The influence of recycled aggregates from precast elements on the mechanical properties of structural self-compacting concrete

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Abstract

Recycled Aggregates (RA) from structural precast elements and the performance of Self-Compacting Concrete (SCC) containing RA in percentage substitutions of 20%, 50% and 100% are described in this paper. Three Control Concretes (CC-30, CC-37.5, CC-45) manufactured with Natural Aggregates (NA), and their corresponding Recycled Aggregate Concretes (RAC-20, RAC-50, RAC-100) are evaluated in terms of physical and mechanical properties. The in-fresh properties results (flowability, viscosity and passing ability) of the RAC were suitable for their use as SSC. Furthermore, the tests of compressive, splitting tensile and flexural strength, as well as density, porosity, water absorption, ultrasonic pulse velocity, stiffness, and both dynamic and static modulus provided results close to those of the SCC with NA, and in compliance with the requirements of current regulations. The recycling process that takes place in the precast factory supposes an economical improvement and an important contribution to global sustainability, in accordance with the concept of the circular economy.

Keywords: Recycling; Mechanical testing; In-fresh properties; Recycled aggregate concrete; Precast; Self-compacting concrete

1 Introduction

The construction industry is one of the sectors bearing the greatest responsibility for the consumption of natural resources and the generation of waste. Construction and demolition is one of the principal focuses of attention in the search for sustainable construction. Mean average production in Europe of Construction and Demolition Waste (CDW) stands at 0.38 t/per person/per year, and only countries such as Denmark and the Netherlands have recycling rates of over 85%. >35 million tons of CDW (1.1 t/per person/per year) are produced in Spain alone [1].

With regard to prefabricated concretes at an international level, the "*Precast Sustainability Strategy and Charter*" of the British Precast Concrete Federation is first and foremost [2]. This plan encourages precast firms to go beyond the requirements of current legislation, by instituting measures on a voluntary basis to add greater sustainability to their products and operations. In 2013, the British Precast Council approved a new battery of measures for implementation throughout the year. The Netherlands and Germany may be highlighted in Europe among the countries that opt for the precast industry, where precast solutions in construction amount to 45% and 38%, respectively [3].

An effort is made to comply with the basic requirement for "sustainable use of natural resources", included in EU Regulation 305/2011 [4] on harmonized conditions for the marketing of construction products. The European Regulation under article 11.2b [4] also includes the objective for Member states to adopt certain measures, among which: to guarantee recycling to a minimum of 70% by weight of Construction and Demolition Wastes (CDW) before 2020. The promotion of research studies related to the sustainability of companies dedicated to concrete products through the incorporation of recycled aggregates is an incentive and an advance for society. A large number of investigations have arisen from the exploitation of these waste products, in which the different forms of using Recycled Aggregates (RA) in the manufacture of concrete have been analysed [5–8], but there are few studies that use RA from the rejected components in a real precast factory for performing high-performance self-compacting precast concrete, manufactured in the same industrial plant where those rejected RA components are produced.

In general, the use of these types of aggregates implies a loss of the physical and mechanical properties in the final product, the water demand of the recycled concrete depends on the substitution rate of RA. At a low replacement ratio, the rheological parameters do not change significantly without any addition of water [9,10]. However, the following aspects can be highlighted: if the Recycled Aggregate Concrete (RAC) is of acceptable workability, it will have consumed more water than conventional concrete [11]; the density, compressive strength, and modulus of elasticity are lower than those of conventional concrete, and the durability of the RAC is affected at a certain w/c ratio in terms of higher permeability and carbonation rates [10,12]. Equally, the manufacturing method, the use of dry aggregate, saturated RA, or coarse saturated aggregate, influences the concrete properties in both the fresh and the hardened state. The incorporation of pre-saturated RA is the theme of some studies [10,13,14], while the method of water compensation is suggested in others [9,10,15–22].

The use of RA from prefabrication processes is not very common among construction sector firms; the efforts of firms in Spain have been reported in papers by Pérez et al. [23] and Thomas et al. [24]. There is also a study on the use of these types of aggregates from precast components in Portugal that covers their mechanical behaviour and durability [25]. Likewise, Xiao, J., et al. [26,27] tested the seismic behavior of precast recycled concrete.

The objective of the present work is to analyse the behaviour of Self-Compacting Concretes (SCC) that incorporate recycled aggregates from precast elements in terms of their physical, mechanical, and elastic properties when used in structural precast components. The recycled aggregates are in turn taken from rejected structural precast concrete pieces. The high-quality of these RA is expected to contribute to the manufacture of high-performance concretes, with good self-compactability and high strengths. This study was carried out on a real precast factory, where the final self-compacting precast concrete was manufactured and where the recycled aggregates were obtained, contributing in this way to a circular and sustainable economy, with the lowest possible disposal and transport of wastes. The precast concrete company has a total quality control system based on the ISO-9001 [28] and an environmental management system based on ISO 14,001 [29].

Various steps were followed in the experimental study. First of all, the reject precast elements were crushed and the RA was characterized. Secondly, the design of the (dosages for the new recycled SCC was performed. Three Control Concrete mixes (CC) were performed based on the required minimal compressive strengths in each case: 30 MPa (CC-30), 37.5 MPa (CC-37.5) and 45 MPa (CC-45). Then, percentage substitutions of 20%, 50% and 100% by weight of RA were added to each CC mix.

Finally, the in-fresh properties (flowability, viscosity, and passing ability) and hardened properties of the designed RAC were evaluated through physical tests (density, absorption, porosity, ultrasonic pulse velocity) and mechanical tests (compressive, splitting tensile, flexural and elasticity), in order to assess the influence of high-quality RA on the behaviour of the RAC manufactured.

2 Materials

The materials, the dosages and the experimental methodology used in the present study are all described in this section.

2.1 Cement, filler, admixtures, and natural aggregates

The raw materials used in this study are the same as those used at the precast factory (from where the RA were taken) to manufacture the self-compacting concrete of their products.

- The cement in use is a CEM I 52.5R, with a density of 3.12 g/cm^3 and a specific Blaine surface of 365 m2/kg. As an Ordinary Portland Cement (OPC), it provides high initial strengths to hardened concrete. Table 1 shows the chemical composition of the cement that is used.
- Limestone filler: The percentage in weight of $CaCO_3$ in the filler was 96.5%. The limestone filler should partially counteract the effect of the surface roughness of the RA, slightly improving its workability and flowability throughout the concrete mass.
- Admixtures: two super plasticizing admixtures usually employed in precast self-compacting concrete, were jointly used. Admixture A: a water entrainment agent, in proportions of 0.5–1%. Admixture B: showing a high performance for SCC with low water content, in proportions of 0.5 to 1.5% by weight of cement.
- Natural Aggregates (NA): Natural rounded siliceous aggregate (NA) was taken from a quarry owned by the precast concrete company. Table 2 shows the characteristics of the two sizes of aggregate in use: NA0/2 (sand) and NA2 /12.5 (gravel). Their grading curves are also shown in Fig. 1.

where:

Dr	Relative density of particle
Dsss	Density of particle saturated with dry surface
A	Water absorption

Dc	Aggregate density
LA	Los Angeles Loss

Table 1 Chemical composition by XRF analysis of the cement.

Cement	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	MgO	TiO_2	C
I-52.5R	68.3	17.5	5.74	3.01	2.38	1.29	1.70	0.38	0.46

Table 2 Properties of the NA.

Property	Dr [g/cm³]	Dsss [g/cm³]	A [% wt.]	Dc [g/cm³]	LA [%]
Standard	EN-1097-6	EN-1097-6	EN-1097-6	EN-1097-6	EN-1097-5
Sand (0/2)	2.63	2.64	0.26	1.62	–
Gravel (2/12.5)	2.61	2.63	1.16	1.61	31

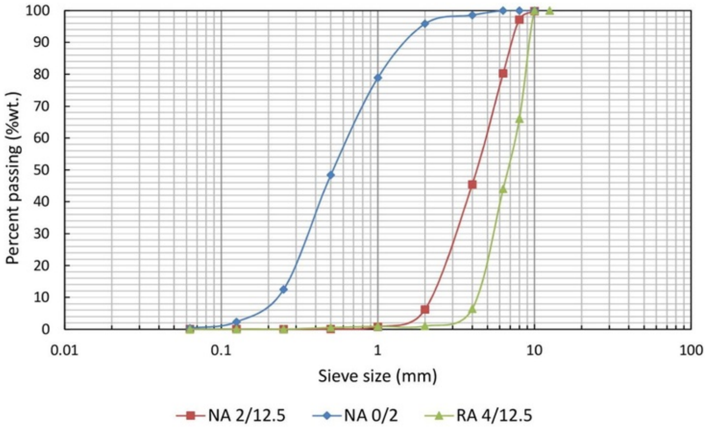

Fig. 1 Grading of the RA and NA.

2.2 Crushing process and properties of RA

The RA was taken from precast components (beams, columns and purlins) with a compressive strength between 30 MPa and 50 MPa at 28 days. The components selected for the production of the RA were at all times taken from rejects due to measurement defects and in no case due to the quality of the concrete, so this RA is expected to be of high quality. Fig. 2 shows different reject pieces at the waste landfill site of the precast factory and a crusher at work during the crushing process to obtain the recycled aggregates.

Fig. 2 Waste landfill site for precast reinforced concrete and their crushing process.

The precast components were crushed at a waste treatment centre. In the first place, the steel reinforcements were removed with a hydraulic clamp, after which a jaw crusher reduced the waste to an aggregate size of 0/150 mm. Crushing was then done with an impact crusher, to produce an aggregate size of around 0/30 mm. A final screening produced an aggregate size of approximately 4/12.5 mm, thereby exploiting 60% of the weight of cement. The excess sizes (12.5/30 mm) could be reused after a second crushing process and the fraction (0/4 mm) could be used as recycled fines. Table 3 shows the chemical composition of the RA 4/12.5 and Table 4 shows its physical properties, together with the values from the literature, related with RA from in situ concrete and RA from precast concrete. The RA grading curve is shown above in Fig. 1, together with those of the NA.

Table 3 Chemical composition by XRF of the RA.

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	MgO	TiO_2	C
RA 4/12.5	37.4	18.5	56.53	1.10	0.16	1.32	0.79	0.09	0.47

Table 4 Properties of the RA.

Properties	Standard	Spanish Standard limits	RA from common or in situ concrete [10,12,21,30–38]	RA from precast concrete [23,24,39–43]	Obtained values
Sieve modulus	–	–	6.2–7.6	6.78	6.68
Fines content (%wt)	EN-933-2	≤1.5	0.27–1.14	0.27–1.14	0.41
Particles smaller than 4 mm (%wt)	EN-933-1	≤10	0.5–2.0	1.38	1.10
Flakiness index (%wt)	EN-933-3	≤35	7–22	10–12	7.9
Shape coefficient (%wt)	EN-933-4	>0.2	1–15	11–12	2.25
Density (g/cm^3)	EN-1097-6	2–3	2.1–2.4	2.48–2.6	2.41
Absorption coefficient (%wt)	EN-1097-6	≤5	4–10	4.19–4.57	4.15
Los Angeles (%wt)	EN-1097-2	≤40	25–45	31–33	37
Soft particles (%wt)	EN-7134-58	≤5	20–60	16.68	21
Mortar adhered (%wt)	Thermal shock	–	30–60	–	52
Crushing value (%wt)	UNE-83112	–	–	30	35
Resistance to magnesium (%wt)	EN-1367-2	≤18	0–20	2	11.51
Alkali reactivity(%lon)	UNE-EN-146509	≤0.4%	–	–	0.02
Light particles (%wt)	EN-1733-1	≤1	0.5–5	0.023	0.01
Clay lumps (%wt)	EN-7133	≤0.25	0.05–0.6	0.25	0.01

Water soluble chloride (%wt)	UNE-1744-1	≤0.05	0.001–0.05	0.0015	0.005
Soluble sulphates in acid (%wt)	UNE-1744-1	≤0.80	0.10–0.62	0.65	0.44
Sulphur compounds (%wt)	UNE-1744-1	≤1	0.43–0.75	0.285	0.25

On the basis of the source that is already known and the analyses of the geometric, dimensional, physical, and chemical properties of the new aggregate that is produced, it can be affirmed that these properties are within the limits defined by standards, producing suitable properties for SCC. Influential values such as the fines percentage and the water absorption rates of the new RA are good in relation to other similar studies, despite the flakiness of the aggregate and its higher volume of paste, due to its source material (precast components).

3 Mix-design

Three CC were manufactured, identified as CC-30, CC-37.5 and CC-45, all of them with NA, of standard use in precast concrete plants. Based on those dosages, the NA was substituted by the RA in different amounts: 20%, 50% and 100% by weight. The mix-design of the mixtures is shown in Table 5.

Table 5 Mix proportions of RAC-30, RAC-37.5 and RAC-45, per cubic meter.

Designation		RAC-30				RAC-37.5				RAC-45			
Substitution		CC-30	20%	50%	100%	CC-37	20%	50%	100%	CC-45	20%	50%	100%
Siliceous Sand (0/2)	kg	650	650	670	720	650	650	670	720	650	650	670	720
Siliceous Gravel (2/12)	kg	1150	920	540	0	1150	920	540	0	1150	920	540	0
RA (4/12)	kg	0	250	540	1040	0	250	540	1040	0	250	540	1040
Limestone filler	kg	320	320	320	320	300	300	300	300	280	280	280	280
CEM I 52.5R	kg	250	250	250	250	290	290	290	290	320	320	320	320
Water	kg	112	112	112	112	112	112	112	112	112	112	112	112
Admixture 1 SP	kg	0.50	0.50	0.65	0.85	0.50	0.50	0.65	0.85	0.50	0.50	0.65	0.85
Admixture 2 SP	kg	1.30	1.30	1.60	2.00	1.30	1.30	1.60	2.00	1.30	1.30	1.60	2.00
Slump flow	mm	680	600	580	550	780	700	580	650	750	710	600	650
T500 slump flow	s	4	5	5	7	3	5	6	6	3	3	4	7
Theoretical w/c ratio		0.45	0.45	0.45	0.45	0.38	0.38	0.38	0.38	0.35	0.35	0.35	0.35
Effective w/c ratio:		0.40	0.39	0.35	0.32	0.31	0.30	0.27	0.25	0.31	0.30	0.27	0.25

The mixtures were completed with the aggregates under laboratory conditions, in a planetary concrete mixer (vertical axis), at an average temperature of 20 °C and at an average humidity of ±45%. The sand NA had humidity levels around 0.15%, while the coarse NA had a humidity of below 0.05%.

The incorporation of RA during the mixing process implies a modification of the theoretical w/c ratios. The amount of admixture was increased in all substitutions, assuming that the aggregates would absorb 70% of their water absorption capacity [44,45].

Fig. 3 shows grading of the mixtures RAC-100 together with Fuller's method, showing good adjustment between then.

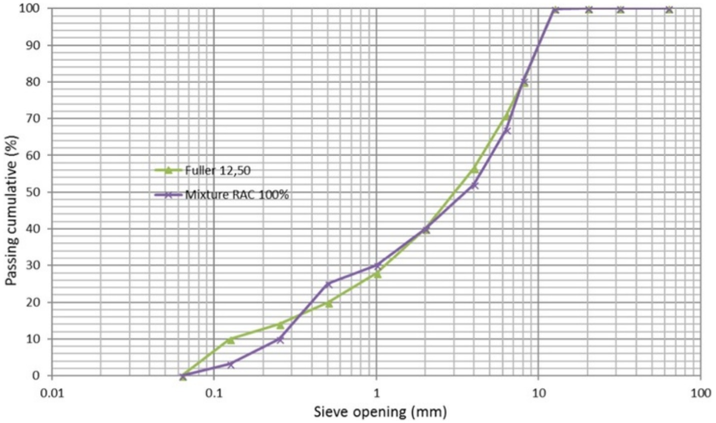

Fig. 3 Grading of mixes and Fuller's curve.

4 Testing program

4.1 In-fresh properties of concrete

The characteristics and requirements of the EFNARC SCC guidelines [46] are shown in Table 6. The requirements for concretes manufactured in this work must as a minimum be as follows: slump-flow SF1, viscosity class VS2 or VF2, passing ability in L-box class PA1, without segregation or exudation.

Table 6 EFNARC prescriptions.

Property	Preferred test method	Specification	Classes	Values
Flowability	Slump-flow test	Slump-flow in mm	SF1	550 ~~to~~ –650 mm
			SF2	660–750 mm
			SF3	760–850 mm
Viscosity (rate of flow)	T_{500} Slump-flow test, or V-funnel test	T_{500}, in s, or V funnel time in s	VS1/VF1	≤2/≤8 s
			VS2/VF2	>2/9–25 s
Passing ability	L-box test	Passing ability	PA1	≥0.80 with 2 rebars
			PA2	≥0.80 with 3 rebars

The control of consistency was studied with the concrete Abrams slump cone test according to EN 12350-2 [47] and the spread slump-flow test according to UNE EN 12350-8 [47], and those results are shown in Table 5 for all the mixtures. It can be observed that in all the cases the slump cone reached the diameter >550 mm. The slump cone decreased as the degree of substitution increased. In general, mixtures RAC-100 corresponded with the slump-flow class SF1. The slump flow differences between CC-mixtures and RAC-20 mixtures were small.

The viscosity was measured through the time necessary to reach a slump cone diameter of 500 mm (T500 slump flow). In all the cases this time was higher than 2 s (viscosity class VS2).

A more exhaustive study of the SSC in-fresh properties, with the viscosity V-funnel test according UNE-83364 [47] and including passing ability with L-box test, was carried out on the intermediate dosage, RAC-37.5. Those results are shown in Table 7. The viscosity by V-Funnel test was also satisfactory, with VF1 class for mixtures CC-37.5 and RAC-37.5-20%, and VF2 class for mixtures RAC-37.5-50% and 100%. The passing ability L-box test (2 rebars) classified all the mixes as PA1. Although the workability was slightly worst in the mixtures with greater percentage of RA, the SSC manufactured in this study fulfilled all the requirements established in EFNARC SCC guidelines [46]. Furthermore, along the in-fresh tests, a good distribution of the coarse aggregates in the mass was verified, as well as an absence of segregation or exudation.

Table 7 In-fresh properties of RAC-37.5 mixtures.

Property	Units	Standard	RAC-37.5			
			CC-37.5	20%	50%	100%
Viscosity by V-funnel test	s	UNE-83364	5 (VF1 class)	6 (VF1 class)	10 (VF2 class)	19 (VF2 class)
Passing ability L-box		EN-12350-9				
T20 s: H1/H2	–		0.88 (PA1 class)	0.87 (PA1 class)	0.85 (PA1 class)	0.80 (PA1 class)
T40 s: H1/H2	–		0.98 (PA1 class)	095 (PA1 class)	0.89 (PA1 class)	0.85 (PA1 class)

4.2 Hardened properties of concrete

The specimens were cured in a climatic test chamber with a moisture level of 95 ± 5 °C and 20 ± 2 °C over 28 days. EN 12390-7 [47] was applied for the determination of the hardened densities of prismatic specimens measuring 150x150x300 mm. Absorption and porosity were determined in accordance with ASTM C-642 [48] using 100x100x100 mm cubes. EN 12390-3 [47] for the determination of compressive strength [47] and EN 12390-6 [47] for the determination of splitting tensile strength on cylindrical specimens with diameters of 150 mm and a height of 300 mm were both applied. Flexural strength tests were also performed according to EN 12390-5 [47] with prismatic specimens of 100 × 100 × 400 mm. The static modulus of elasticity was determined in accordance with EN-UNE-83316 [47], using cylindrical specimens of 150x300 mm. Three specimens were prepared for each test, taking their arithmetical mean.

The modulus of dynamic elasticity was determined by measuring the propagation speed of the ultrasonic waves, in accordance with EN 12504-4 [47], on cylindrical specimens of 150 × 300 mm. Two measurements were taken in the direction of the directrix of the specimen. Having obtained the propagation speeds from Ultrasonic Pulse Velocity test (UPV), Eq. (1) was applied:

$$E_d = V_l^2 \rho \frac{(1+\upsilon)(1-2\upsilon)}{1-\upsilon} \tag{1}$$

where

υ Poisson coefficient (0.2)

ρ concrete density

V_l longitudinal velocity

5 Results and discussion

The characterization results of the hardened concrete, the control and the recycled concretes cured during 28 days, are summarized in Table 8, which shows the average of the three test specimens in each test performed. Likewise, these results are represented in several figures in the following sections, showing the three values of each test carried out for each of the concretes.

Table 8 Physical and mechanical properties of the hardened concrete.

Designation		RAC-30				RAC-37.5				RAC-45			
Substitution	unit	CC-30	20%	50%	100%	CC-37	20%	50%	100%	CC-45	20%	50%	100%
Apparent density	g/cm³	2.37	2.36	2.34	2.29	2.37	2.36	2.30	2.30	2.40	2.37	2.36	2.31
Relative density	g/cm³	2.41	2.40	2.39	2.33	2.42	2.40	2.41	2.34	2.43	2.41	2.40	2.35
Saturate density	g/cm³	2.42	2.41	2.40	2.38	2.43	2.42	2.41	2.35	2.44	2.43	2.42	2.36
Absorption coefficient	%wt.	3.30	3.40	3.79	4.10	3.12	3.31	3.52	3.11	2.95	3.01	3.20	3.05

Open porosity	%vol.	7.30	7.50	8.15	8.50	6.25	5.92	6.25	7.14	5.15	5.80	6.0	6.30
Ultrasonic pulse velocity	km/s	4.98	4.87	4.83	4.75	4.95	4.91	4.85	4.71	4.92	4.95	4.87	4.80
Compressive strength	MPa	49.09	49.98	55.64	56.75	58.30	60.25	58.52	70.56	63.36	64.13	66.82	72.81
Splitting tensile strength	MPa	5.17	5.06	4.85	4.92	5.50	5.15	5.20	5.32	5.30	5.21	4.95	5.00
Flexural strength	MPa	6.20	6.30	6.35	5.60	6.90	7.58	6.15	6.70	7.95	7.80	7.90	7.80
Elastic modulus	GPa	36.98	38.50	35.15	34.03	38.55	41.50	36.62	36.40	40.83	42.60	38.01	37.80
Dynamic modulus	GPa	52.87	52.72	48.15	45.10	53.17	53.05	47.80	47.50	54.01	53.04	51.07	48.92

5.1 Physical properties

RA that is incorporated in any type of concrete will, as is known, reduce the density of the concrete in proportion with the quantity of its substitution. The relation between concrete density and effective w/c ratio is of a linear nature, reflecting its clear tendency to increase at a smaller w/c ratio and to diminish as the degree of substitution increases [10]. Fig. 4 presents the relative densities of both the CC and the RAC as a function of the effective w/c ratio. The value curves are similar to those found by different authors for RA from different sources [49,50] and from precast concrete components [24,25].

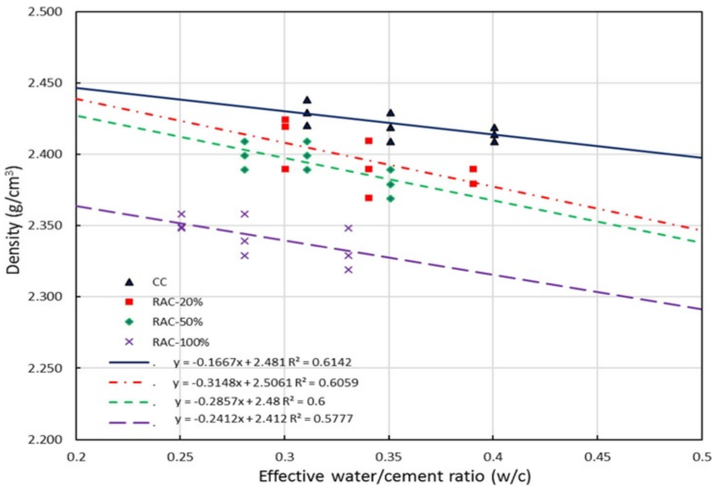

Fig. 4 Density of CC and RAC as a function of the w/c ratio.

In contrast, several authors have shown that the porosity responded to a logarithmic law based on its w/c ratio [10,51]. In this way, both the absorption and the porosity, Figs. 5 and 6, may be compared with the effective w/c ratio according to this criterion.

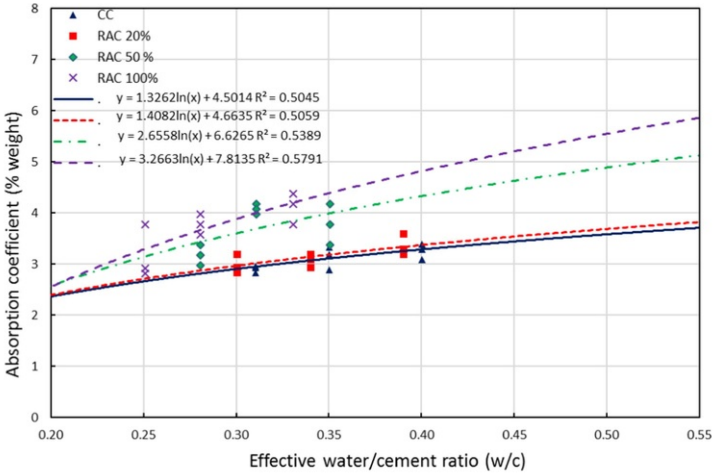

Fig. 5 Water absorption of CC and RAC as a function of the w/c ratio.

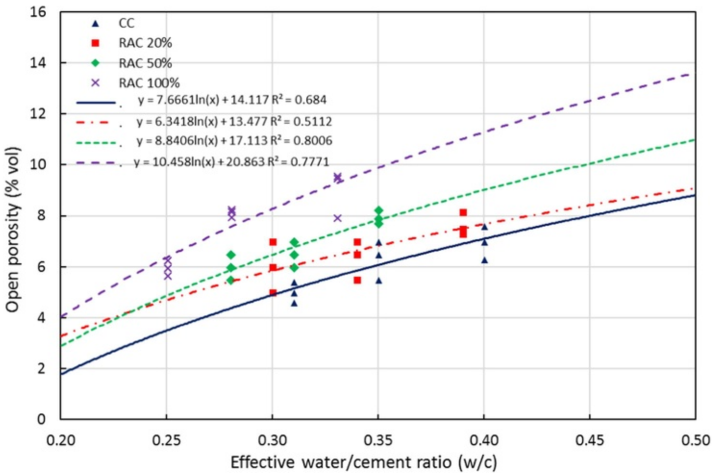

Fig. 6 Open porosity of CC and RAC as a function of the w/c ratio.

It may be observed that the incorporation of RA implies an increase in the accessible porosity of the concrete. The porosity values are situated below 15%, a value considered as a limit by the Comate Euro-International du Béton (CEB-1998) [52], for a good quality concrete.

As was expected, the higher the w/c ratio and the degree of RA substitution the more absorbent the concretes. The influence of RA on the water absorption coefficient was not the same for the w/c ratios. As the w/c increases, the influence of RA on the water absorption coefficient was greater and when the w/c ratio was low, its influence decreased. In this sense, it can be observed that the curves of the concretes with 50% and 100% of RA have much greater slope than the concrete with 20% of RA (similar to CC- reference concrete). The confluence of the curves in low w/c ratio shows that the incorporation of RA with those w/c ratios has less influence on the concretes, reaching the water absorption values close to those of the CC. This effect may be due to the paste that is in these cases more impermeable, with better coverage of the RA surfaces and definitively reducing concrete porosity [10,53]. Furthermore, the highest w/c ratios corresponded to the concrete with the lowest resistance (30 MPa), where the recrystallization of the cement components was lower, and therefore the porosity and absorption were greater [10,41,53]. In fact, other studies of recycled concrete with strengths of between 60 MPa and 100 MPa obtained absorption coefficients lower than the current study [41].

5.2 Ultrasonic pulse velocity

The Ultrasonic Pulse Velocity (UPV) results are presented in Fig. 7, for the different RAC, as a function of the effective w/c ratio. The UPV is influenced by the elastic properties of the material through which the waves are propagated.

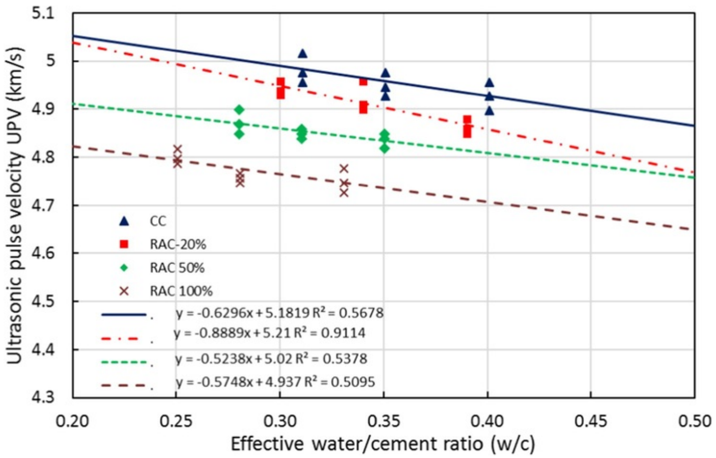

Fig. 7 UPV values of CC and RAC as a function of the effective w/c ratio.

Other similar studies [39,41,54] on high-strength concretes reflected the same linear trend between UPV and the incorporation of RA, showing decreases of around 2–5% for RAC with respect to the CC mixes. The results of those studies reflected the values obtained in the present work.

The RA, with a lower stiffness than the NA, reduced the propagation speed of the ultrasonic waves [55–57]. All the values exceeded 4.50 km/s, for which reason they are classified in the range of excellent values, in accordance with the values obtained by Whitehurst [58], among others.

5.3 Compressive strength

Table 6 shows the compressive strength values of the RAC and CC. Apparently, the incorporation of the RA leads to an increase in compressive strength. Nevertheless, this effect is due to the reduction of the w/c ratio effective, caused by the incorporation of a dry RA with greater absorption [51,59].

It is known that the behaviour of the compressive strength as a function of the w/c ratio, according to several studies based on the law of Abrahams [51,59,60], can be fitted to an exponential curve with Eq. (2):

$$y = Ae^{-B\left(\frac{W}{C}\right)} \quad \textbf{(2)}$$

where,

- y is compressive strength for a cured age,
- w/c is the effective water/cement ratio,
- A and B are the parameters to be calculated.

Considering our results, the corresponding parameters were calculated. Thus, the strength values obtained and the exponential curves are represented in Fig. 8.

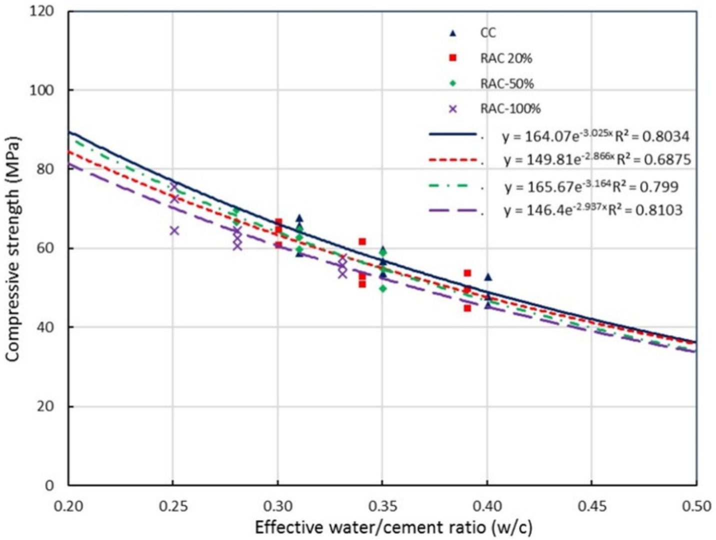

Fig. 8 Compressive strength of CC and RAC as a function of the w/c ratio.

Now, as may be confirmed in Fig. 8, the incorporation of RA caused a small loss of strength for all the effective w/c ratios. In addition, there was a slight merging of the curves as the w/c ratio increased, practically reflecting the w/c ratio of 0.50. According to the graph in Fig. 8, when a CC is of the same strength as an RAC at substitutions of 100%, the w/c ratio will approximately have descended to 0.05.

Fig. 9 shows the comparison of the present study (obtained values CC and RAC-100%) with several studies from the literature (values from the literature CC and RAC-100), where we can observe the similarities between them.

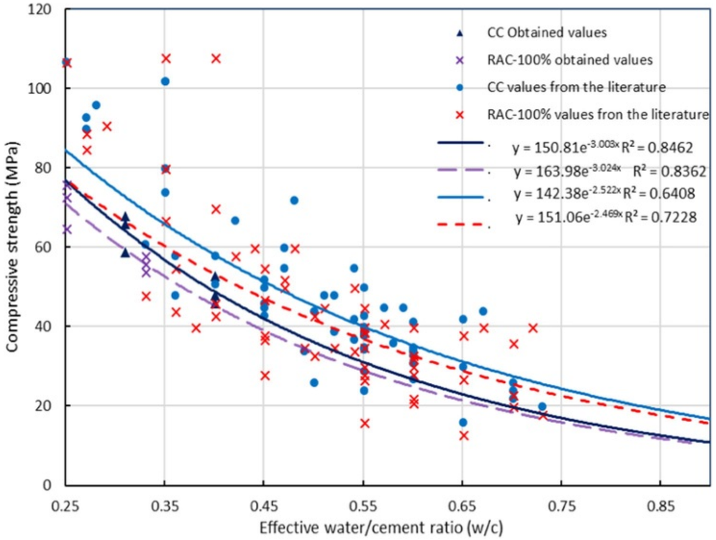

Fig. 9 Comparison of CC and RAC-100% values with those found in other studies from the literature [6,12,25,31,39,40,55,61–70].

Similar studies [6] using RA taken from concretes with strengths of 30–50 MPa at substitutions of 100% obtained compressive strength reductions of 10%, as against of 12% observed here. González and Etxeberria [41] observed similar reductions for concretes of the same strength and with initial strengths of 60 and 100 MPa, the difference in compressive strength between the CC and RAC-50% and 100% being negligible.

Based on the literature review thus far on aggregates from precast components, the strengths are clearly higher [23–25], due to the high quality of the aggregate and the use of superplasticizers [64,71,72].

5.4 Splitting tensile strength and flexural strength

The values of splitting tensile strength and flexural strength, both for RAC and for CC are shown in Table 8, and represented in Figs. 10 and 11, respectively. The adjustment of the strength values was also done according to Eq. (2), fitting the values to descending exponential curves as a function of the w/c ratio.

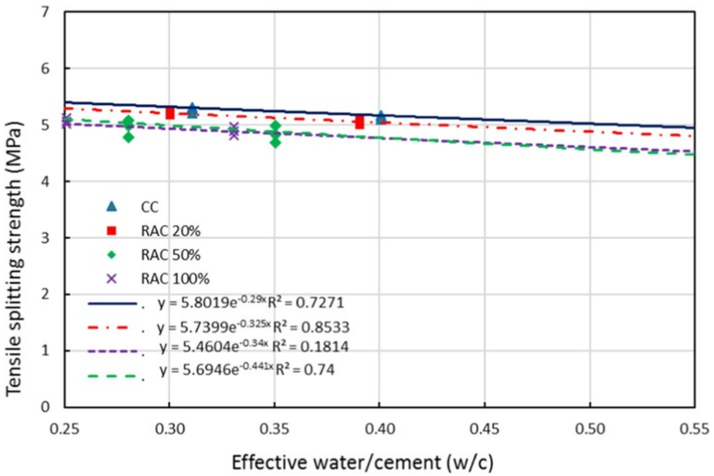

Fig. 10 Splitting tensile strength of CC and RAC as a function of the w/c ratio.

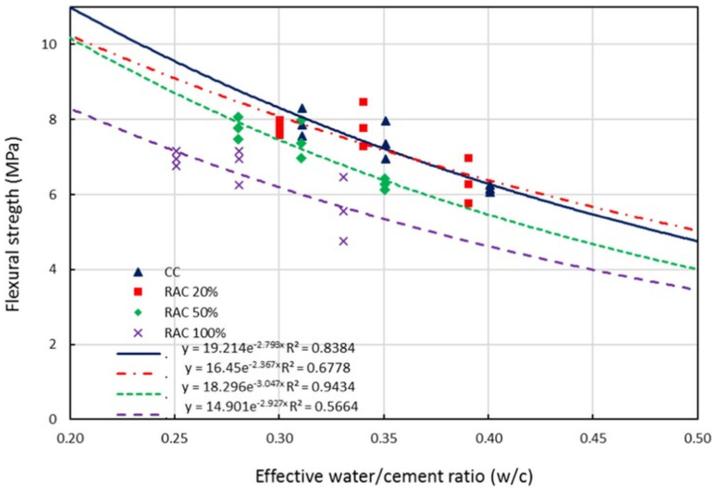

Fig. 11 Flexural strength of CC and RAC as a function of the w/c ratio.

With regard to the results for both splitting tensile and flexural strengths, once again the tendencies of the fitted curves showed an increase in strength with the reduction of the effective w/c ratio, although the values were lower with the degree of substitution. This variation is very small for splitting tensile strength and a little greater for flexural strength.

In the same way as for compressive strength, flexural strength curves tended to converge when the water/cement ratios increased. Neither can convergence be observed in the case of splitting tensile strength where the curves are almost straight lines.

A reduction in the w/c ratio by around 0.15 would be necessary to achieve the same splitting tensile strength between the control concrete and the concrete with 100% RA.

The results of flexural strength at substitutions of 100% caused strength losses of between 2% and 3% and were significantly lower than the state-of-the-art values that fluctuated between ±20%, according to the studies of Alaejos [73], due presumably to the high quality of our RA.

5.5 Static elasticity modulus

The values of the static elasticity modulus are shown in Table 8. Variations in stiffness, as function of w/c ratio, evaluated in other studies [10,45] are defined by an a straight line as the Eq. (3):

$$y = -Ax + B \tag{3}$$

where,

y is elasticity modulus,

w/c is the effective water/cement ratio,

A and B are parameters to be calculated.

In Fig. 12, a fit of this type is introduced, using the experimental values of elasticity modulus that have been obtained. In general, the elasticity modulus diminishes with the degree of substitution in the three mixes, in agreement with the lower elasticity modulus of the RA with regard to the NA, due to higher porosity and to the higher volume of adhered cement paste. In this section, it should be stressed that the SCC, the source of the RA, usually presents a higher paste/aggregate ratio than non-self-compacting concretes.

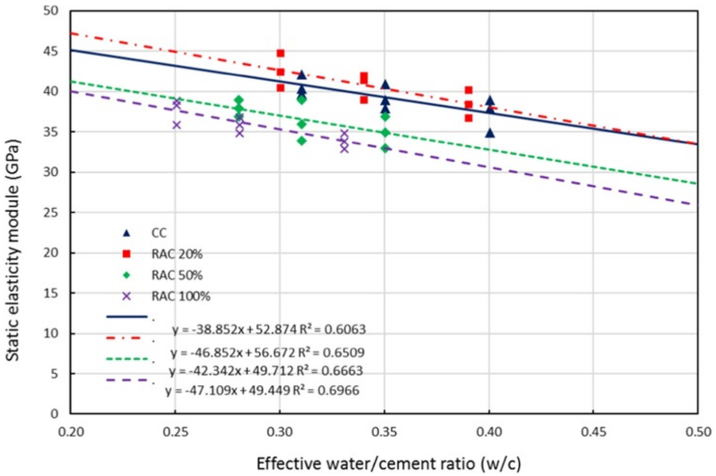

Fig. 12 Static elasticity modulus of CC and RAC as a function of the w/c ratio.

The static elasticity moduli values of both CC and RAC-20% were similar though slightly higher in the latter. Silva et al [74] studied the relation between the modulus of elasticity and compressive strength, establishing interesting conclusions relating to the positive variation of elasticity modulus caused by the influence of several crushing processes and the incorporation of several methods of water compensation, which modified the Interfacial Transition Zone (ITZ) between RA and the new cement mortar. It was concluded that the double crushing and the use of dry RA facilitated the adherence between the RA and the cement mortar, reaching good ITZ and increasing the stiffness of the mixes. This conclusion could be the explanation for the slightly increased stiffness in the RAC-20% mixes.

On the other hand, the values of the RAC 50% and 100% were 7–10% lower than those obtained in the CC; results that agreed with those of other authors on the use precast RA [21,31,32,75,76]. However, those differences in studies that used RA with a lower quality were around 20–25% with similar strengths [73]. Gonzalez-Etxeberría [41] obtained similar values of static elasticity modulus for concretes with strength of 40 MPa and 60 MPa, however the decrease of the elasticity modulus in RAC with strengths of 100 MPa with respect to the CC was even less than 7%.

It may be highlighted that the influence of RA on the elastic modulus was appreciably higher than on the compressive strength and other mechanical properties. It is therefore assumed that the elastic modulus will be a significantly more limiting factor than compressive strength, when seeking to incorporate RA.

In the bibliography, different models can be found for predicting the elasticity modulus. Some of them are shown below. The ACI code [77] proposed a ratio between the density ratio and compressive strength, expressed in Eq. (4):

$$E = 53{d_s}^{3/2}\sqrt{f_c}10^6 \tag{4}$$

Ravindraraja and Tam [30] presented a differentiated formulation between the CC and the RAC as a function of the compressive strength (Eqs. (5) and (6)).

$$E = 5.31f_{cu}^{0.51/3} + 5.83\,\text{conventional concrete} \tag{5}$$

$$E = 3.02f_{cu}^{0.51/3} + 10.67\,\text{aggregate concrete} \tag{6}$$

Dhir et al [78] expressed the Eq. (7), also as a function of a simple formula for compressive strength:

$$E = 370f_c + 13100 \tag{7}$$

The Spanish Concrete Instruction EHE-08 [79] is shown in Eq. (8):

$$E = 7.58\sqrt[3]{f_{cm}} \tag{8}$$

Kakizaki [80] expressed Eq. (9) as a function of relative density and simple compressive strength:

$$E = 2.1\left(\frac{d_s}{2.3}\right)^{1.5}\left(\frac{f_c}{200}\right)^{0.5} \tag{9}$$

Zilch and Ross [81] set out the following Eq. (10)

$$E = 634fcu + 13100 \tag{10}$$

Dillmann [82] advanced the parameter of relative density and compressive strength to obtain the equation for the modulus of elasticity (11):

$$E = 9100x(f_{cu} + 8)^{1/3}\left(\frac{\rho}{2400}\right)^2 \tag{11}$$

The above formulations were applied to the data obtained in the present study and the results obtained by the aforementioned models are presented in ordinate axis of the Fig. 13, together with the experimental elasticity moduli (abscissa axis). As may be seen in the lineal adjustment (see equation y = Ax for each model in the Fig. 13), the results predicted by Kakizaki and those of the ACI code achieved the best fit with the results that were obtained experimentally, with a relation close to 1 as indicated by parameter A [83,84].

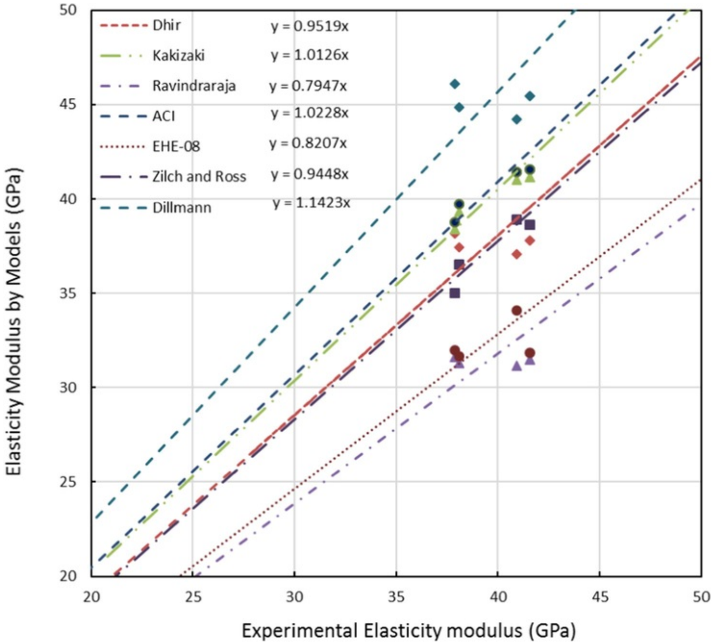

Fig. 13 Experimental modulus of elasticity compared to those predicted by models (Prainsa, Dhir, Kakizaki, Ravindraraja, Code ACI and Structural Spanish EHE-08).

5.6 Dynamic elasticity modulus

The fit of the dynamic elasticity modulus and the effective w/c ratio was calculated with Eq. (3), as in the case of static elasticity modulus. The decreasing straight-line is show in Fig. 14.

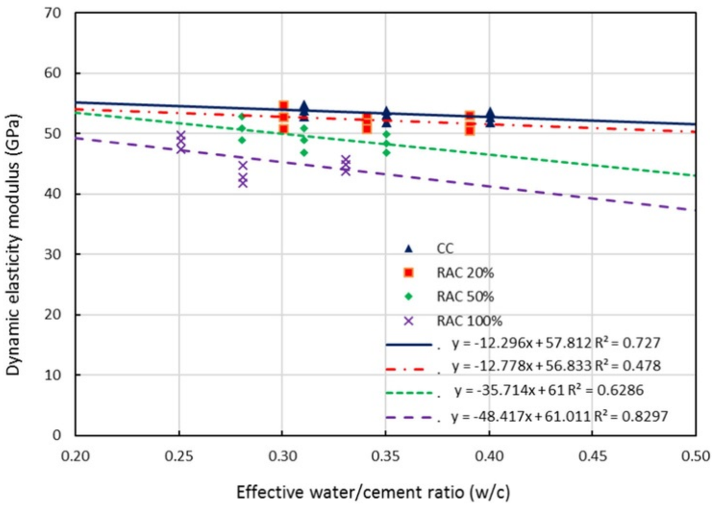

Fig. 14 Dynamic elasticity modulus of CC and RAC as a function of the w/c ratio.

In the same way as for the modulus of static elasticity, a reduction of the dynamic elasticity module may be observed while the w/c ratio increased, to a greater extent, at substitutions of 50% and 100%. The CC and RAC-20% behaved, as was expected, in a completely similar manner. The feasibility of linking the UPV with the dynamic elasticity module when applied to recycled concretes is detailed in other studies [85].

5.7 Correlation between static and dynamic elasticity modulus

The ratio between the static modulus and the dynamic modulus (Est/Edy) for the different concretes -CC and RAC- are shown in Fig. 15, as a fit of straight lines. The slope of the curve linking these two parameters may be seen to increase when using RA. The ratio between the secant and the dynamic modulus for a conventional concrete depends on its compressive strength, due (in part) to the properties of flowability that influence the static modulus.

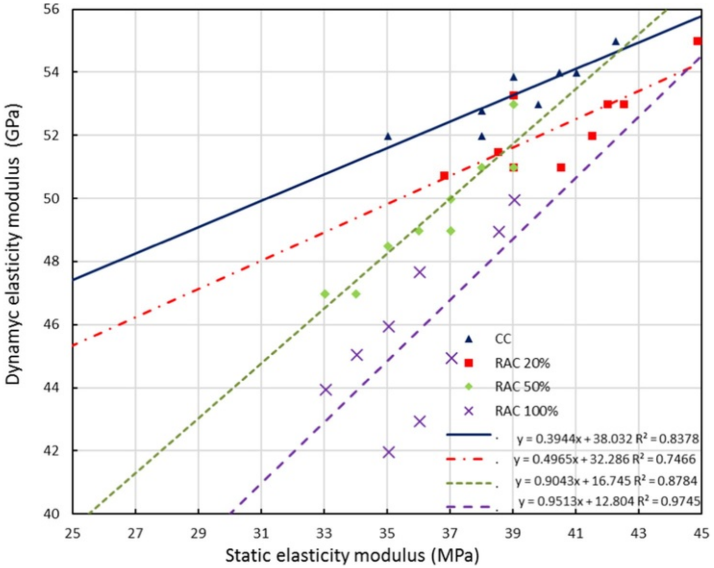

Fig. 15 Relation between dynamic and static elasticity moduli.

The ratios between the different moduli and their compressive strengths are shown in Fig. 16. The recorded slopes are seen to diminish notably as the proportion of RA present in the mixture increases. The values of the curves shown for CC, RAC-20%, RAC-50% and RAC-100% can be calculated with the equations. The slopes of CC and RAC-20% show that as the strength of the concrete increases, there is a notable increase in the Est/Edy ratio and, in consequence, the static modulus values converge towards the dynamic modulus values, reducing the creep effect, which is the main effect that causes the dispersion or differences between both moduli.

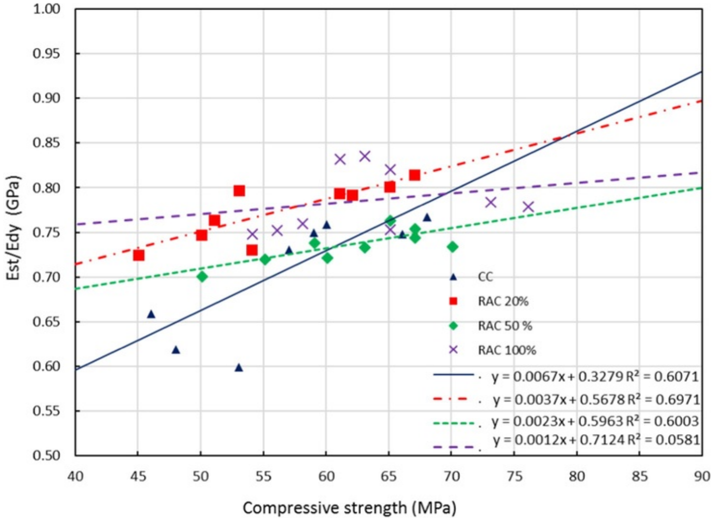

Fig. 16 Ratio between Est/Edy and compressive strength.

RAC-50% and RAC-100% show values that are one half lower than the CC and RAC-20%. In consequence, the Est/Edy ratio hardly increases with the gradual increase in concrete strength. Creep is therefore maintained and is not reduced as in the earlier case. The observed creep and plastic behaviour in Fig. 16, reflected by the higher slope of the lines in concretes with higher degree of substitution is due to the higher volume of cement paste, even higher than in the case of RA from CDW.

6 Conclusions

The conclusions of this work can be summarized as follows:

- The RA obtained from precast elements had been shown to be a high-quality aggregate, within the recommended limits of the current Spanish standard EHE-08. Among others, an RA fines content of 0.41% and an RA water absorption coefficient of 4.15% were lower than the requirements specified in the standard for limits of 1.5% and 5%, respectively.
- The use of RA produced a reduction of the effective w/c ratio that was compensated by the use of superplasticizer additives, in order to achieve the correct slump flow of the SSC performed.
- Despite the increase of superplasticizer in the mixtures, the slump cone decreased with the incorporation of RA, probably due to the high RA water absorption coefficient and the constant water content in the mixtures. Therefore, the study of the physical and mechanical properties of the manufactured SSC in this work was done by taking into account the effective w/c ratio.
- The three control mixtures (CC-30, CC-37.5 and CC-45) and their corresponding concretes manufactured with 20%, 50% or 100% of RA (identified as RAC-20, RAC-50 and RAC-100, respectively) gave results of in-fresh and hardened properties suitable for use as self-compacting concrete.
- According to the requirements of the EFNARC SCC guidelines, all the RAC-100 were classified with a flowability class of SF1 (slump-flow between 550 and 650 mm) and a viscosity class of VS2 (T500 > 2 s). As was expected, the flowability increased in the mixes with a lower content of both cement and RA.
- Likewise, mixture RAC-37.5 with 100% of RA obtained a VF2 viscosity class in the V-funnel test and PA1 passing ability class in the L-box test.
- The physical and mechanical results represented as a function of effective w/c ratio permits a simple and practical method for use with other RAC, making it possible to extrapolate the trend curve to other dosages.
- The porosity and water absorption of the mixtures increased with the percentage of aggregates substitutions, while the density decreased.
- In general, compressive, splitting and flexural strength of RAC mixes achieved slightly lower results the higher the percentage of RA. Despite this observation, RAC-100 for all the mix-designs reached values of compressive strength between 57 and 73 MPa, of splitting strength at around 5 MPa and a flexural strength between 5 and 8 MPa.
- The UPV of the RAC mixes underwent decreases of less than 5% compared to the CC mixes. Likewise, the moduli of static and dynamic elasticity diminished as the degree of RA substitutions increased. These decreases were due to the lower stiffness of RA with regard to NA. Those moduli should therefore be seen as more limiting than conventional compressive strength.
- The good global results obtained in this RAC study have likewise indicated that the durability performance of the concretes in this study was also good.

7 Declarations of interest

None.

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Graphical abstract

Highlights

- High-quality recycled aggregates (RA) produced from structural precast elements.
- Self-Compacting Concrete (SCC) manufactured with RA fulfilled current regulations.
- Slump loss due to water absorption of RA compensated with superplasticizers.
- SSC with different w/c ratios compared by extrapolation of fitted curves.
- Loss of stiffness is more limiting than loss of compressive strength.

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