.

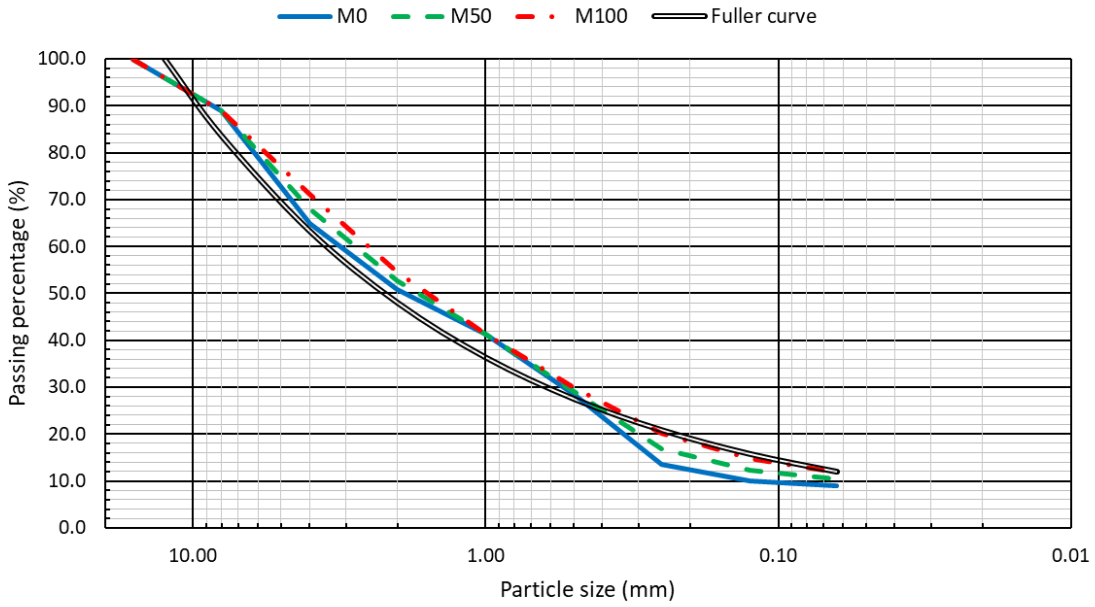

Figure 3. Mix design granulometry.

3.3. Experimental procedure

A three-stage mixing process was performed for proper hydration of all the components, maximization of flowability, and to prevent the absorption of additive into the aggregates [40]. First, coarse RCA and fine fractions (siliceous sand 0/ 4 mm and/or fine RCA) were loaded in the concrete mixer bowl with half of the mix-water and mixed for 30 s. Then, the cement, filler and the rest of the water were added, followed by another 30 s of mixing. Finally, the additive dissolved in 0.2 liters of water was added and mixed for the last 30 s. The aggregates were used under laboratory conditions, at an average

temperature and humidity of 20 ºC and 45 %, respectively, thus adjusting the experimental procedure to the most economically advantageous methodology [41].

Having completed the mixing process, in-fresh state tests, following the EFNARC recommendations, were performed [32] and the specimens were molded to carry out the hardened state tests. The tests, the standards, the age of the test, and the type and the number of test samples at each dosage are summarized in Table 6. The samples were held in a wet chamber at a humidity of 95 ± 5 % and at temperature of 20 ± 2 ºC until the time of the test. In addition, images from a Scanning Electron Microscope (SEM) were used to evaluate the quality of the ITZ in one of the worst performing specimens of mix M75.

Test	Regulations [35]	Test age (days)	Number and type of sample tested per mixture
Slump flow	EN 12350-8	Sample of fresh concrete	
V-funnel	EN 12350-9		
2-bar L-box	EN 12350-10		
Sieve segregation	EN 12350-11		
Fresh density	EN 12350-6		
Air content	EN 12350-7		
Compressive strength	EN 12390-3	1, 7, 28, 90	3 cylindrical samples 10x20 cm at each age
Hammer rebound index	EN 12504-2		2 cylindrical samples 10x20 cm at each age
Ultrasonic Pulse Velocity (UPV)	EN 12504-4		2 prismatic samples 10x10x40 cm at each age
Hardened density	EN 12390-7	28	2 cubic samples 10x10x10 cm
Splitting tensile strength	EN 12390-6	7, 28, 90	2 cylindrical samples 15x30 cm at each age
Flexural strength	EN 12390-5		2 prismatic samples 10x10x40 cm at each age
Static modulus of elasticity and Poisson coefficient	EN 12390-13		3 cylindrical samples 10x20 cm at each age
Stress-strain curves	-	90	2 cylindrical samples 10x20 cm
Abrasion resistance	EN 1340 EN 14157		2 cubic samples 10x10x10 cm

Table 6. Tests, regulations, and samples used for each mix.

The mechanical properties measured by these tests were evaluated both descriptively, which allows visual detection of differences in the behavior of the mixes, and by statistical analysis through one-way ANOVA at a significance level of 5 %. This statistical analysis was to study the effect of each factor (age and fine RCA content) for each mechanical property under study and to establish homogeneous groups, i.e., factor values for which a certain mechanical property is significantly equal.

3.4. Theoretical calculations

The experimental values of each mechanical property were compared with the theoretical values obtained from the formulas of the Spanish structural concrete standard EHE-08 [34], an adaptation of the Eurocode 2 regulation [39], based on the recommendations of the International Federation for Structural Concrete (CEB-FIP) [42].

According to EHE-08 [34], experimental compressive strengths at 28-days can be considered a medium 28-day compressive strength ($f_{c,m}$), with which the characteristic compressive strength ($f_{c,k}$) can be

estimated, according to equation (1). Having done so, the medium tensile strength ($f_{ct,m}$) can be determined, according to equation (2), and the medium flexural strength ($f_{ct,m,fl}$), as a function of the beam height (h) in mm by applying equation (3). These last two strengths were compared with the values of splitting tensile strength and flexural strength, experimentally obtained at 28 days.

$$f_{c,k} = f_{c,m} - 8 \tag{1}$$

$$\begin{Bmatrix} f_{ct,m} = 0.30 \cdot f_{c,k}^{2/3} \; if \; f_{c,k} \leq 50 \; MPa \\ f_{ct,m} = 0.58 \cdot f_{c,k}^{1/2} \; if \; f_{c,k} > 50 \; MPa \end{Bmatrix} \tag{2}$$

$$f_{ct,m,fl} = max\left\{\left(1.6 - \frac{h}{1{,}000}\right) \cdot f_{ct,m}; f_{ct,m}\right\} \tag{3}$$

EHE-08 [34] specifies the formula for estimating the static concrete elasticity modulus at any age, equation (4). The expression contains the following factors: curing time in days (t); the 28-day secant modulus of elasticity ($E_{c,m}$) calculated with equation (5); the medium compressive concrete strength at t days ($f_{c,m}(t)$), obtained with equation (6); and, the secant modulus of elasticity at t days ($E_{c,m}(t)$). The units of strength and the modulus of elasticity in all the expressions can only be introduced in Megapascals (MPa).

$$E_{c,m}(t) = \left(\frac{f_{c,m}(t)}{f_{c,m}}\right)^{0.3} \cdot E_{c,m} \tag{4}$$

$$E_{c,m} = 8{,}500 \cdot \sqrt[3]{f_{c,m}} \tag{5}$$

$$f_{c,m}(t) = exp\left\{0.2 \cdot \left[1 - \left(\frac{28}{t}\right)^{1/2}\right]\right\} \cdot f_{c,m} \tag{6}$$

The structural concrete design guidelines of the American Concrete Institute (ACI) [38] contain formulas, equations (7) and (8), for calculating the tensile strength of concrete and its modulus of elasticity from its compressive strength, respectively. The variables of the equation refer to compressive strength, (f_c), tensile strength, (f_t), and the modulus of elasticity, (E). These expressions are easier to apply than those indicated above, and their validity is also analyzed in this study.

$$f_t = 0.56 \cdot f_c^{0.5} \tag{7}$$

$$E = 4{,}700 \cdot \sqrt{f_c} \tag{8}$$

Simple regression equations are provided, to complement this analysis, which were developed for the mechanical properties (splitting tensile strength, flexural strength, and modulus of elasticity) measured in this study. These formulas can be used as a basis for more general models taken from the literature, for accurate estimation of the properties of SCC made with RCA.

On the other hand, the value of the dynamic modulus of elasticity (E_d) at different ages of curing can be calculated from the test results with equation (9) [33], using the density of the concrete (ρ), the UPV (V_l), and the Poisson coefficient (v). All the above-mentioned properties were precisely established with the tests performed.

$$E_d = \rho \cdot V_l^2 \cdot \frac{(1+\nu)\cdot(1-2\cdot\nu)}{1-\nu} \quad (9)$$

4. Results and discussion

The experimental results of the in-fresh and the hardened states, as well as the theoretical estimation of the mechanical properties from the concrete design standards are presented in this section.

4.1. Fresh properties

It is clear from the bibliography that the addition of RCA clearly reduces the flowability of the SCC, due to its higher water absorption, resulting in a lower effective w/c ratio for any given w/c ratio without RCA [20; 33; 43]. In addition, the crushing process of the RCA produces irregular shapes, which means that the aggregate particles will not flow easily in the paste [44; 45]. Although the effective w/c ratio decreases with the coarse RCA, its irregular shaped particles have the most notable effects [33; 46]. The predominant effect of the fine RCA results from its high level of water absorption that decreases the effective w/c ratio [43]. Regarding the maximum diameter obtained in the slump-flow test, the decrease in initial flowability is as much as 36 % with 100 % coarse RCA and up to 19 % with 100 % fine RCA [43-45].

The adjustment of the water absorbed by the RCA solves the water absorption problem, preventing the effective w/c ratio from decreasing [19; 37]. Another possibility is to increase the proportion of the finest aggregate fraction (<0.125 mm), thereby increasing the volume of paste. Balanced proportions of fine and coarse aggregates are therefore fundamental for good performance of SCC [21].

In the concretes under study, the water content was adjusted by increasing the percentage of fine RCA aggregate, thereby increasing the effective w/c ratio. In addition, that increase of fine RCA aggregate also led to an increase in the fine fraction (<0.125 mm) within the overall granulometry of the mixtures. Both aspects compensated the negative effects of RCA and even improved the slump flow and the passing ability of the SCC. Some of the in-fresh state tests are shown in Figure 4 and their results, presented in Table 7, are consistent with the above-mentioned aspects.

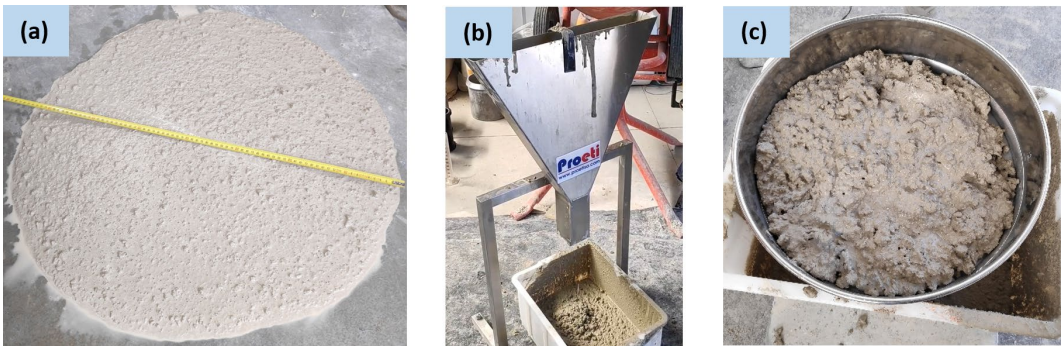

Figure 4. In-fresh state tests for M50 mix. (a) slump-flow; (b) V-funnel; (c) sieve segregation

Test/Mix	M0	M25	M50	M75	M100
Viscosity t_{500} slump flow test (s)	3.40	3.60	4.00	4.20	4.80
Slump flow (mm)	680	695	730	740	755
Viscosity V-funnel test (s)	6.40	8.40	10.20	12.60	15.20
Passing ability L-box test H_2/H_1	0.86	0.88	0.92	0.93	0.94
Sieve segregation (%)	1.70	1.52	1.67	1.53	1.36
Air content (%)	4.80	3.75	4.35	4.00	4.15
Fresh density (Mg/m^3)	2.40	2.31	2.25	2.16	2.12

Table 7. In-fresh state test results

As reported in similar studies [43], the lower density of the RCA, compared to the NA, and the increase in water content decreased the fresh density of the SCC [46; 47]. The air content, very similar in all mixtures, mainly depended on the admixtures and the chemical reactions they produced, with no clear influence of fine RCA.

Based on the results of the in-fresh state tests and the EFNARC recommendations [32], the developed SCCs presented:

- A slump-flow class SF2 (maximum diameter between 660 and 760 mm).
- A viscosity class, according to the slump-flow test, VS2 (time to reach a diameter of 500 mm greater than 2s) and, according to the V-funnel test, VF2 (time to empty the V-funnel greater than 8s), except for the M0 mixture which was class VF1.
- A passing-ability class PA1, according to the 2-bar L-box test (blocking ratio greater than 0.80).
- A segregation-resistance class SR2 (sieve segregation less than 15 %).

The maximum diameter in the slump-flow test increased by 11 % (from 680 mm for M0 to 752 mm for M100), following the addition of 100 % fine RCA, which in turn increased the effective w/c ratio by 15 % (from 0.46 to 0.53). In this case, the passing ability was also increased by 9 % (from 0.86 to 0.94). The fines content of the mix M25 influenced the flowability of the SCC. A fine RCA content of 25 % and an effective w/c ratio of 0.47, slightly higher than 0.46 (corresponding to mix M0), led to a higher slump flow and passing ability. However, it was not possible to compensate all the negative effects of RCA by increasing the proportion of water and fines, as viscosity was negatively affected, resulting in higher slump-flow viscosity and emptying times (V-funnel test). This performance can be explained by two

aspects: the irregular shapes of the coarser fine RCA particles that move more slowly within the cement paste than the rounded siliceous sand particles; and the higher proportion of cement paste, resulting from the increased volumes of fines, following the addition of RCA, leaving the SCC with a more viscous consistency.

Resistance to segregation was not negatively affected by the addition of fine RCA and was even improved by the increase of the fine RCA content. In fact, the sieve segregation of the mixture M100 (1.36 %) was 25 % lower than that of the mixture M0 (1.70 %). Even though fine RCA had a higher content of particles smaller than NA (≤0.125 mm), the use of fine RCA produced higher long-term water absorption levels that reduced segregation.

4.2. Hardened state behavior

The analysis of the mechanical properties aims to evaluate the effect of fine RCA on the development of strength at different curing ages. Some of these tests, such as for splitting tensile strength, flexural strength, and modulus of elasticity, are shown in Figure 5.

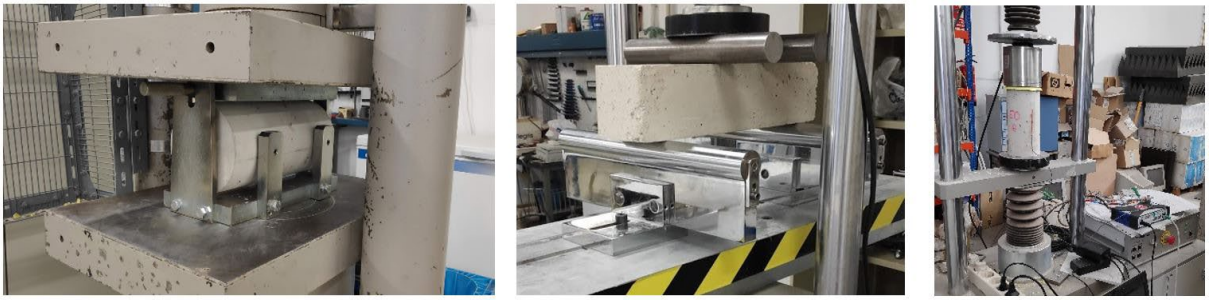

Figure 5. Mechanical tests: splitting tensile strength (left); flexural strength (middle); modulus of elasticity (right)

4.2.1. Density

The lower density of RCA compared to NA reduced the hardened density of the SCC, as the RCA content increased (Table 8), in line with the existing bibliography [33; 37; 48]. The decrease of the hardened density compared to the fresh density showed no clear trends, although it was higher in the mixtures with a higher NA content (mixture M0 showed a decrease of 4.2 %, while this decrease for mixture M50 was only 0.4 %), which may be due to the lower water evaporation, because of the higher water absorption of fine RCA [33].

Test/Mix	M0	M25	M50	M75	M100
Hardened density (Mg/m^3)	2.30	2.29	2.24	2.13	2.10
Decrease with respect to its fresh density (%)	4.2	0.9	0.4	1.4	1.0
Decrease with respect to the M0 density (%)	0	0.4	2.6	7.4	8.7

Table 8. Hardened density of the mixes

4.2.2. Compressive strength, UPV, and hammer rebound index

The addition of coarse RCA is known to reduce the compressive strength of concrete [49], although reductions of just 5 MPa for 100 % coarse RCA content were obtained in some studies [45; 50]. The reduction was higher when fine RCA was added [36], and in some studies the decrease caused by 100 % fine RCA in SCC reached 26 % compared to the reference concrete (0 % coarse and fine RCA) [20; 51]. Nevertheless, if the effective w/c ratio is reduced, the loss of strength can be compensated, especially when only coarse RCA is used [33; 46]. In the present study, as expected, the compressive strengths of the concretes under study decreased as their fine RCA content increased and with it, the w/c ratio (Table 5), as shown in Figure 6. At 28 days, the decrease in strength, with regard to the reference mixture M0 (60 MPa), was 7 % for mixture M25 (56 MPa), 27 % for mixture M50 (44 MPa), and 47 % and 51 % for mixtures M75 and M100, respectively (strengths of 31 and 30 MPa). Regarding the overall trend, mixture M25 showed a much lower than expected strength decrease, possibly due to its very similar effective w/c ratio to mix M0.

The compressive strength results showed less dispersion with higher additions of fine RCA content, although that dispersion increased at advanced ages. The strengths of the mixtures with high RCA contents were more closely limited at early ages.

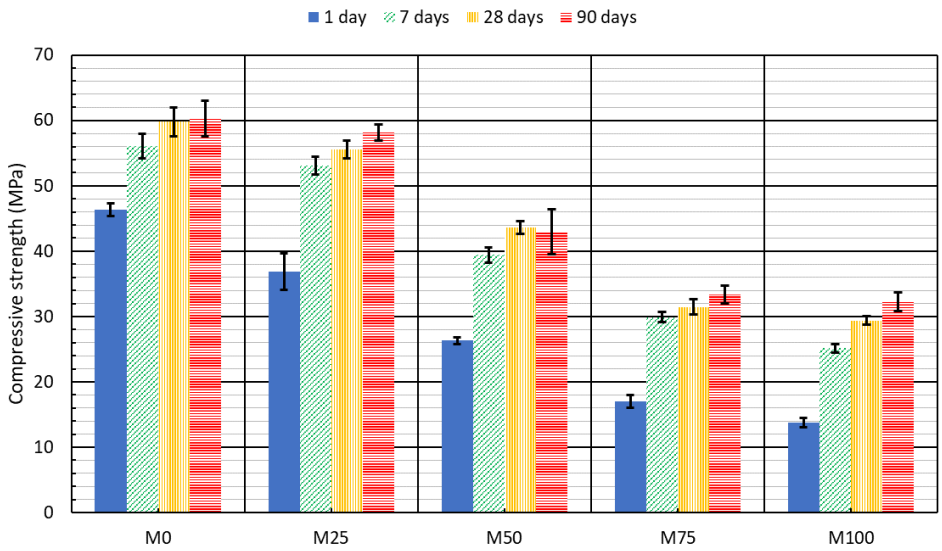

Figure 6. Compressive strength of the SSC mixtures

The compressive strength developed at 1 and 7 days, with regard to the strength at 28 days, were in percentage terms 78 % and 94 % for the reference mix, M0; 60 % and 90 % for M50; and 47 % and 86 % for M100. Strength development, in percentage terms, was slower as the fine RCA content increased.

The UPV and the hammer rebound tests, two conventional methods for estimating the compressive strength of non-recycled concrete, were measured at all ages. Pearson's symmetrical correlation matrix between these three properties for all mixtures and ages simultaneously is shown in Figure 7. A clear linear relationship between these variables can be observed, as in other similar studies [28; 52], although an individual analysis carried out in each mix showed that the exponential model had the best overall fit. Table 9 shows the least square exponential adjustment of compressive strength (variable "y") as a function of the UPV (variable "x") and the hammer rebound index (variable "z"). The adjustment had a coefficient R^2 higher than 0.90 in 80 % of the cases. Mixture M100 had the coefficients R^2 closest to 1.00. The validity of these indirect measures was not influenced by the addition of RCA. Figure 8 and Figure 9 show this adjustment for each mixture and it may be noted that the increase in RCA content increased the curvature of the models.

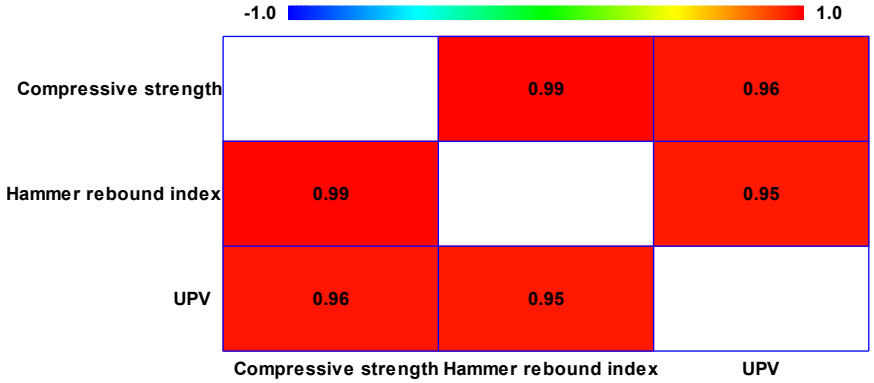

Figure 7. Pearson's symmetrical correlation matrix for compressive strength, hammer rebound index and UPV

Test/Mix		M0	M25	M50	M75	M100
UPV (km/s)	1 day	3.94	3.76	3.73	3.27	3.19
	7days	4.28	4.00	4.03	3.63	3.68
	28 days	4.32	4.20	4.09	3.80	3.71
	90 days	4.34	4.30	4.09	3.79	3.71
Exponential adjustment: compressive strength-UPV		y=3.666· exp(0.643x)	y=1.854· exp(0.811x)	y=0.155· exp(1.376x)	y=0.312· exp(1.232x)	y=0.130· exp(1.461x)
Coefficient R^2 UPV		**0.96**	**0.87**	**0.99**	**0.95**	**0.98**
Hammer rebound index	1 day	46	40	34	27	24
	7days	56	52	42	33	33
	28 days	58	54	42	39	37
	90 days	58	56	45	39	40
Exponential adjustment: compressive strength- hammer rebound index		y=17.443· exp(0.021z)	y=11.669· exp(0.029z)	y=5.236· exp(0.048z)	y=4.804· exp(0.050z)	y=3.871· exp(0.054z)
Coefficient R^2 hammer rebound index		**0.98**	**0.99**	**0.92**	**0.85**	**0.98**

Table 9. Exponential adjustment between UPV and hammer rebound index and compressive strength

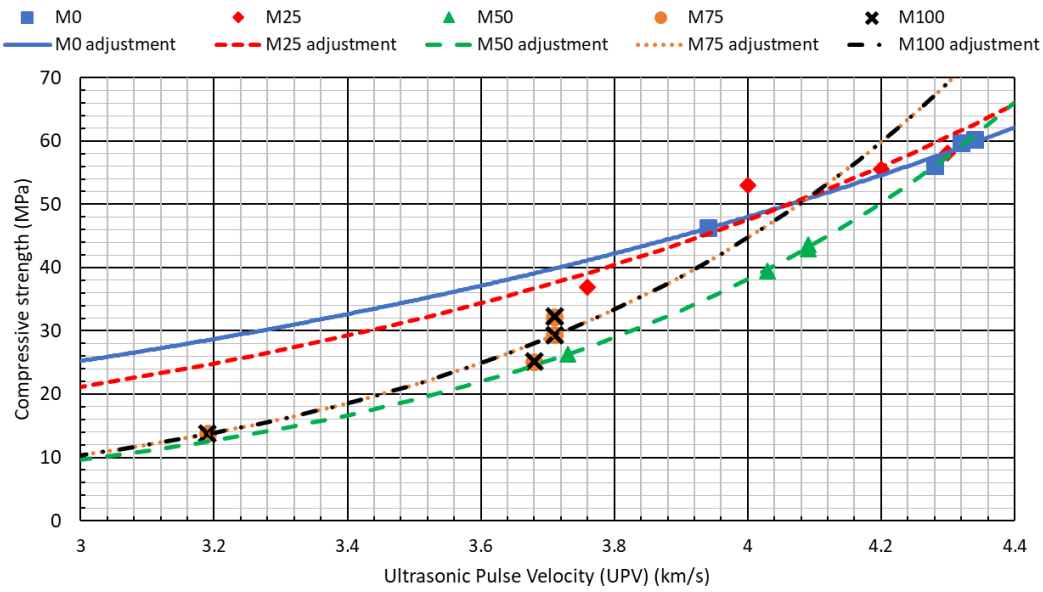

Figure 8. Adjustment of the compressive strength as a function of the UPV

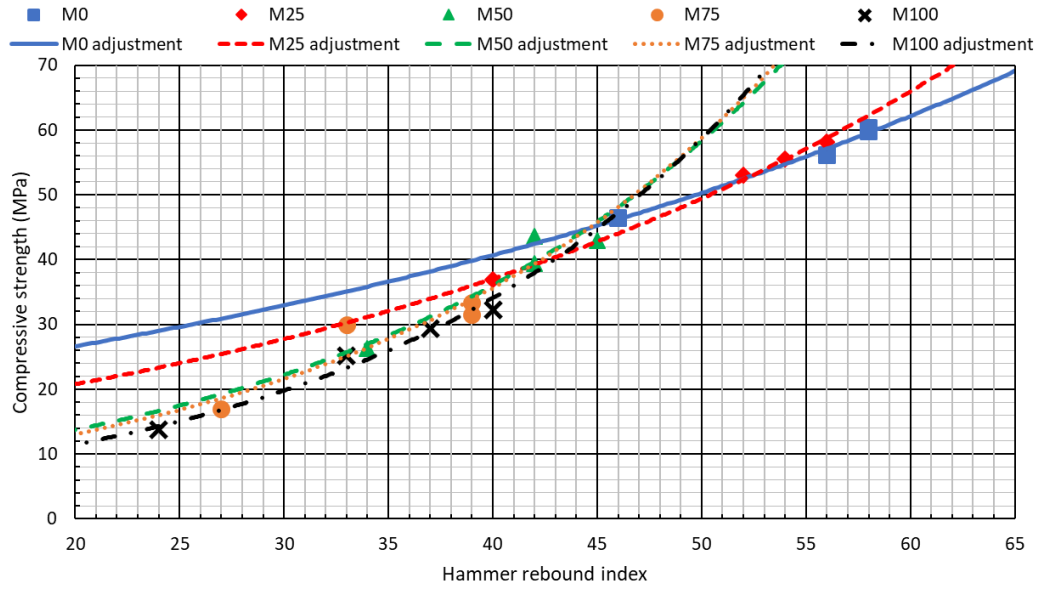

Figure 9. Adjustment of the compressive strength as a function of the hammer rebound index

4.2.3. Splitting tensile strength and flexural strength

The results, obtained at 7, 28, and 90 days, showed that the addition of fine RCA decreased both the splitting tensile strength (Figure 10) and the flexural strength (Figure 11), a widely reported behavior in the literature [33; 37; 51]. The harmful effect of fine RCA can be compensated and if the dosage is correctly modified, it is possible to obtain a splitting tensile strength equal to that of the reference concrete [27]: reducing the water content, increasing the cement content, or using alternative binders such as fly ash or silica fume [53; 54].

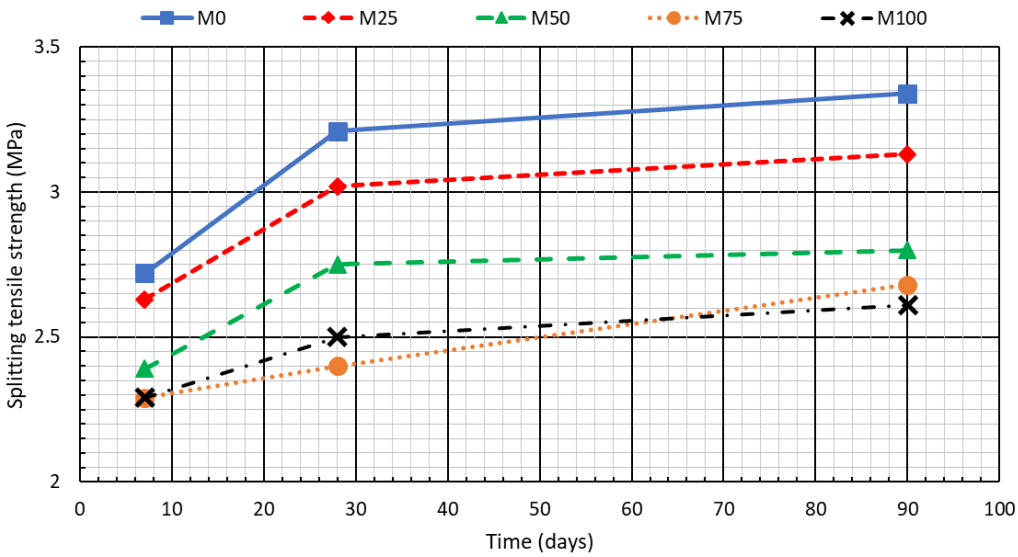

Figure 10. Splitting tensile strength

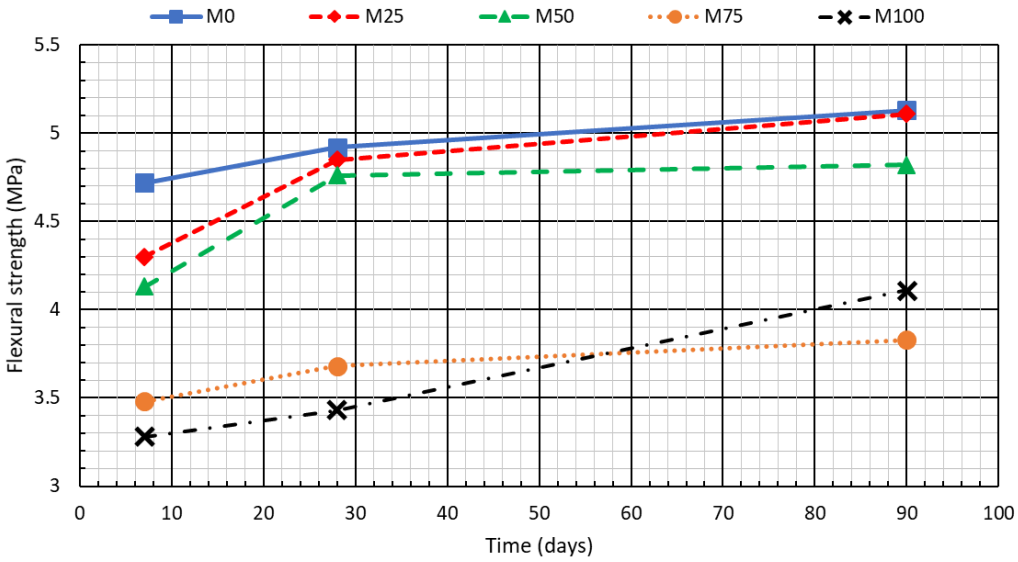

Figure 11. Flexural strength

In this study, the decrease was mainly observed for the flexural strength, with different behavior in two groups (fine RCA up to 50 % and above 50 %). Compared to M0, the decrease of the flexural strength at 28 days of the mixture M100 was 30 % (3.4 versus 4.9 MPa) and was only 22 % for the splitting tensile strength (2.5 versus 3.2 MPa). However, there were some exceptions, such as the higher flexural strength of mix M100 compared to M75 at 90 days, due to the low adhesion between the cement paste and the coarse aggregate, in the mixes with high fine RCA content. It was observed that high additions of fine RCA also favored a more uniform strength over time, and a less predictable behavior.

Some studies have shown that the theoretical tensile strength value, calculated according to the EC2 [39], was lower than the experimental value in SCC made with coarse RCA, whilst the experimental

value was overestimated in SCCs with high fine RCA content [37]. The theoretical tensile strength values as per EHE-08 [34], shown in Figure 12 and calculated with equation (2), were higher than the experimentally obtained results for all the mixtures in this study, although the adjustment was improved by increasing the fine RCA content (the experimental tensile strength of M100 was higher than the theoretical value). In relation to the values estimated with equation (7) from the ACI [38], it can be observed that the theoretically calculated values also overestimated the results. The SCCs with the highest fine RCA content were those that showed the least difference between both values: in M0, the theoretical value at 28 days (4.3 MPa) was 34 % higher than the experimental value (3.2 MPa), while this overestimation in the mixture M100 was only 20 % (3.0 versus 2.5 MPa). As the increase in compressive strength after 7 days was higher than the increase in splitting tensile strength, the adjustment was better for advanced ages. Similarly, the design values of flexural strength (Figure 13) also overestimated the experimental values, once again with a better fit as fine RCA was added. From all the above, it can be deduced that both the splitting tensile strength and the flexural strength were, in general, lower than expected, especially in the case of concretes with few recycled fines. The use of the equations from the standards applied to the test mixtures would imply strength overestimations of around 25 %, especially with fine RCA contents up to 50 %.

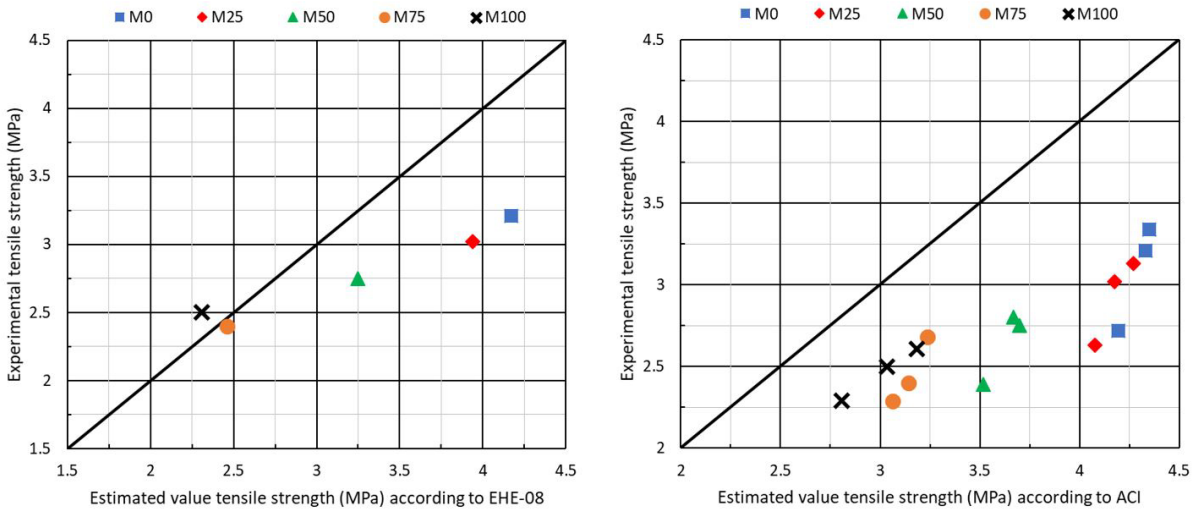

Figure 12. Relationship between the experimental tensile strength and the estimated value as per EHE-08 (left) and ACI (right)

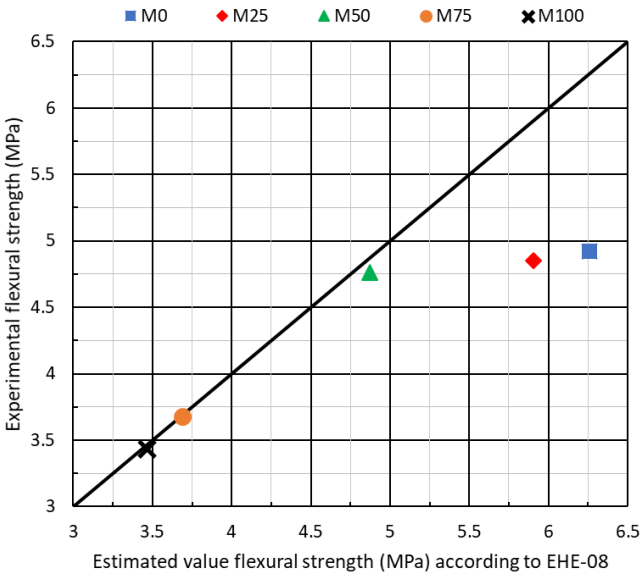

Figure 13. Relationship between the experimental flexural strength and the estimated value as per EHE-08

The standard formulas [34; 38] relate both tensile strength and flexural strength to compressive strength by means of a square or cubic root. Nevertheless, the best-fit model (coefficient R^2 of 0.86) of the splitting tensile strength (*STS*, in MPa) as a function of compressive strength (*CS*, in MPa), shown in equation (10), established a polynomial relationship between both variables. In contrast, the flexural strength (*FS*, in MPa), equation (11), with a coefficient R^2 of 0.88, has an inverse relationship with the compressive strength.

$$STS = 8.46 - 0.79 \cdot CS + 0.04 \cdot CS^2 \quad (10)$$

$$FS = \left(2.55 - \frac{19.26}{CS}\right)^2 \quad (11)$$

4.2.4. Static modulus of elasticity and Poisson coefficient

The presence of adhered mortar and the ITZs, which were weak and not very dense, meant that the SCC with RCA was, in general, more deformable than the SCC with NA [25; 33], observations supported by the results from this study that are shown in Figure 14. A higher fine RCA content led to a lower modulus of elasticity at all ages: at 28 days, M100 presented a modulus of elasticity of 18.8 GPa, 54 % lower than the mix M0 (40.6 GPa). The addition of 100 % fine RCA to an SCC with 100 % coarse RCA, as performed in this study, led to a greater decrease in the modulus of elasticity than when this amount of fine RCA is added to an SCC with no coarse RCA, which is around 24 % [37; 51].

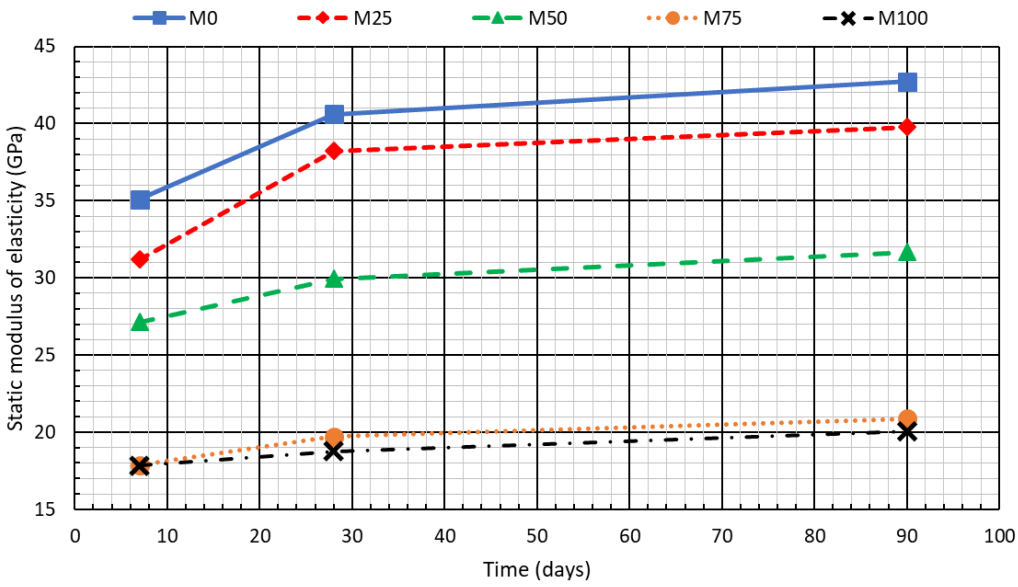

Figure 14. Static modulus of elasticity

The trends for the modulus of elasticity over the curing, once again showed a different behavior between the mixtures with low/medium percentages and those with high percentages of fine RCA: the mixtures with low percentages of fine RCA (M0 and M25) showed a very marked increase in the modulus of elasticity up to 28 days, while the increase in concretes with higher contents (M75 and M100) was practically uniform over time.

The adjustment of the theoretical values, obtained with equation (4), to the experimental values was quite poor (Figure 15). In mixtures with low percentages of fine RCA (M0 and M25), the design values were lower than the experimental values (at 28 days, the design value of mixture M25 was 32.4 GPa, 15 % lower than the experimental value, 38.2 GPa). The theoretical expressions overestimated the modulus of elasticity in the mixtures with high contents of fine RCA (M75 and M100), by approximately 40 % at all ages of curing. Mixture M50 was in an intermediate situation: its theoretical value at 7 days (28.2 GPa) was higher than the experimental value (29.9 GPa), with the opposite situation at 90 days (theoretical value of 30.7 GPa and experimental value of 31.7 GPa). The same situation was observed for the ACI [38] formula, once again showing that mixture M50 had the best fit. These results are in line with the conclusions of other studies, which also showed that the theoretical expressions underestimated the modulus of elasticity in SCCs with low percentages of RCA and overestimated it in mixtures with high percentages of RCA [37; 55].

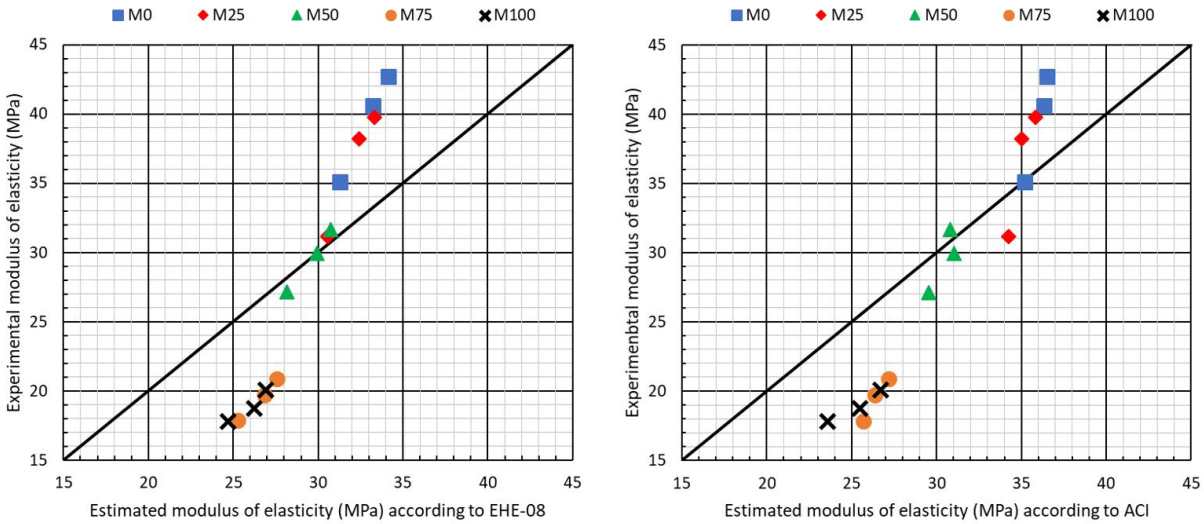

Figure 15. Relationship between compressive strength and modulus of elasticity according to EHE-08 (left) and ACI (right)

Equation (12) shows that there is an exponential relationship between the modulus of elasticity (*ME*, in GPa) and the logarithm of compressive strength (*CS*, in MPa), similar to that shown by EHE-08 [34] in equation (6). Its coefficient R^2 is 0.96.

$$ME = exp\left(-0.62 + 1.05 \cdot ln(CS)\right) \quad (12)$$

Increasing percentages of fine RCA increased both the deformability of the concrete in the load direction and the volume variation under load, as shown by the lower Poisson coefficient (Figure 16) of the concrete with additions of fine RCA: after 28 days, the difference of the Poisson coefficient between mixtures M0 (0.20) and M100 (0.16) was 19 %. This trend was similar to the one obtained in vibrated concretes with only coarse RCA [56; 57], although a constant w/c ratio appeared to prevent the Poisson coefficient from decreasing [58]. The temporal evolution of this coefficient was similar in all the mixtures: a marked decrease in the first days, less noticeable as time goes by, although M100 showed a much more remarkable decrease after 28 days than the rest of the mixtures. The conventional value of the Poisson coefficient for concrete (0.2) was higher than the experimental values, except for concretes with less than 50 % fine RCA at 7 days, that had slightly higher experimental values.

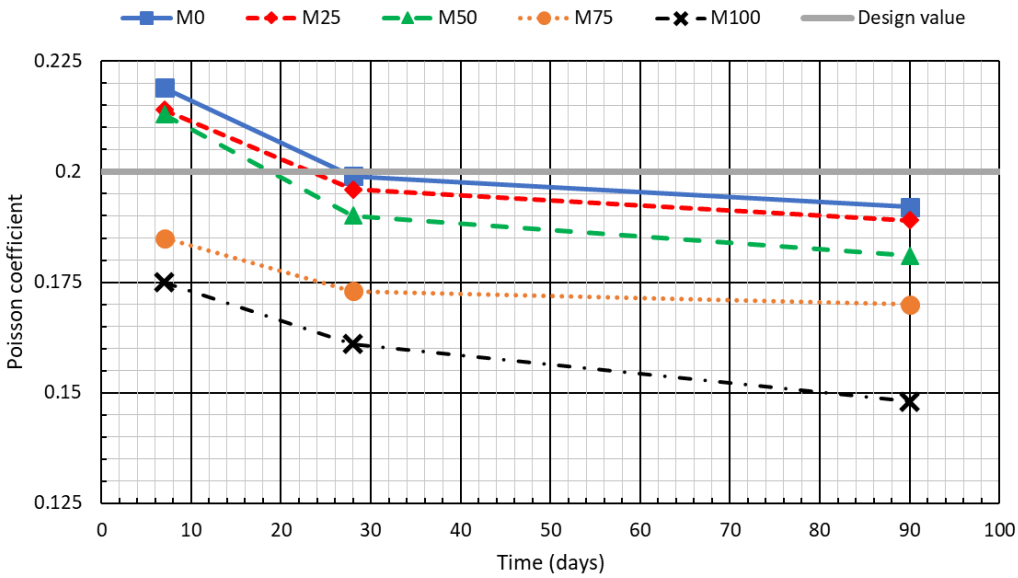

Figure 16. Poisson coefficient

4.2.5. Stress-strain curves

The stress-strain curves that are used to evaluate the plastic behavior of concrete usually show an elastic behavior at low load levels and reduced fracture strain values (theoretical value of 3,500 µm/m) [34; 38; 39]. Higher fines contents will usually result in higher strain values after the ultimate strength value of the concrete is reached [59]. When this aspect was addressed in recycled concrete, it was concluded that coarse RCA reduced fracture strain [60]. No reference to this behavior was found for SCCs made with coarse and fine RCA, such as those reported in this article. Cylindrical specimens of 10 and 20 cm in diameter and height, respectively, were subjected to compressive strength tests until failure at 90 days, yielding the curves shown in Figure 17. The stress and strain values were recorded at a frequency of 15 Hz.

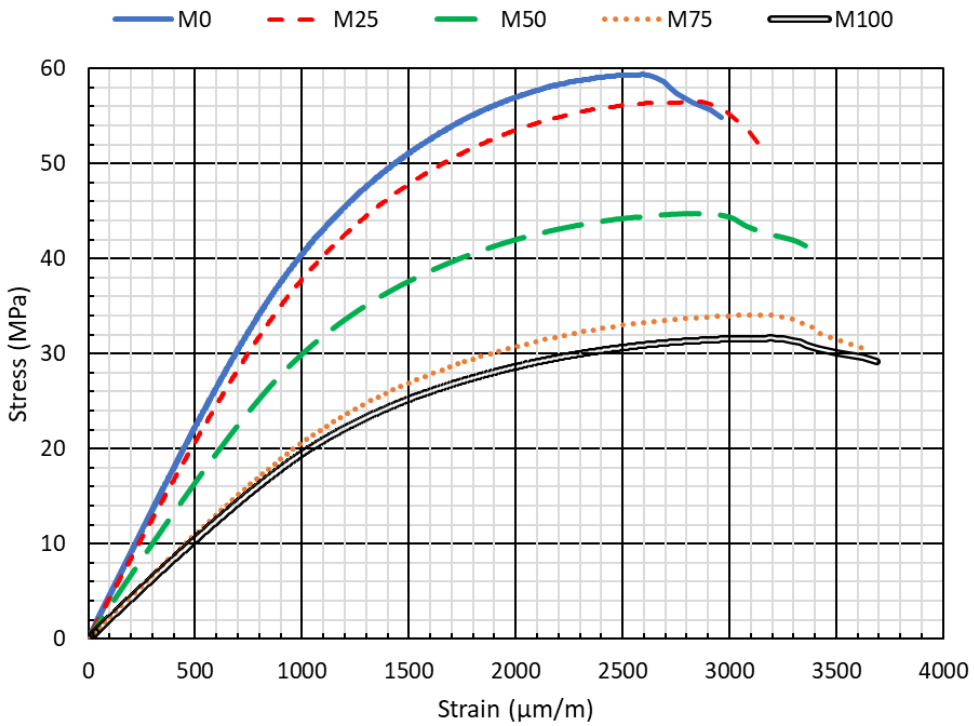

Figure 17. Stress-strain curves of the mixtures

The stress-strain curves reflected the decrease, both in compressive strength (ultimate strength) and in the modulus of elasticity, as the fine RCA content increased, as previously discussed (section 4.2.2). Other relevant aspects of the structural design with this type of concrete are:

- The proportional limit (the point where linear elastic strain ends) was produced for a deformation of 720 µm/m for M0 and 580 µm/m for M100, increasing the plastic deformation with the fine RCA content.
- An increase in the fine RCA content led to a higher fracture strain: mixtures M0 and M25 showed strain values that were 18.9 % lower than mixtures M75 and M100 (3,000 µm/m versus 3,700 µm/m). The strain values of mixture M50 (3,300 µm/m) were the closest to the theoretical value. Thus, the mixtures with higher fine RCA contents presented higher safety design coefficients, as they exceeded the theoretical values calculated with the formulas from the standards. This behavior was contrary to the one observed when only coarse RCA was added [60].
- The strain values corresponding to the ultimate strength increased with higher contents of fine RCA in the mixtures (2,650 µm/m for mixture M0 and 3,250 µm/m for mixture M100). The ratios between the fracture strain and peak strain for mixtures M0 and M100 were 1.16 and 1.13, respectively, and the remaining strain after breakage increased in SCCs with low fine RCA contents. The reference specimen, mixture M0, showed the highest safety factor after failure.

4.2.6. Dynamic modulus of elasticity through the UPV

The dynamic modulus of elasticity decreased with the addition of fine RCA. According to other studies, in mixtures with 50 % coarse RCA, the decrease was approximately 4 %, reaching 9 % for 100 % replacements [33; 61]. No other study has been found in which this property is evaluated in SCCs with fine RCA. The results of this study (Figure 18) showed the same overall trend as the static modulus of elasticity (Figure 14), both in terms of fine RCA content and its temporal evolution. The results for all properties based on the calculation of this modulus of elasticity, according to equation (9), were consistent with each other.

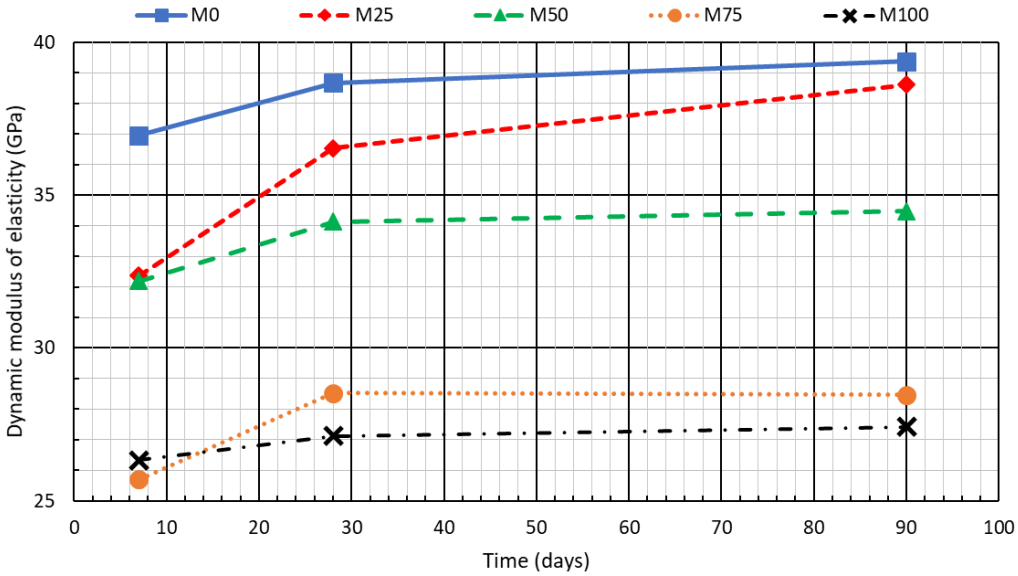

Figure 18. Dynamic modulus of elasticity through the UPV

Two groups of concretes may be distinguished: high and low/medium fine RCA content. Mixtures with fine RCA content of less than 50 % had a lower dynamic modulus of elasticity through the UPV than the static modulus of elasticity (e.g. the values of the static and dynamic modulus of elasticity of M25 at 28 days were 38.2 and 36.5 GPa respectively). Meanwhile mixtures M75 and M100 showed higher stiffness under dynamic loading: the dynamic modulus of elasticity through the UPV of mixture M100, at 28 days, was 44.1 % higher than the static modulus of elasticity (27.1 GPa versus 20.1 GPa).

4.2.7. Abrasion resistance

Resistance to abrasion was evaluated by the footprint caused by an abrasive disc on the surface of the material on cubic samples of 10x10x10 cm at 90 days (Figure 19), which measures the hardness of the surface cement paste [62]. According to other studies, the addition of fine RCA increased the size of the footprint [63]. Nevertheless, the use of RCA from a concrete with a strength of over 70 MPa can improve the surface resistance of the concrete [64].

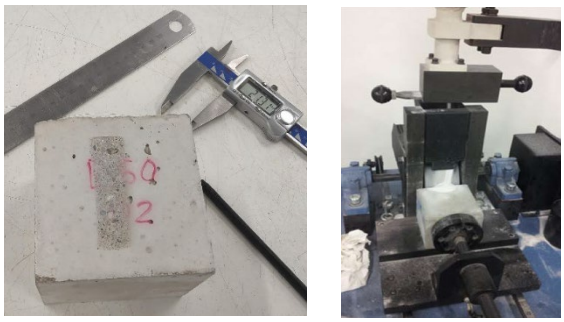

Figure 19. Abrasion test. Left: footprint on the M50 mix. Right: sample set up in the testing machine

In this research, the increase in fine RCA generated a cement paste with a lower surface hardness, which increased the footprint size, as shown in Figure 20. These results were in line with the results of the 90-day rebound index: a higher rebound index was produced in those mixtures with a smaller footprint width (mix M75 had a lower rebound index, 39, and a footprint size of 21 mm that was 27.3 % larger than the M0 footprint). Once again, there were two different groups of concretes, according to the results of this test: high and low/medium fine RCA content.

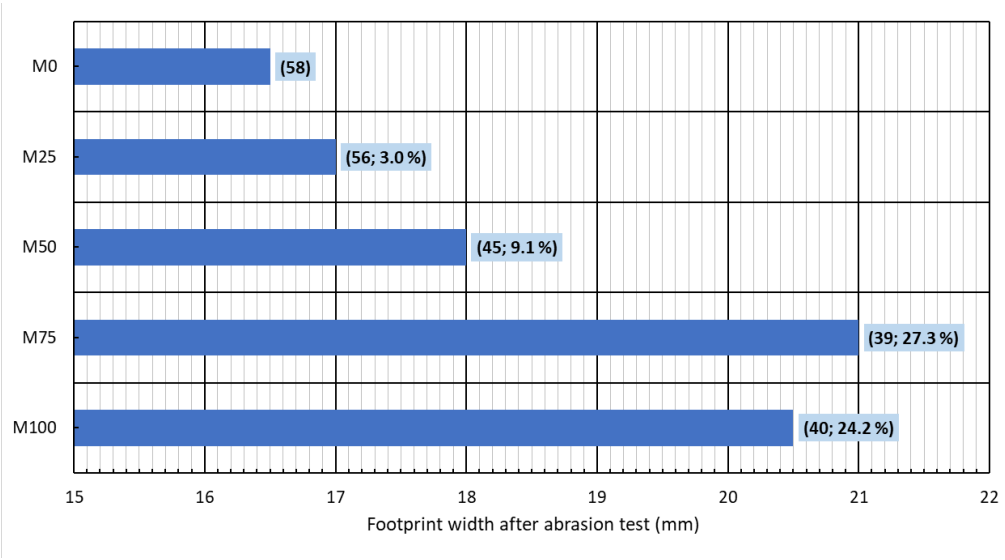

Figure 20. Resistance to abrasion test results. The hammer rebound index and the increase in footprint size, in relation to mixture M0, are shown between brackets.

4.2.8. Statistical analysis of mechanical properties

The descriptive analysis was completed with a statistical analysis based on one-way ANOVA (Table 10). It showed that both age and fine RCA content significantly influenced the behavior of the mixes in all tests (p-value lower than the significance level considered, 0.05). The homogeneous groups revealed that, in general, mixes M0 and M25, as well as M75 and M100, have no significant difference in their mechanical properties regardless the age. In contrast, the mechanical properties of mixes with low fine RCA contents (M0 and M25) hardly showed significant variations between 28 and 90 days, while the mechanical properties of mixes M75 and M100, at 7, 28 and 90 days, can be considered statistically equal in several tests. Mix M50 showed an intermediate behavior.

Test	Factor	Condition	P-value	Homogeneous groups
Compressive strength	**Fine RCA percentage**	Age of 1 day	0.0001	M75 and M100
		Age of 7 days	0.0001	M0 and M25; M75 and M100
		Age of 28 days	0.0002	M0 and M25; M75 and M100
		Age of 90 days	0.0001	M0 and M25; M75 and M100
	Age	0 % fine RCA	0.0007	7, 28 and 90 days
		25 % fine RCA	0.0003	7, 28 and 90 days
		50 % fine RCA	0.0001	7, 28 and 90 days
		75 % fine RCA	0.0002	7, 28 and 90 days
		100 % fine RCA	0.0001	28 and 90 days
Splitting tensile strength	**Fine RCA percentage**	Age of 7 days	0.0017	M0 and M25; M50, M75 and M100
		Age of 28 days	0.0233	M75 and M100
		Age of 90 days	0.0282	M75 and M100
	Age	0 % fine RCA	0.0370	**None**
		25 % fine RCA	0.0230	**None**
		50 % fine RCA	0.0239	28 and 90 days
		75 % fine RCA	0.0351	7 and 28 days
		100 % fine RCA	0.0349	28 and 90 days
Flexural strength	**Fine RCA percentage**	Age of 7 days	0.0173	M25 and M50; M75 and M100
		Age of 28 days	0.038	M0, M25 and M50; M75 and M100
		Age of 90 days	0.017	M0 and M25
	Age	0 % fine RCA	0.0001	28 and 90 days
		25 % fine RCA	0.0004	28 and 90 days
		50 % fine RCA	0.0001	28 and 90 days
		75 % fine RCA	0.0003	7, 28 days and 90 days
		100 % fine RCA	0.0015	7 and 28 days
Static modulus of elasticity	**Fine RCA percentage**	Age of 7 days	0.0002	M75 and M100
		Age of 28 days	0.0001	M0 y M25; M75 y M100
		Age of 90 days	0.0002	M0 y M25; M75 y M100
	Age	0 % fine RCA	0.0260	28 and 90 days
		25 % fine RCA	0.0173	28 and 90 days
		50 % fine RCA	0.0104	28 and 90 days
		75 % fine RCA	0.0256	7, 28 and 90 days
		100 % fine RCA	0.0394	7, 28 and 90 days
Poisson coefficient	**Fine RCA percentage**	Age of 7 days	0.0083	M25 and M50
		Age of 28 days	0.0158	M0 and M25
		Age of 90 days	0.0118	M0 and M25
	Age	0 % fine RCA	0.0285	**None**
		25 % fine RCA	0.0327	**None**
		50 % fine RCA	0.0211	**None**
		75 % fine RCA	0.0441	28 and 90 days
		100 % fine RCA	0.0303	**None**
Dynamic modulus of elasticity through the UPV	**Fine RCA percentage**	Age of 7 days	0.0023	M25 and M50; M75 and M100
		Age of 28 days	0.0016	M75 and M100
		Age of 90 days	0.0010	M0 y M25; M75 y M100
	Age	0 % fine RCA	0.0344	28 and 90 days
		25 % fine RCA	0.0465	**None**
		50 % fine RCA	0.0351	28 and 90 days
		75 % fine RCA	0.0222	28 and 90 days
		100 % fine RCA	0.0455	7, 28 and 90 days
Abrasion resistance	**Fine RCA percentage**	Age of 90 days	0.0043	M0, M25 and M50; M75 and M100

Table 10. One-way ANOVA of mechanical properties

4.2.9. SEM analysis

As commented in the introduction, the presence of adhered mortar in the RCA leads to the formation of an ITZ that is less dense and of poorer quality than the ITZ between the NA and the cementitious

matrix [22; 25], as may be observed in the image of Figure 21, obtained from a low-strength M75 test specimen. In this image, two particles of siliceous aggregate of the RCA can be seen in both the lower right and left-hand-side corners; the old cementitious matrix (mortar adhered to the NA) of a darker color in the central part, corroborated by the microanalysis spectrum; and, the new cementitious matrix of a lighter color on the right-hand side and towards the upper right-hand-side corner. It is clear that the ITZ has failed due to its poor quality; the new cement paste shows low adhesion to the RCA, both with the mortar phase and the siliceous aggregate phase. This poor behavior of the ITZ, when adding large quantities of fine RCA, explained the variable behavior of the mixtures with high contents of fine RCA, especially in relation to the splitting tensile strength and the flexural strength.

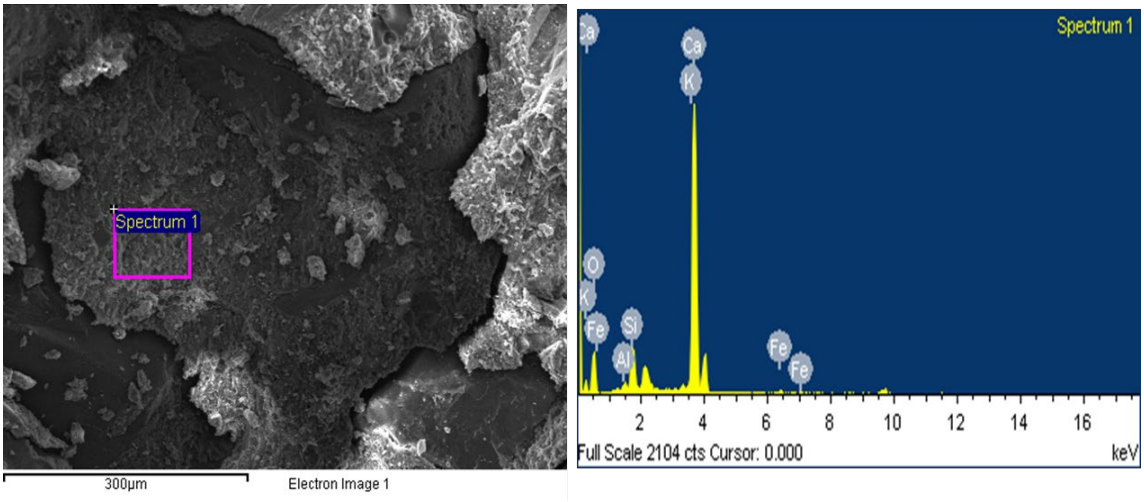

Figure 21. SEM analysis of mix SA75

5. Conclusions

In this study, the physical and mechanical behavior, at different curing ages, of a Self-Compacting Concrete (SCC) manufactured with coarse and fine Recycled Concrete Aggregate (RCA) has been studied. A preliminary statistical analysis showed an acceptable mechanical behavior of the concretes manufactured with 100 % of coarse RCA. Therefore, SCCs with 100 % RCA in the coarse fraction and different percentages (0 %, 25 %, 50 %, 75 % and 100 %) of fine RCA in substitution of Natural Aggregate (NA), 0/4 mm, were performed. The conclusions relating to the effect of the incorporation of fine RCA on these recycled SSCs are set out below:

- Increasing the mix water according to RCA water absorption was insufficient to maintain the flowability of the SCC manufactured with NA 0/4 mm when fine RCA was added. Instead, the effective water/cement ratio had to be increased. The increase in the fines content of the RCA, in comparison with NA, was favorable in the slump-flow test and the passing ability.

- All developed recycled SCCs had fresh property values within the limits of the EFNARC recommendations [32]. SCC were obtained in slump-flow class SF2, viscosity class VS2 and VF2, passage ability class PA1, and resistance to segregation class SR2.
- The mechanical properties of the SCC worsened as the percentage of fine RCA increased at all ages of curing. On the one hand, fine RCA contents of 0 % and 25 % allowed to obtain compressive strengths above 50 MPa (high strength concrete). On the other hand, the SCC with a high content of fine RCA (75 % and 100 %) showed a worsening of their mechanical properties with compressive strengths below 35 MPa. The one-way ANOVA showed that there was no significant difference between the mechanical properties for mixes with fine RCA percentages of 0 % and 25 %, and for 75 % and 100 %.
- The stress-strain curves showed that the mixtures with 75 and 100 % fine RCA were much more deformable, with fracture strains of 3.7 ‰, 18.9 % higher than the fracture strain of the mixture with 0 % fine RCA, which had a value of 3 ‰.
- In general, recycled SSCs with high fine RCA contents showed more uniform mechanical properties over time than those with less fine RCA. According to one-way ANOVA, mixes with 0 % and 25 % of fine RCA showed the same strength and stiffness values at 28 and 90 days, meanwhile mixes with 75 % and 100 % of fine RCA had the same values at 7, 28, and 90 days.
- The adjustment of the experimental values to the theoretical design values provided by the regulations was different for each property and each recycled SCC. The theoretical values of tensile strength were higher than the experimental values, both from the European standard [34; 39; 42] and the ACI regulations [38], a fit that was improved by increasing the fine RCA content. The theoretical modulus of elasticity, calculated with both the European and the USA standard, underestimated the experimental value in mixtures with up to 25 % fine RCA, while the modulus of elasticity was overestimated by percentages greater than 75 %.
- Indirect measurements, such as the Ultrasonic Pulse Velocity (UPV) and the hammer rebound index yielded accurate compressive strength estimates for the concretes under analysis, with the most linear adjustment for the mixtures with low contents of fine RCA. The best statistical adjustment was obtained for the mixture with 100 % fine and coarse RCA.

In view of the above, SCC of optimum flowability and with adequate mechanical behavior can be produced using high RCA contents in such a way that the SCC is valid for use in structural components. In the present study, the combination of 100 % coarse RCA and a 50 % fine RCA was the limit value, after which a notable worsening of the mechanical properties ensued, suggesting that the use of a fine RCA content higher than 50 % in structural concretes would not be advisable in structural applications from a mechanical point of view. Nevertheless, when service requirements are considered, the higher

deformability of the SCC due to higher fine RCA contents, shown in the stress-strain curves, is a good reason for limiting the content of fine RCA to 25 %.

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Conflict of interest

The authors declare that there is no conflict of interest

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