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Original Article

Simultaneous addition of slag binder, recycled concrete aggregate and sustainable powders to self-compacting concrete: a synergistic mechanical-property approach

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ABSTRACT

The behavior of Self-Compacting Concrete (SCC) is very sensitive to the use of by-products in replacement of conventional cement or finer aggregate fractions. The high proportions of these raw materials in SCC can in great part explain this performance. 18 SCC mixes of slump-flow class SF3 were prepared for a thorough evaluation of different sustainable materials and for the prediction of their effects as binder or fine/powder aggregate on the mechanical properties of SCC. The mixes incorporated 100% coarse Recycled Concrete Aggregate (RCA); different amounts (0%, 50% or 100%) of fine RCA; CEM I ordinary Portland cement and CEM III/A (with 45% ground granulated blast furnace slag); and more sustainable powders compared to conventional limestone filler <0.063 mm (such as limestone powder 0/0.5 mm and RCA powder 0/0.5 mm). Flowability, hardened density, strength under compression, tensile and bending stresses and modulus of elasticity were all studied. The addition of 50% fine RCA yielded an SCC of adequate strength, stiffness and flowability. SCC manufactured with limestone powder 0/0.5 mm showed the best overall performance, while SCC behavior was improved when adding CEM III/A by adjusting the mix composition. The experimental results of all the mechanical properties were compared with the values predicted by the compressive-strength-based formulas from the European and USA standards. Overall, the values resulting from those expressions

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overestimated all the mechanical properties. Therefore, since all these properties followed the same simple-regression trend, a statistical analysis was performed to develop a global model capable of accurately predicting them all.

1. Introduction

Figures collected by different official organizations show the great problem posed by Construction and Demolition Waste (CDW) worldwide. For example, 500 million tons of this waste are generated in the United States each year [1], reaching 800 Mt in the European Union [2] and 2000 Mt in mainland China [3]. CDW is estimated to represent 25%–40% of the total volume of all waste deposited in landfills [4], thus significantly contributing to land occupation [5]. This waste usually consists of a mixture of concrete, asphalt, brick, wood, vegetation, rock, and potentially contaminated soil [6]. This mix of materials and the risk of contaminants [7] mean that the use of this residue in the production of concrete must be carefully considered, so that any problems, the most notable of which is decreased mechanical strength, may be minimized [8,9]. However, if the CDW used in replacement of Natural Aggregate (NA) is of a uniform composition, hydraulic [10] and bituminous [11] concretes with optimum mechanical [12] and structural [13] performance can be obtained.

Recycled Concrete Aggregate (RCA) is a special quality of CDW that can replace NA when manufacturing concrete [14]. This material is obtained by crushing rejected concrete elements, usually from the precast industry [15]. Its suitability for the manufacture of concrete is proven if its particular characteristics are considered when designing the concrete mix [16], as the coarse particles of RCA contain adhered mortar [17], there are altered cement and mortar in the fine fraction [18], and the presence of some contaminants is probable [19]. These aspects mean that RCA is of lower hardness and strength in comparison with NA, as well as having higher water absorption levels [20]. In addition, RCA weakens and alters the Interfacial Transition Zones (ITZ) [21], which will potentially cause poor adhesion between the mix components [22]. However, if RCA is obtained from a parent concrete of higher compressive strength, the recycled aggregate concrete is likely to show better mechanical performance [23].

Like NA, conventional cement can also be replaced with sustainable materials [24,25], in this case by those with hydraulic or pozzolanic properties [26], hugely reducing the cement carbon footprint [27]. Thus, for example, Ground Granulated Blast Furnace Slag (GGBFS), obtained after immersion in water for abrupt cooling followed by grinding of the blast furnace slag [28], is valid as binder if its proportion in the concrete mix is adequate [29,30]. Over the past few years, this material has demonstrated its validity for producing concrete of adequate strength that is even suitable for reinforced concrete elements [31]. However, this waste complicates the achievement of an adequate workability of concrete that guarantees its correct placement without segregation [32], since its smaller particle size compared to conventional cement usually hinders the dragging of the coarser aggregate particles [33].

Various studies that have evaluated the strength behavior of concrete when incorporating RCA and GGBFS have shown that, in general, their addition reduces all concrete strengths [34]. On the one hand, the addition of 100% coarse RCA of standard quality (strength of the parent concrete of around 30–45 MPa [35]) can reduce the compressive strength of concrete by around 50% [36]. It also causes an average reduction between 30% and 40% of the splitting tensile strength [37], so its impact is lower than it is on compressive strength [38]. On the other hand, additions of large amounts of fine RCA also reduce concrete strength [14]: the smaller the fraction of fine RCA the more noticeable the strength decrease [39]. Regarding GGBFS, the partial substitution of cement with this by-product in the same amount not only reduces strength [33], but also slowdowns any strength development over time [40]. Furthermore, both residues have a higher flexibility than NA [41] and conventional cement [40] respectively, which reduces the modulus of elasticity of the resulting concrete [42]. There are different strategies to compensate for the detrimental effects described above. The most common one consists of reducing the effective water-to-cement (w/c) ratio [43], by keeping the water amount constant when adding the RCA and taking advantage of the high water absorption of this residue [44]. Although concrete workability will in this way be lower [45], its strength when adding 100% coarse RCA can be increased by up to 38% with regard to the reference concrete [20].

Recently, the use of wastes has been extended to Self-Compacting Concrete (SCC) [46]. The main characteristic of this type of concrete is its high flowability that assists its placement without vibration. This behavior is achieved through the use of large quantities of superplasticizers, whose amount has to be carefully chosen to get an adequate balance between all fresh properties of SCC [47], as well as a high w/c ratio [45]. The high proportion of fine aggregate compared to coarse aggregate is also important in the SCC mix design to achieve uniform dragging of all aggregate particles [43]. In fact, it is common to use limestone filler <0.063 mm in the manufacture of SCC, to achieve adequate self-compactability [48]. This material has a high carbon footprint due to its manufacture based on air separation [49] and, to date, efforts to replace it with more sustainable fine aggregate fractions have met with little success.

The design conditions discussed above cause the detrimental effects of fine RCA on the hardened behavior to be amplified [50], while the flowability of SCC is more affected when reducing the effective w/c ratio to balance the decrease of mechanical properties caused when using coarse RCA [20]. Moreover, in SCC, the cement paste is intended to drag the aggregate particles [26], so modification of the binder type can

Table 1 – Physical properties of aggregates.

Aggregate	24-h water absorption (%)	15-min water absorption (%)	Density (Mg/m^3)
Coarse RCA	6.25	4.90	2.42
Fine RCA	7.36	5.77	2.37
Fine NA	0.25	0.18	2.57
Limestone powder	2.57	1.95	2.60
RCA powder	7.95	6.32	2.31
Limestone filler	0.54	0.37	2.77

significantly affect its flowability in the fresh state [14]. From all of the above, it is clear that an optimal balance between desired flowability and strength is essential in SCC and that the dosage should be adjusted in line with the by-product that is used, to achieve adequate values for both properties [43]. Nevertheless, the existing literature in which the use of fine RCA and GGBFS has been addressed to produce SCC is very scarce and, if sustainable aggregate powders in replacement of limestone filler are considered, even scarcer.

In view of the above, the simultaneous effects of adding GGBFS and RCA on the mechanical properties of SCC are investigated. Moreover, different sustainable aggregate powders (limestone powder and RCA powder) as replacements of conventional limestone filler and their behaviors are also evaluated. The study of the simultaneous effect of all these by-products and their interactions in the mechanical performance of SCC can be considered novel in the literature.

The mixtures under study were as follows: 18 SCC mixtures of slump-flow class SF3 (EN 206 [51]) incorporating 100% coarse RCA; several percentages (0%, 50% and 100%) of fine RCA; and aggregate powders from different sources and characteristics (limestone filler <0.063 mm, RCA powder 0/0.5 mm, and limestone powder 0/0.5 mm). Furthermore, half of the mixes incorporated CEM III/A, with a GGBFS proportion of 45%. Flowability, hardened density, strength properties, such as compressive strength, splitting tensile strength and flexural strength, and modulus of elasticity were evaluated in all the mixtures. In addition, the experimental results were compared with the theoretical values specified in current USA and European standards [52–54], finally proposing a simple-regression model valid for the estimation of all the mechanical properties of the mixtures.

2. Materials and methods

2.1. Materials

RCA was the most abundant aggregate in all the SCC mixes, which was obtained from precast concrete elements (strength higher than 45 MPa) rejected due to production defects. Its initial particle size, 0/31.5 mm, had a very large maximum aggregate size to produce SCC [55]. Furthermore, it prevented the separate use of the coarse and fine fractions of this aggregate, action necessary to obtain a joint granulometry with the adequate amount of fine aggregate for SCC production [55]. Therefore, the fine and coarse fractions, sized 0/4 mm, and 4/12.5 mm, respectively, were separated by sieving. The fine aggregate content of the mixes without 100% fine RCA was completed by adding siliceous sand 0/4 mm. Table 1 collects the density and water absorption of RCA, while Fig. 1 shows their gradation.

Aggregate powder was added to provide sufficient aggregate particles <0.5 mm to reach self-compactability [14]. Three different materials were considered as aggregate powder: limestone filler <0.063 mm, limestone powder and RCA powder. The last two aggregate powders, sized 0/0.5 mm, are sustainable alternatives to limestone filler, due to their lower energy consumption during their manufacture (limestone powder) [49] and their source (recycled material, RCA powder) [18]. Table 1 and Fig. 1 shows their physical properties and granulometry, respectively.

Cement, mains water and admixtures were also components of SCC:

- Two different cement types were used (EN 197-1 [51]): CEM III/A 42.5 N (specific weight of approximately 3 Mg/m^3) and CEM I 52.5 R (specific weight around 3.1 Mg/m^3). The use of CEM III/A yielded concretes of greater sustainability, due to the substitution of 45% cement clinker by GGBFS.
- Both a plasticizer and a viscosity regulator were used to improve the flowability of the mixtures.

2.2. Mix design

The composition of the mixes was defined, considering that all the mixes should be of high self-compactability, *i.e.*, they should all have a filling-ability class SF3 (slump flow between 750 mm and 850 mm) as per EN 206 [51]. For this purpose, every mix composition was modified in three ways, using the volume-correction method for all material substitutions:

- First, the water amount was accurately defined when adding RCA to balance its high-water absorption [56]. Thus, the effective w/c ratios of all the CEM I mixes remained constant and equal to 0.50, while for CEM III/A mixes this ratio was 0.40.
- Second, the content of the 0/0.25 mm aggregate fraction was defined on the Fuller curve, as shown in Fig. 2, for the CEM III/A mixtures manufactured with 50% fine RCA. The result prompted an increase in the aggregate powder content when using limestone and RCA powder [57].
- Finally, the amount of coarse aggregate in the SCC mixes with CEM III/A was reduced by 20%, while the cement content was increased. In this way, uniform dragging without segregation of the coarser aggregate particles when adding GGBFS to SCC was achieved [32]. In addition,

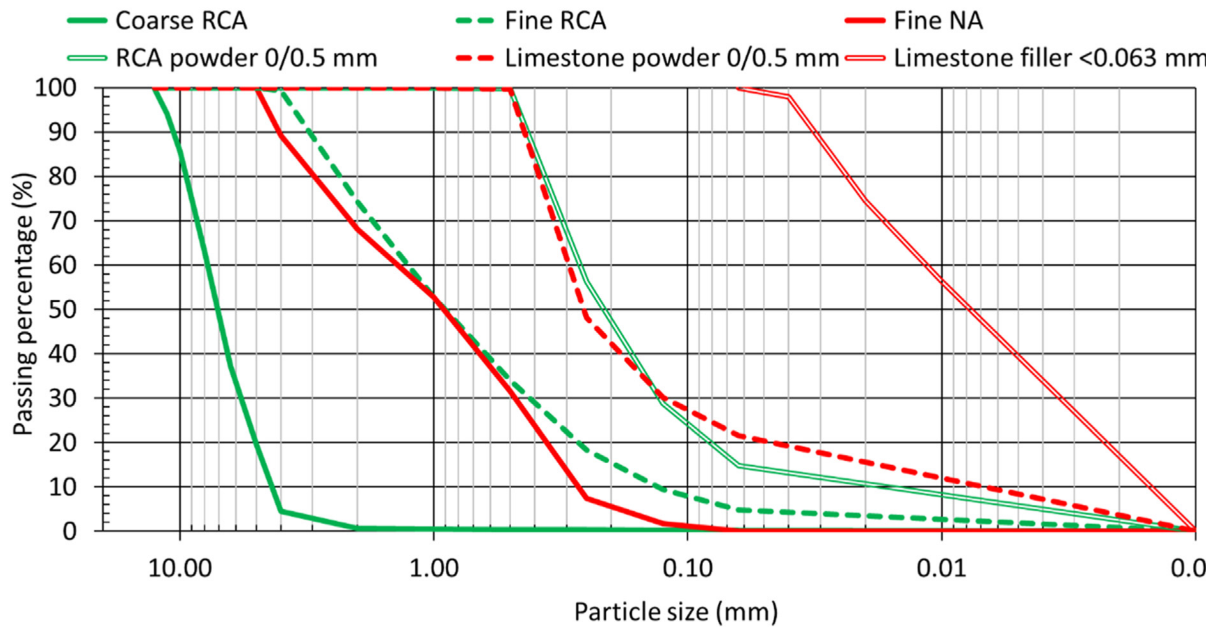

Fig. 1 – Aggregate granulometry.

this procedure also compensated for the decrease of strength when replacing conventional cement with GGBFS [40]. Thus, the mixes produced with 0% fine RCA and the same aggregate powder had similar compressive strengths on cylindrical specimens at 7 days regardless of the binder (difference of only 5–6 MPa). A detailed study could therefore be performed of both the fine RCA and the GGBFS and their effects on the mechanical behavior of SCC.

In all mixes, 100% coarse RCA 4/12.5 mm was used; an amount that in another study from the same authors [58] successfully increased the sustainability of SCC. In addition, the mixes had 0%, 50% or 100% fine RCA, replacement rates also justified in the conclusions of the same study [58]. The combination of these three fine RCA contents with the two cement types (CEM III/A or CEM I) and the three aggregate powders considered (limestone filler, limestone powder and RCA powder) resulted in a total of 18 mixtures.

The dosage of all SCC mixes is shown in Table 2, which reflects the addition of different binders, aggregate powders and percentages of fine RCA. The mix labelling also showed these aspects following the code *A-B/C*:

- Letter *A* refers to the type of cement added: *I*, CEM I with 100% Portland clinker, and *III*, CEM III/A with 55% Portland clinker and 45% GGBFS.

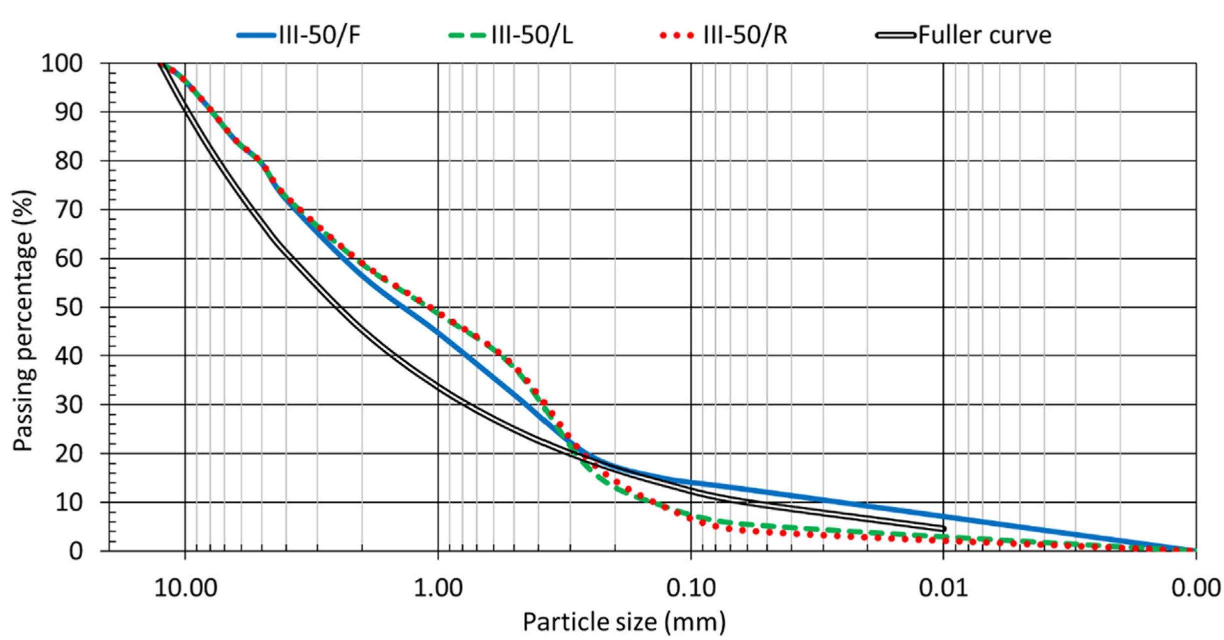

Fig. 2 – Granulometry of CEM III/A SCC mixes manufactured with 50% fine RCA.

Table 2 – Mix design.

Component	III – 0/F	III – 50/F	III – 100/F	I – 0/F	I – 50/F	I – 100/F
CEM I	0	0	0	300	300	300
CEM III/A	425	425	425	0	0	0
Water	185	210	235	185	210	235
Limestone filler	170	170	170	170	170	170
Fine RCA	0	510	1020	0	510	1020
Fine NA	1120	560	0	1120	560	0
Coarse RCA	430	430	430	530	530	530
Viscosity regulator	2.30	2.30	2.30	2.30	2.30	2.30
Plasticizer	4.50	4.50	4.50	4.50	4.50	4.50
Component	**III - 0/L**	**III - 50/L**	**III - 100/L**	**I - 0/L**	**I - 50/L**	**I - 100/L**
CEM I	0	0	0	300	300	300
CEM III/A	425	425	425	0	0	0
Water	185	210	235	185	210	235
Limestone powder	340	340	340	340	340	340
Fine RCA	0	440	880	0	440	880
Fine NA	960	480	0	960	480	0
Coarse RCA	430	430	430	530	530	530
Viscosity regulator	2.30	2.30	2.30	2.30	2.30	2.30
Plasticizer	4.50	4.50	4.50	4.50	4.50	4.50
Component	**III - 0/R**	**III - 50/R**	**III - 100/R**	**I - 0/R**	**I - 50/R**	**I - 100/R**
CEM I	0	0	0	300	300	300
CEM III/A	425	425	425	0	0	0
Water	200	220	245	200	220	245
RCA powder	305	305	305	305	305	305
Fine RCA	0	440	880	0	440	880
Fine NA	960	480	0	960	480	0
Coarse RCA	430	430	430	530	530	530
Viscosity regulator	2.30	2.30	2.30	2.30	2.30	2.30
Plasticizer	4.50	4.50	4.50	4.50	4.50	4.50

- Letter *B* means the content of fine RCA in percentage terms: 0%, 50% or 100%.
- Finally, letter *C* shows the nature of the aggregate powder used. Therefore, an *L* stands for limestone powder, an *R* for RCA powder, and an F for limestone filler.

2.3. *Experimental work*

Once the mix design had been defined, the SCC mixes and the specimens for the different experimental tests were manufactured. Other authors have shown that a staged mixing process achieves higher self-compactability when using RCA [50], due to the fact that both binder hydration and water absorption of the aggregates is maximized in this type of process [38]. Therefore, when mixing, the components were added in three stages: (1) addition of all aggregates and 50% of water; (2) binder incorporation (CEM I or CEM III/A) and pouring in the remaining water; (3) addition of the admixtures. The SCC was left to mix and rest for three and 2 min, respectively, after each stage. These times were determined through pre-testing with different mixing and resting times. All components were used under laboratory conditions (humidity and temperature of 60 ± 5% and 20 ± 2 °C, respectively).

When mixing ended, the fresh tests were carried out: slump flow (EN 12350-8 [51]) and L-box (EN 12350-10 [51]). Subsequently, specimens were prepared for the hardened state tests (Table 3 and Fig. 3), which remained in a humid chamber (humidity and temperature of 90 ± 5% and 20 ± 2 °C, respectively) until the test. The results of the hardened state tests were firstly analyzed in a descriptive way. Subsequently, they were statistically analyzed using one-way ANalysis Of VAriance (ANOVA), which allowed evaluating the significance of the effect of each modification in the composition of the SCC (addition of GGBFS, of

Table 3 – Specimens used in hardened-state tests.

Test performed	Testing age (days)	Specimens number	Specimens	Regulation [51]
Hardened density	28	2	10 × 10 × 10-cm cubic specimens	EN 12390-7
Compressive strength	1, 7, 28, 90	3	10 × 10 × 10-cm cubic specimens	EN 12390-3
Compressive strength	7, 28	2	10 × 20-cm cylindrical specimens	EN 12390-3
Modulus of elasticity	7, 28	2	10 × 20-cm cylindrical specimens	EN 12390-13
Splitting tensile strength	7, 28	2	10 × 20-cm cylindrical specimens	EN 12390-6
Flexural strength	7, 28	2	7.5 × 7.5 × 27.5-cm prismatic specimens	EN 12390-5

Fig. 3 – Compressive-strength tests on cylindrical specimen (left) and cubic specimen (right).

different amounts of fine RCA and of aggregate powders of different nature) and their interactions on every hardened property of SCC.

2.4. *Theoretical assessment of mechanical properties*

Once the experimental results of the different properties studied were known, these were compared with the theoretical values calculated with the formulas from the different European and US standards [52–54].

Both ACI 318-19 [52] (US standard) and Eurocode 2 (EC2) [53] (European standard), on which the Spanish standard EHE-08 [54] is based, include expressions to estimate all the mechanical properties (Table 4). All these properties are estimated through the compressive strength. No specific expressions are found in these standards for recycled aggregate SCC. The specifications in relation to this waste are limited to the establishment of criteria on the characteristics that the RCA should have, in order to be used in concrete production [59,60]. The suitability of these formulas for the RCA mixtures is evaluated in this study. In addition, a simple-regression-based model was developed, with which the different mechanical values of the mixtures could be studied with precision, serving as a basis for their use in similar mixtures.

Table 4 – Formulas to estimate mechanical properties according to European and US regulations.

Modulus of elasticity		
EC2 [53]	EHE-08 [54]	ACI 318-19 [52]
$E_{c,m} = \left\| exp\left\{0.2 \times \left[1-\left(\frac{28}{t}\right)^{0.5}\right]\right\}\right\|^{0.5} \times E_{c,m,28}$ $E_{c,\,m,28} = 21,500 \times \left(\frac{\rho}{2.2}\right)^2 \times \left(\frac{f_{c,m,28}}{10}\right)^{0.3}$	$E_{c,m} = \left(\frac{f^*_{c,m}}{f_{c,m,28}}\right)^{0.3} \times E_{28}$ $E_{c,m,28} = 8,500 \times \sqrt[3]{f_{c,m,28}}$ $f^*_{c,m} = exp\left\{0.2 \times \left[1-\left(\frac{28}{t}\right)^{1/2}\right]\right\} \times f_{c,m,28}$	$E_{c,m} = 4,700 \times \sqrt{f_{c,m}}$
Splitting tensile strength		
EC2 [53]	**EHE-08** [54]	**ACI 318-19** [52]
$\left\{\begin{array}{l} f_{ct,m} = 0.30 \times (f_{c,m}-8)^{2/3} \text{ if } f_{c,m} \le 58\,MPa \\ f_{ct,m} = 2.12 \times \ln(1+0.1 \times (f_{c,m})) \text{ if } f_{c,m} > 58\,MPa \end{array}\right\}$	$\left\{\begin{array}{l} f_{ct,m} = 0.30 \times (f_{c,m}-8)^{2/3} \text{ if } f_{c,m} \le 58\,MPa \\ f_{ct,m} = 0.58 \times (f_{c,m}-8)^{1/2} \text{ if } f_{c,m} > 58\,MPa \end{array}\right\}$	$f_{ct,m} = 0.56 \times f_{c,m}^{0.5}$
Flexural strength		
EC2 [53]	**EHE-08** [54]	**ACI 318-19** [52]
$f_{ct,m,fl} = 0.435 \times (f_{c,m}-8)^{2/3}$	$f_{ct,m,fl} = max\left\{\left(1.6-\frac{h}{1,000}\right) \times f_{ct,m}; f_{ct,m}\right\}$	$f_{ct,m,fl} = 0.94 \times f_{c,m}^{0.5}$

$f_{c,m}$: medium compressive strength (experimental value) at the age considered, in MPa; $f_{c,m}$*: medium compressive strength calculated theoretically, in MPa; $f_{c,m,28}$: 28-day medium compressive strength (experimental value); $E_{c,m}$: medium static modulus of elasticity, in MPa; $E_{c,m,28}$: 28-day medium static modulus of elasticity, in MPa; $f_{ct,m}$: medium splitting tensile strength, in MPa; $f_{ct,m,fl}$: medium flexural strength, in MPa; ρ, hardened density of concrete, in Mg/m^3; t: curing age, in days; h: height of the specimen tested in flexural-strength test, in mm.

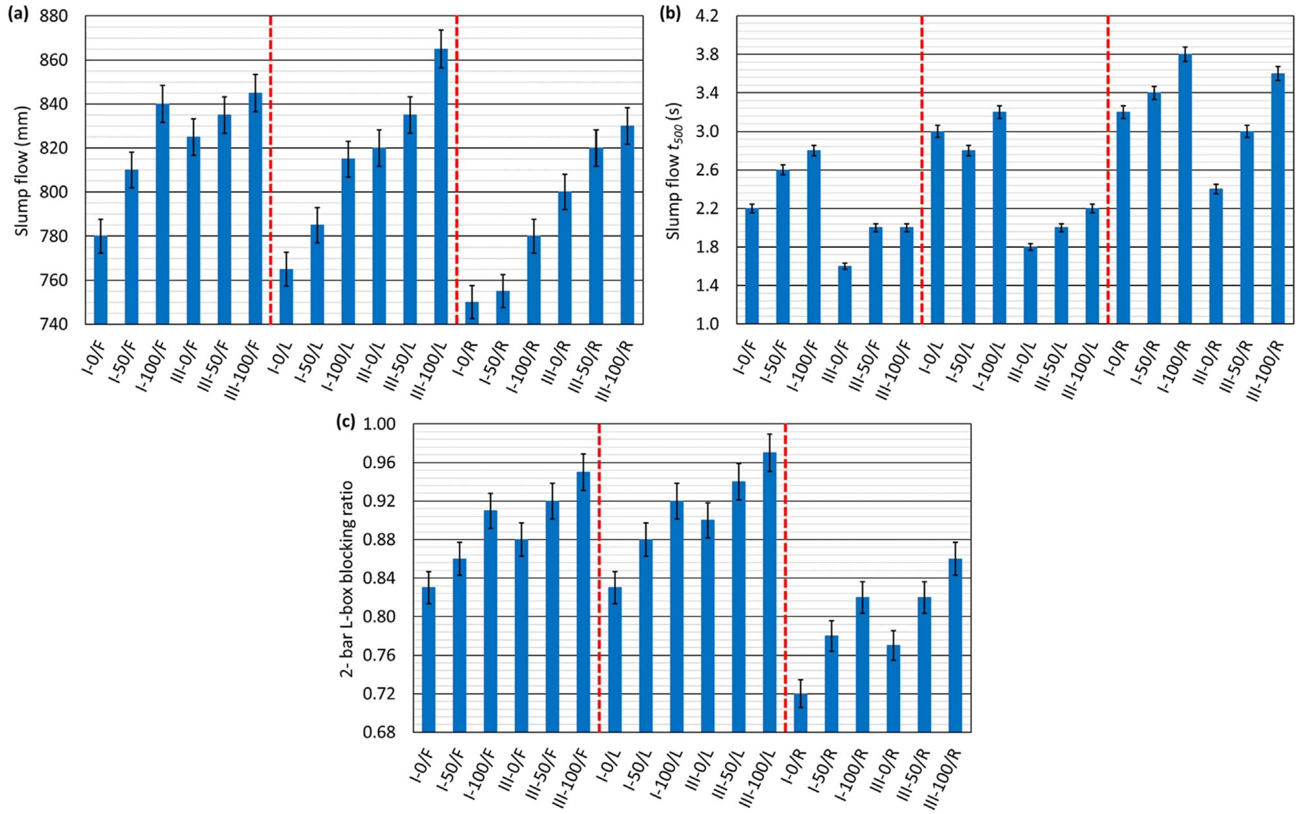

Fig. 4 – Fresh performance of the mixes: (a) slump flow; (b) slump flow t_{500} (s); (c) 2-bar L-box blocking ratio.

3. Results and discussion

3.1. *Filling and passing ability*

Both the slump-flow test and the 2-bar L-box test were used to measure the flowability of the SCC mixes, with the results shown in Fig. 4. A more detailed study of the fresh behavior of similar mixtures has been reported in other article by the authors [17], in which it was studied the temporal evolution, up to 1 h after the end of the mixing process, of all the fresh properties (slump flow, passing ability, V-funnel viscosity and sieve segregation) of this kind of SCC mixes. It was concluded that this kind of SCC mixes met all the requirements for them to be considered as having high flowability.

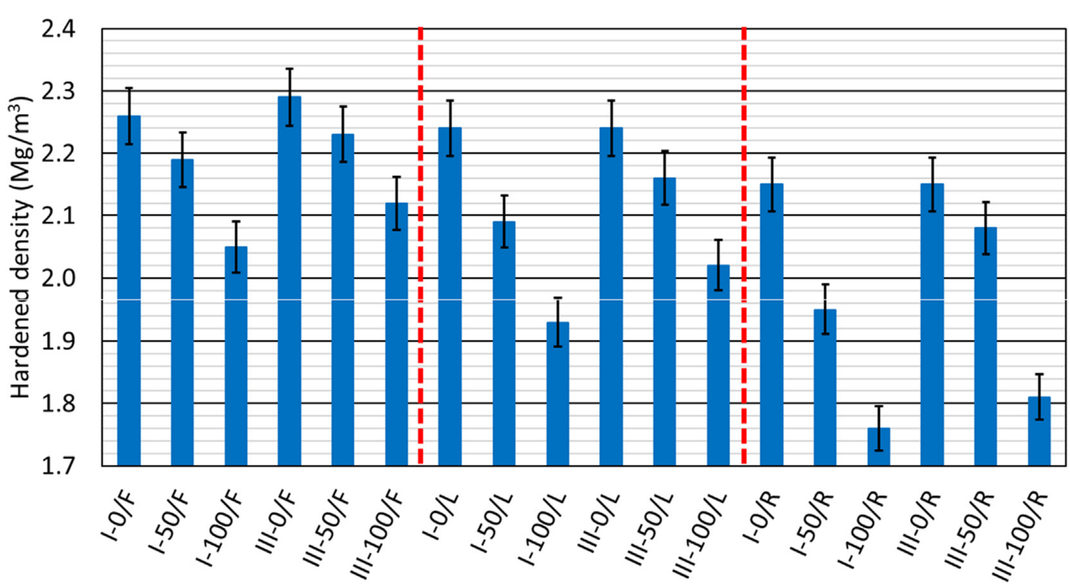

Fig. 5 – Hardened density of SCC mixes.

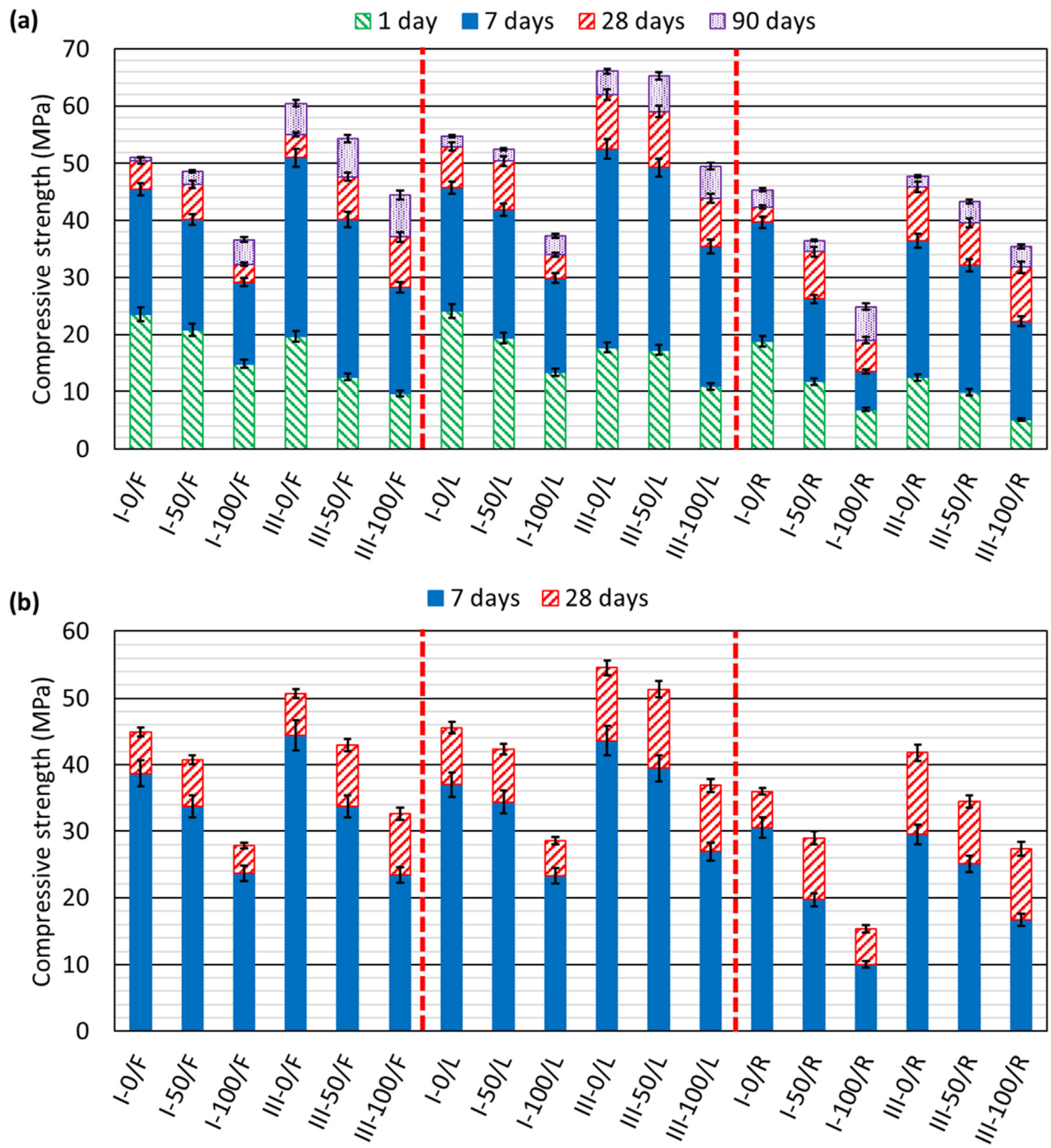

Fig. 6 – Compressive strength on: (a) cubic specimens; (b) cylindrical specimens.

The results showed that the filling capability (Fig. 4(a)) and passing ability (Fig. 4(c)) improved when using CEM III/A and fine RCA:

- First, the lower amount of coarse RCA and, therefore, the higher proportion of fine aggregate in the CEM III/A mixes improved the fresh behavior of SCC, even though the effective w/c ratio was lower.
- Secondly, the higher proportion of the 0/0.25 mm fraction of fine RCA, compared to NA (Fig. 1), also increased the flowability of SCC.

Both aspects demonstrate the great importance of the finer aggregate fractions in the fresh behavior of SCC [45]. Increasing the proportion of the finer fractions of aggregate improved the flowability when adding fine RCA without modifying the effective w/c ratio [43]. It was possible due to the simultaneous substitution of all the fine NA (0/4 mm) for RCA and the higher fine particle content of the latter. If the substitution had been performed size by size, the flowability of SCC may have decreased due to the more irregular shape of RCA particles [50]. The CEM III/A mixes with full replacement of fine NA for RCA had the highest slump flow and blocking ratio, with mean values of 840 mm and 0.93, respectively.

Although the mixtures made with RCA had a higher filling and passing ability than the NA mixes, the addition of RCA was negative for the viscosity of the mixtures (Fig. 4(b)). The addition of 100% of this residue caused an average increase of

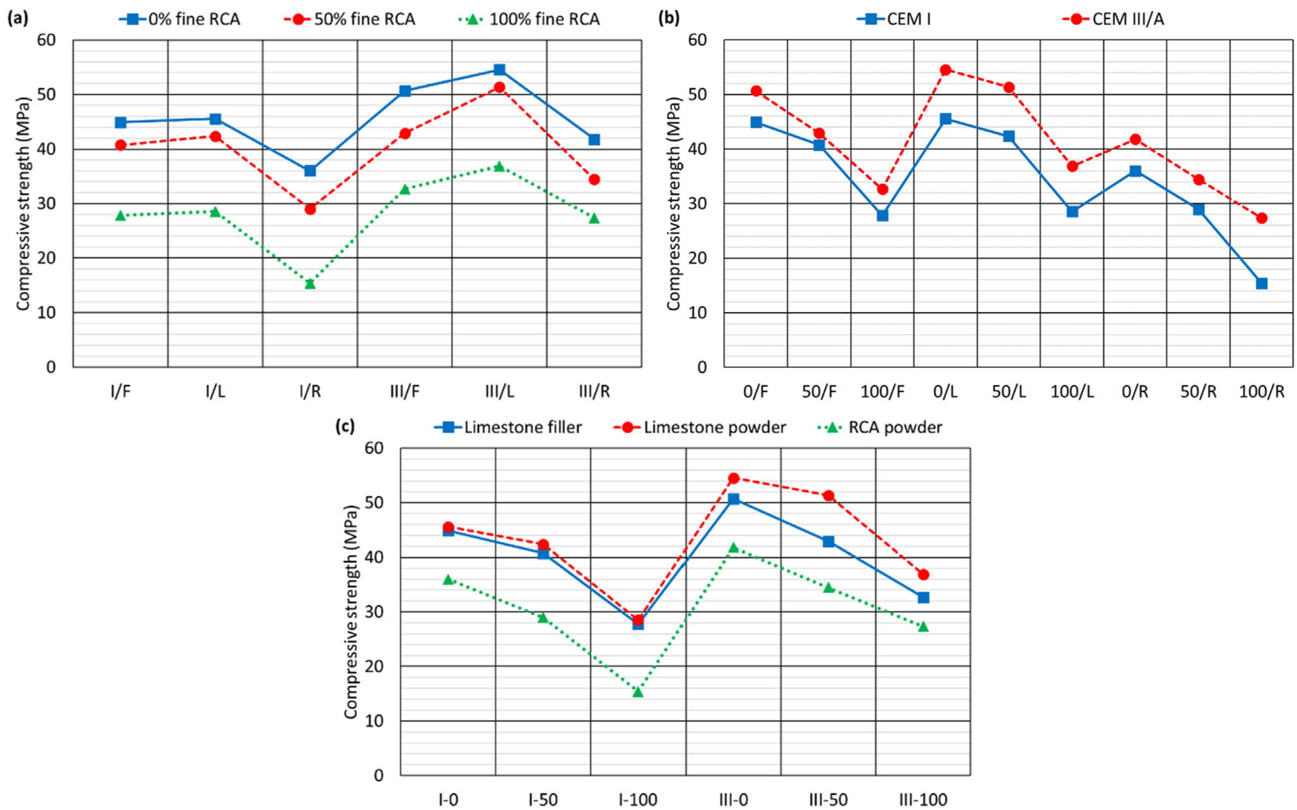

Fig. 7 – Effect of the factors on 28-day compressive strength on cylindrical specimens: (a) content of fine RCA; (b) cement type; (c) nature of aggregate powder.

Table 5 – Confidence intervals ($\alpha = 0.05$) for the coefficient k (Equation (1)).

Mix modification		7 days	28 days
Cement	CEM I	(0.789; 0.824)	(0.835; 0.870)
	CEM III/A	(0.793; 0.840)	(0.869; 0.899)
Fine RCA percentage	0%	(0.803; 0.855)	(0.867; 0.908)
	50%	(0.784; 0.841)	(0.849; 0.889)
	100%	(0.757; 0.816)	(0.824; 0.868)
Aggregate powder	Limestone filler	(0.819; 0.861)	(0.867; 0.910)
	Limestone powder (0/0.5 mm)	(0.773; 0.827)	(0.837; 0.873)
	RCA powder (0/0.5 mm)	(0.740; 0.794)	(0.822; 0.892)
All mixes (regardless of the composition)		(0.794; 0.825)	(0.855; 0.880)
		(0.825; 0.851)	

0.6 s in the t_{500} values. Therefore, the higher proportion of the 0/0.25 mm fraction of fine RCA was not enough to compensate the negative effect of the RCA, as previously reported in the literature [14]. On the contrary, the decrease in the coarse RCA content when incorporating CEM III/A in the mixes did increase the SCC flow velocity: the t_{500} was reduced by 0.4 s on average.

Finally, it appears that the effect of each natural aggregate powder on the initial flowability of SCC was linked to its particle size [49]: the F mixtures showed the best results, followed by the L mixtures. The RCA powder, with high water absorption and irregular shape [18] worsened the fresh performance. Thus, the slump flows of the I-100/R mix and the I-100/F mix were 780 mm and 840 mm, respectively.

3.2. *Hardened density*

Fig. 5 shows the hardened density of the SCC mixes. The density of both the cement and the aggregates conditioned the density value of the resulting SCC, decreasing as the amount of RCA increased, regardless of the fraction used [20]. Furthermore, the higher proportion of cement in the CEM III/A mixes increased mix density, because CEM III/A is denser than coarse RCA, whose content was reduced to improve

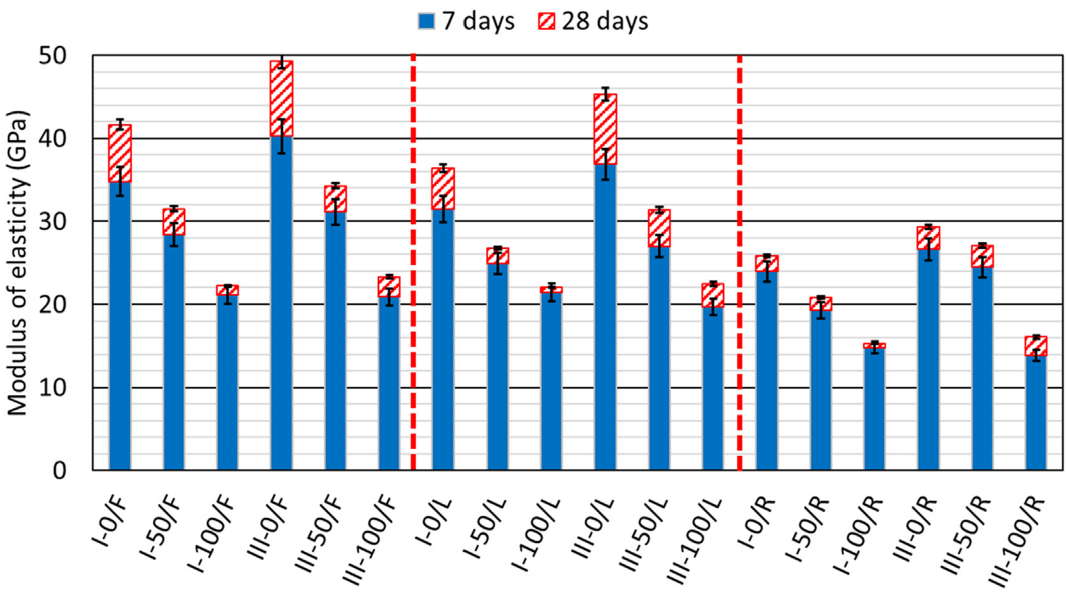

Fig. 8 – Modulus of elasticity on cylindrical specimens at 7 and at 28 days.

flowability. Mix I-100/R (CEM I, 100% fine RCA and RCA powder) had a remarkably low density of 1.76 Mg/m^3.

3.3. *Compressive strength*

In an overview of mix performance, both the compressive-strength results for the 10 × 10 × 10-cm cubic specimens at different curing ages (1, 7, 28, and 90 days) and for the 10 × 20-cm cylindrical specimens at 7 and 28 days are depicted in Fig. 6. Fig. 7 shows the influence of the different factors under analysis (percentage of fine RCA, cement type and nature of the aggregate powder) considering the compressive strength of the cylindrical specimens at 28 days. Despite the addition of 100% coarse RCA, strengths suitable for structural use (45–50 MPa in cylindrical specimens) [52,53] were reached.

The addition of 50% fine RCA to the mixes produced with limestone aggregate powder decreased their 28-day compressive strength by 3–4 MPa on average (Fig. 7(a)). However, the addition of 100% of this waste decreased the compressive strength by 15–16 MPa on cubic specimens. It therefore appears that the use of a limestone aggregate powder and the filler effect caused by fine RCA due to its high proportion of 0/0.25 mm particles could reduce the decrease in compressive strength when adding 50% fine RCA in comparison with other studies [18]. In the CEM III/A mixtures manufactured with RCA powder, the addition of fine RCA led to decreases in their compressive strength similar to those found in the mixes manufactured with CEM III/A and natural aggregate powders, possibly due to good interaction between the RCA powder and the GGBFS. However, this loss of strength increased very noticeably in the CEM I mixes with RCA powder: 28-day compressive strength decrease of 13.6 MPa when 50% fine RCA was added, and 26.2 MPa for 100% fine RCA contents, respectively, considering cubic specimens. Regardless of the aggregate powder in use, the compressive strength acquisition was delayed in time when fine RCA was added, as shown in Fig. 6 [42].

The compressive strength of the CEM III/A mixes was higher than that of the CEM I mixes, despite their higher flowability (Fig. 7(b)). A higher strength that can be explained by the increased proportion of cement and the adjustment of the w/c ratio in compensation for the strength loss that occurred when replacing conventional cement with GGBFS [33], although it delayed strength development (Fig. 6) [40].

No significant difference was detected between limestone filler and limestone powder, especially when using CEM I (Fig. 7(c)). However, limestone powder provided, in general, slightly higher strengths, with the III-0/L mix (CEM III/A, 100% fine RCA and limestone powder) exceeding 65 MPa in the cubic specimens (55 MPa in the cylindrical specimens). The addition of RCA powder yielded the lowest compressive-strength mixes, although its combination with coarse RCA (100% fine NA) and CEM III/A yielded compressive strengths of around 45 MPa. The use of RCA as aggregate powder also delayed strength development, so the percentage increase of compressive strength from 28 to 90 days was higher when this aggregate powder was used, as depicted in Fig. 6(a). The higher water absorption of RCA powder compared to limestone aggregate powders and, therefore, its higher delayed-on-time release of water, may have caused cement hydration to continue for a longer period of time. This phenomenon is known as internal curing [38].

3.3.1. *Relationship between the compressive strengths of cylindrical and cubic specimens*

It is widely known that the compressive strength of cylindrical specimens (CS_{cyl}) is lower than the compressive strength of cubic specimens (CS_{cub}), due to the less compact shape and greater slenderness of the cylinder. Usually, both are linearly related through Equation (1), in which the coefficient k takes a value between 0.8 and 0.85 [53]. Regarding the SCC mixes analyzed in this study, the average coefficient R^2 for the linear regression was 98%, quite a high value that shows the validity of the traditional method at correlating the compressive

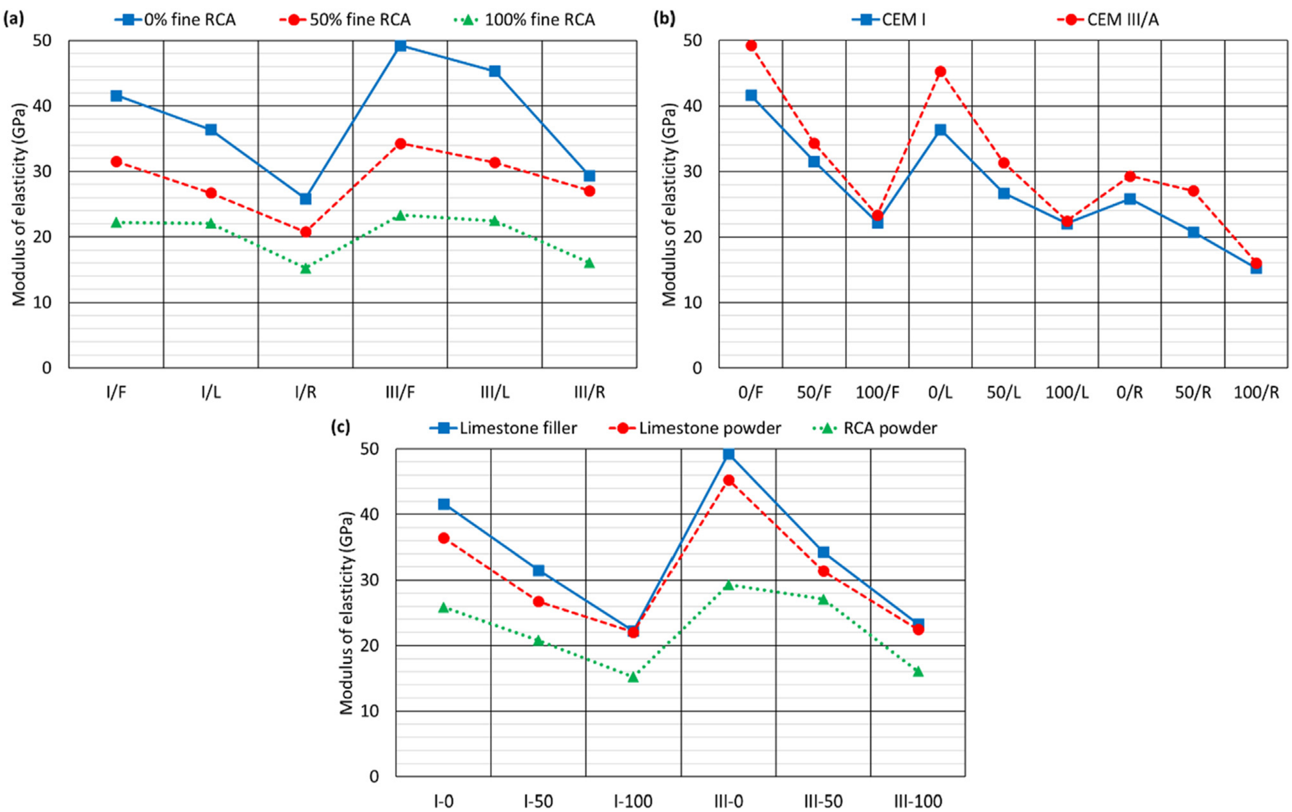

Fig. 9 – Effect of the factors on the modulus of elasticity at 28 days: (a) content of fine RCA; (b) cement type; (c) nature of aggregate powder.

strengths of both the cylindrical and the cubic specimens for these sorts of mixes. The confidence intervals (5% significance level) for the adjustment coefficient k obtained from the results of the different mixtures are shown in Table 5. The results are presented distinguishing between the modifications performed in the SCC composition.

$$CS_{cyl} = k \times CS_{cub} \quad (1)$$

Apart from the fact that the traditional values are valid for the SCC mixes, the confidence intervals show that this coefficient is notably linked to the brittle-breakage mode of the cylindrical specimen. For this reason, the CEM III/A mixes, with a higher cement proportion, and natural aggregate powder, especially limestone filler, presented higher values for this coefficient. Along the same lines, the higher deformability of RCA compared to NA [61] decreased the value of this coefficient. With respect to age, the coefficients were slightly higher at 28 days, due to the higher strength development and, therefore, to a more brittle breakage of the concrete specimens.

3.4. *Modulus of elasticity*

The elastic deformability of concrete is measured by its modulus of elasticity [52]. This property was measured on 10 × 20-cm cylindrical specimens at 7 and 28 days, as depicted in Fig. 8. The influence of each factor (fine RCA amount, cement type, and aggregate-powder nature) is shown in Fig. 9.

The elastic stiffness of the mixtures with 100% fine NA (0% fine RCA but 100% coarse RCA) was high. One example is mix I-0/F (CEM I, 0% fine RCA and limestone filler) that had a 28-day modulus of elasticity of 41.6 GPa. When adding fine RCA, the modulus of elasticity decreased with the fine RCA content (Fig. 9(a)) due to the higher flexibility of RCA [23]. This decrease was especially notable in the mixes manufactured with CEM III/A and natural aggregate powder. Furthermore, the addition of RCA as aggregate powder caused an even higher decrease of the elastic stiffness of SCC (Fig. 9(c)). Thus, the I-100/R mix reached a modulus of elasticity of only 15.2 GPa at 28 days. This shows the clearly cumulative effect that the addition of RCA, regardless of its fraction, has on the modulus of elasticity [42]. The difference between the 7-day and the 28-day modulus of elasticity was higher when low amounts of RCA were added, due to the more prolonged stiffness development in the long term that is associated with the use of fine RCA, as shown in Fig. 8 [58].

In principle, the CEM III/A mixes should be of greater stiffness, due to their higher cement content and strength [53]. Thus, CEM III/A mixes made with 0% fine RCA had a higher modulus of elasticity than the mixes with CEM I made with the same fine RCA content. However, a higher RCA content caused the moduli of elasticity of the mixes with both types of cement to equalize, as clearly shown in Fig. 9(b). For example, the difference in this mechanical property at 28 days between mixes III-0/L and I-0/L (0% fine RCA and limestone powder, but different type of cement) was 9 GPa, while it was reduced to only 0.5 GPa between mixes III-100/L and I-100/L. This result shows that the interaction between GGBFS and fine RCA was negative for the elastic stiffness of SCC. Furthermore, the addition of CEM III/A also delayed the acquisition of elastic stiffness, as observed in other studies [62].

There was no clear influence of the different natural aggregate powders on the elastic stiffness of SCC. The limestone filler provided a slightly higher stiffness to the mixtures, although this difference became smaller as the amount of fine RCA in SCC increased (Fig. 9(c)). So, mix III-0/F had the highest modulus of elasticity of all mixes, 49.3 GPa. The addition of RCA powder resulted in the SCC mixes with the lowest modulus of elasticity.

3.4.1. *Estimation of the modulus of elasticity*

The estimation of this mechanical property, according to EC2 [53] and EHE-08 [54], is done through the 28-day compressive strength, regardless of the age at which the elastic modulus is estimated. The ACI 318-19 [52] formula uses the compressive strength obtained at the same age for which the modulus of elasticity is to be determined. All these expressions (see Table 4) generally overestimated the experimental modulus of elasticity (Fig. 10 and Fig. 11). However, the overestimation was lower when using the EHE-08 expression [54], while the worst fit occurred for the ACI 318-19 formula [52]. With the latter formula, only the experimental values of the CEM III/A mixes that incorporated 100% fine RCA and natural aggregate powder exceeded the theoretical estimations.

Apart from the expression under consideration, other aspects also affected the accuracy of this estimation:

- The modifications to mix composition [14]. Thus, the addition of RCA, regardless of its fraction, increased this overestimation.
- The type of specimen utilized for the measurement of compressive strength. Thus, the fit improved when using the compressive strength of the cylindrical specimens.
- The age of the concrete, since the overestimation of the modulus of elasticity was slightly lower at more advanced ages.

Finally, the use of the density correction from EC2 [53] (see Table 4) improved the estimation. With the use of this correction, the overestimation of the modulus of elasticity had an average value of 8 and 5 GPa when considering the compressive strength of the cubic and the cylindrical specimens, respectively (Fig. 12). Without this correction, the overestimation was between 10-to-12 GPa (Figs. 10 and 11).

3.5. *Splitting tensile strength*

Analogies and differences can be detected between the trends shown by the compressive strength and the splitting tensile strength, as shown in Fig. 13, trends that also emerge when the effect of each factor (percentage of fine RCA, cement type,

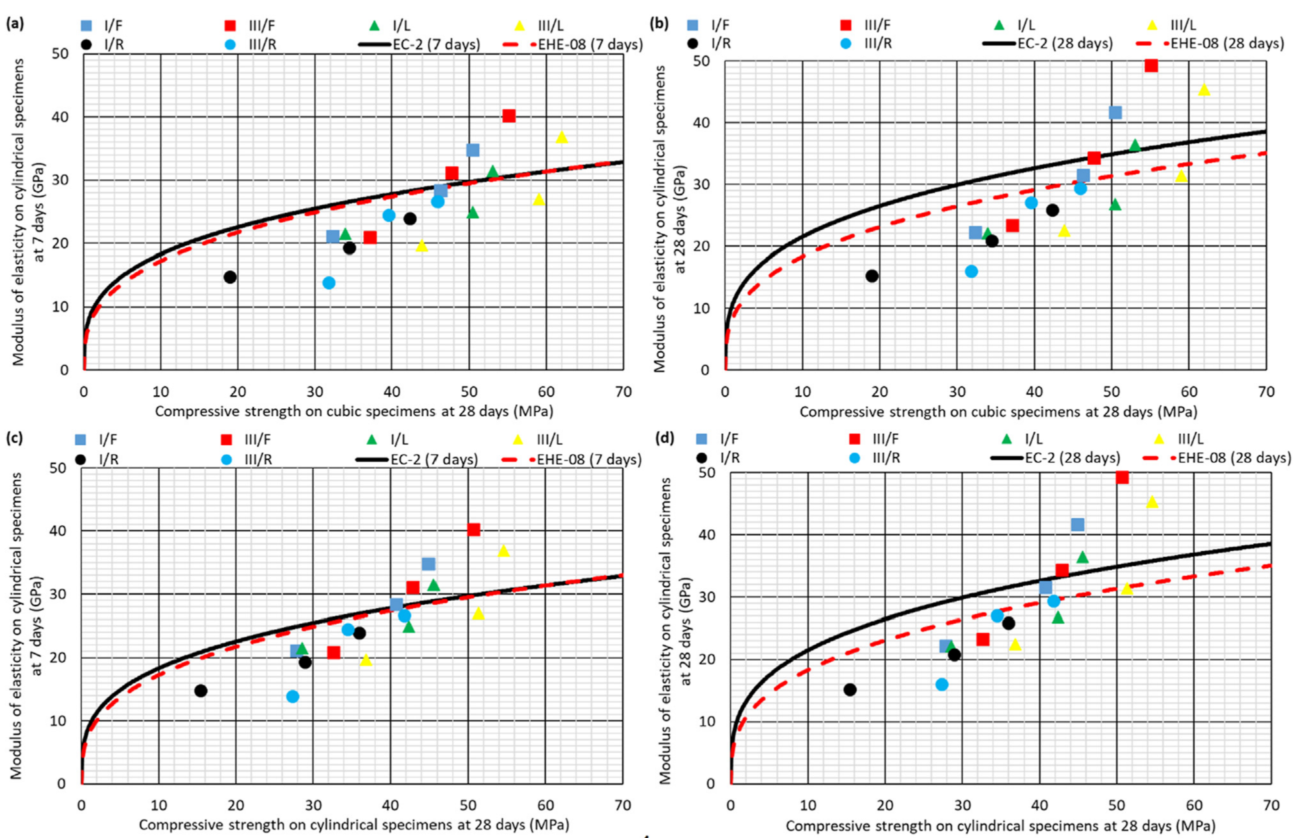

Fig. 10 – Relation between estimated and experimental elastic moduli as per EC2/EHE-08 [53,54]: (a) 7-day elastic modulus of cubic-specimen compressive strength; (b) 28-day elastic modulus of cubic-specimen compressive strength; (c) 7-day elastic modulus of cylindrical-specimen compressive strength; (d) 28-day elastic modulus of cylindrical-specimen compressive strength.

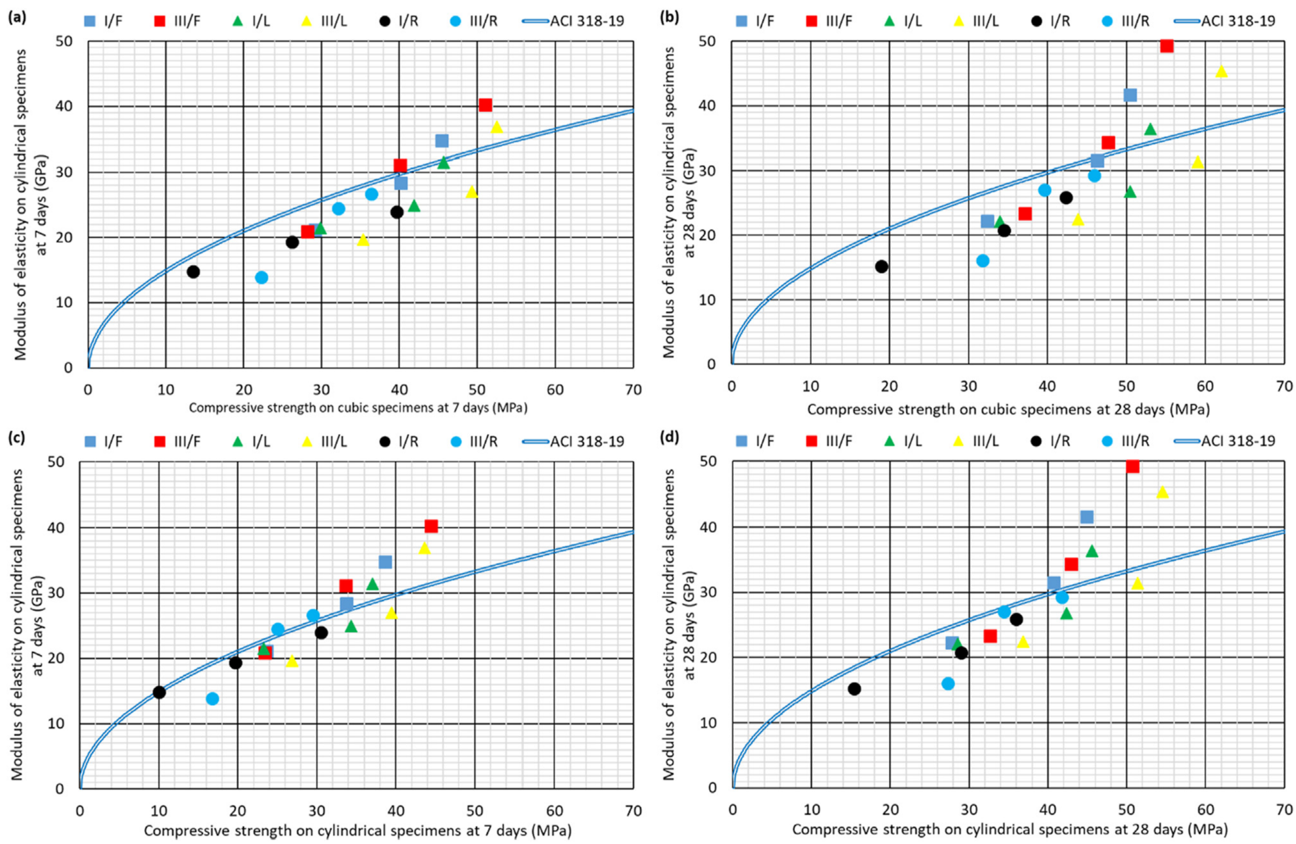

Fig. 11 – Relation between estimated and experimental elastic moduli as per ACI 318-19 [52]: (a) 7-day elastic modulus of cubic-specimen compressive strength; (b) 28-day elastic modulus of cubic-specimen compressive strength; (c) 7-day elastic modulus of cylindrical-specimen compressive strength; (d) 28-day elastic modulus of cylindrical-specimen compressive strength.

and nature of the aggregate powder) is individually analyzed (Fig. 14).

The analogies between compressive and splitting tensile strengths are evident regarding the effect of fine RCA, as it clearly decreased both strengths (Fig. 14(a)), although the use of 100% coarse RCA yielded adequate values for this mech/anical property [52,53]. Nevertheless, the relative reduction in splitting tensile strength when 50% fine NA was replaced with RCA was significantly greater than the reduction of the compressive strength, which shows the higher sensitivity of splitting tensile strength to the addition of medium fine RCA contents, as has also been confirmed in other studies [9]. Thus, for example, the splitting tensile strength was 2.55 MPa for the III-50/L mix (CEM III/A, 50% fine RCA and limestone powder) and 2.28 MPa for the III-100/L mix, while this property was 3.59 MPa for the III-0/L mix. This very similar relative decrease caused by both fine RCA contents, especially in the CEM III/A mixes, could be because the use of fine RCA produced a cement paste that presented poor adhesion with the coarse RCA [63], and the content of coarse aggregate of SCC had to be reduced when CEM III/A was used. The addition of GGBFS also reduced the gain of splitting tensile strength between 7 and 28 days (Fig. 13), which is attributed to longer strength development over time [64].

Increasing the cement content in the CEM III/A mixtures led to an increase of the compressive strength. However, the CEM I mixes had a higher splitting tensile strength (Fig. 14(b)). Furthermore, this difference was greater in the mixes with higher splitting tensile strength, such as the mixes made with limestone powder: the III-0/L mix (CEM III/A, 0% fine RCA and limestone powder) at 28 days (3.59 MPa) had a splitting tensile strength that was 15.5% lower than that of the I-0/L mix (4.25 MPa). This behavior could be due to two aspects. First, the lower content of coarse RCA in the CEM III/A mixes [20], which was necessary to ensure that no segregation occurred in the slump-flow test. Second, the worse behavior of GGBFS than conventional clinker under tensile stresses when this alternative binder was used in large quantities [40].

Regarding the aggregate powder, the mixes made with limestone powder presented higher strengths (Fig. 14(c)). The result of using RCA as aggregate powder was better than expected [18], especially in the mixes with 0% fine RCA. Thus, the splitting tensile strengths of mix I-0/R (CEM I, 0% fine RCA and RCA powder) and mix III-0/R were 3.66 MPa and 3.18 MPa, respectively. These values were higher than those of the mixes manufactured with limestone filler (3.33 MPa when using CEM I and 3.15 MPa when adding CEM III/A). The good

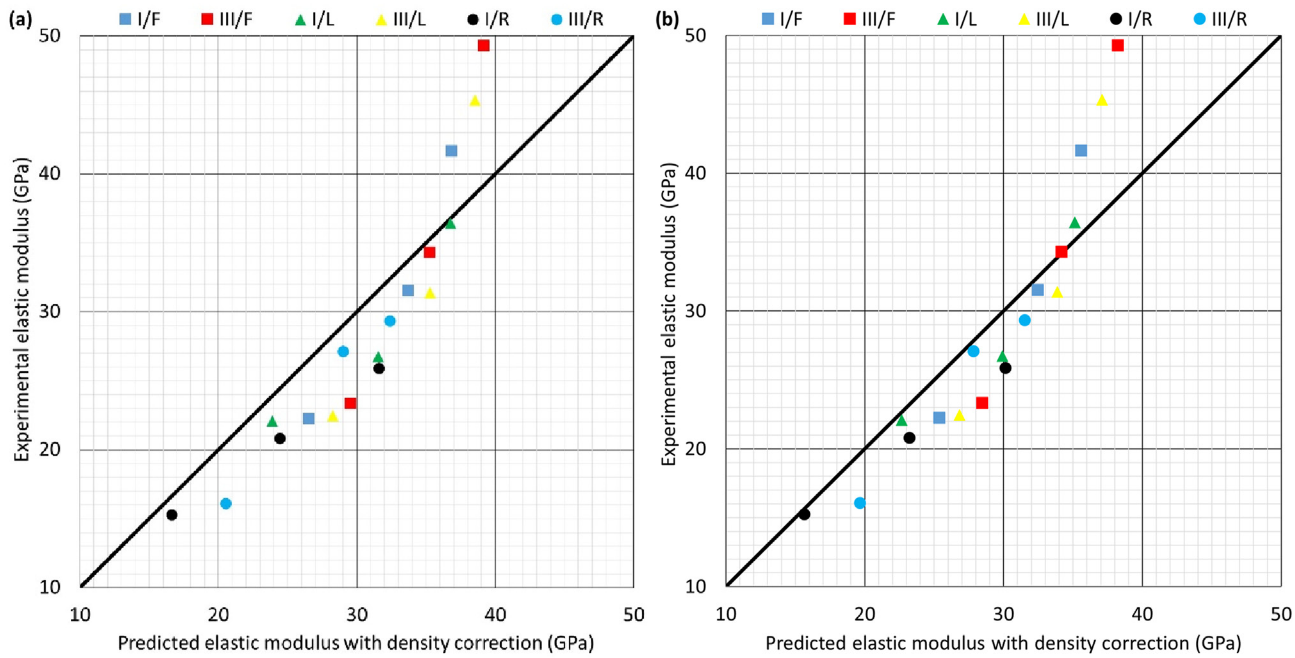

Fig. 12 – Comparison between experimental and estimated (with density correction) elastic modulus according to EC2 [53]: (a) cubic-specimen compressive strength at 28-days; (b) cylindrical-specimen compressive strength at 28-days.

interaction between the GGBFS and the RCA powder could explain these slightly surprising results.

3.5.1. *Estimation of the splitting tensile strength according to the standards*

Fig. 15 and Fig. 16 show the comparison between the theoretical and experimental (see Table 4) splitting tensile strength, considering the compressive strengths of both the cubic and the cylindrical specimens. In general, the formulas of all standards overestimated the experimental values, indicating that all the mixtures had lower experimental splitting tensile strengths than expected. This phenomenon is common in SCC, where the high fine aggregate content required to achieve self-compactability usually implies that this type of concrete presents a lower splitting tensile strength [14].

The overestimation was higher when using the ACI 318-19 [52] formula, which overestimated the strength of practically all the mixtures. On the other hand, the EC2 [53] and EHE-08 [54] formulas overestimated between 50% and 80% of the experimental results, depending on the age and the type of specimen considered to obtain the compressive strength. The

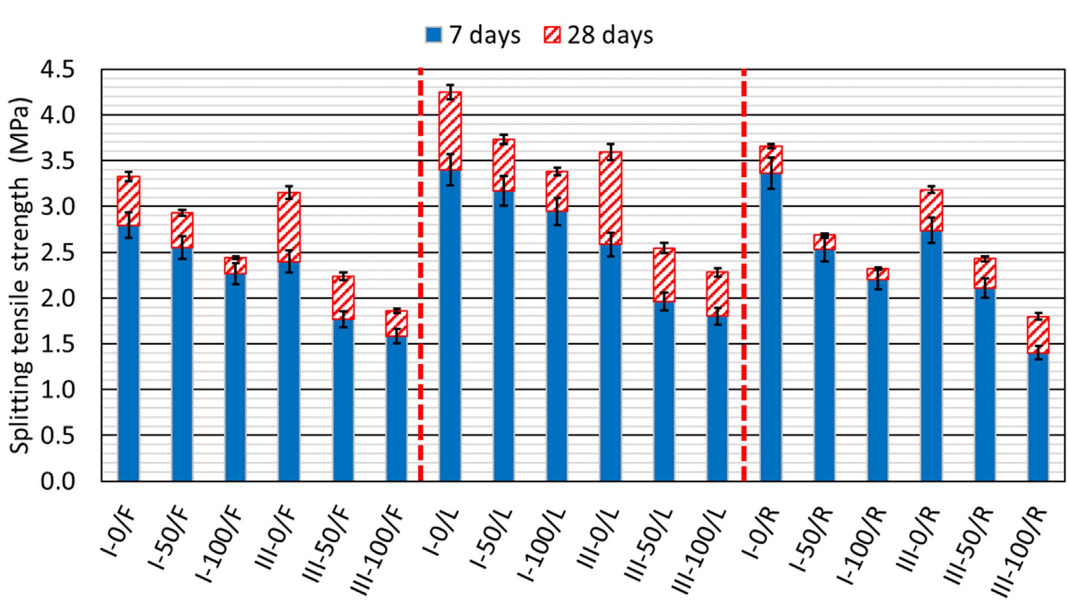

Fig. 13 – 7-Day and 28-day splitting tensile strength.

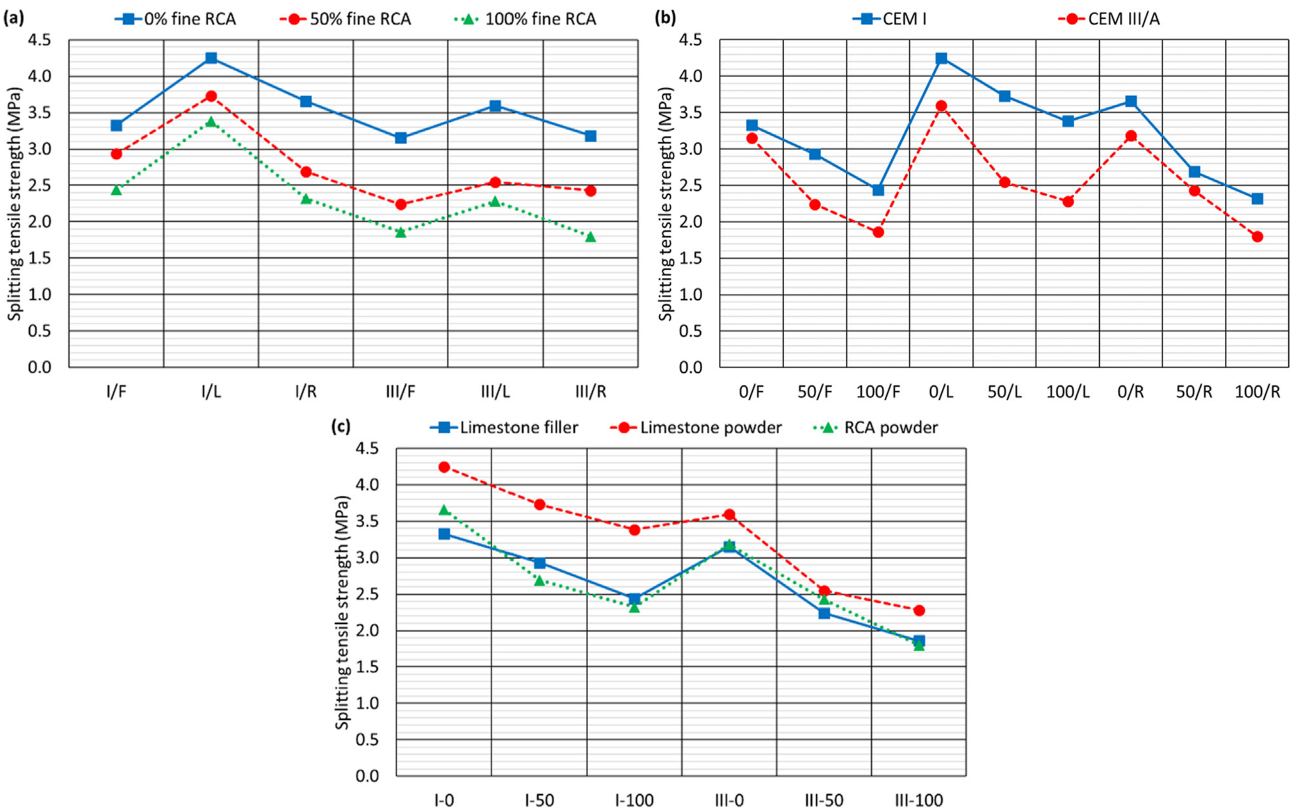

Fig. 14 – Effect of the factors on 28-day splitting tensile strength: (a) content of fine RCA; (b) cement type; (c) nature of aggregate powder.

application of these formulas with the compressive strength obtained on cubic specimens, higher than on cylindrical specimens, also led to higher overestimations. Similarly, the use of the 28-day compressive strength slightly improved the accuracy of this estimation. In summary, the best estimate was obtained from the 28-day compressive strength results on cylindrical specimens and with the formulation of the European standards.

In relation to the composition of SCC, the mixtures I/L and I/R presented the best estimation, the splitting tensile strength of which was underestimated in most cases. Therefore, the use of this formulation with those mixtures was safe. On the other hand, the mixes with CEM III/A, which had low splitting tensile strengths taking into account their compressive strengths, exhibited the worst fit.

3.6. *Flexural strength*

The performance of the mixes regarding their flexural strength was very similar to that of the splitting tensile strength, except for the effect of CEM III/A, as shown in Fig. 17 for both 7 and 28 days, and in Fig. 19 regarding the effect of the

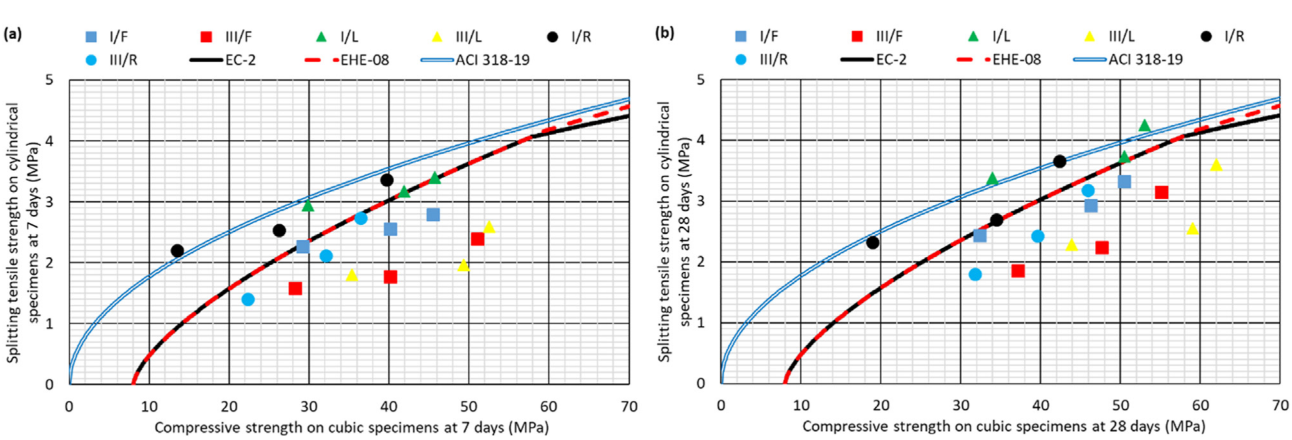

Fig. 15 – Relation between experimental and theoretical splitting tensile strength calculated from the compressive strength of cubic specimens: (a) 7 days; (b) 28 days.

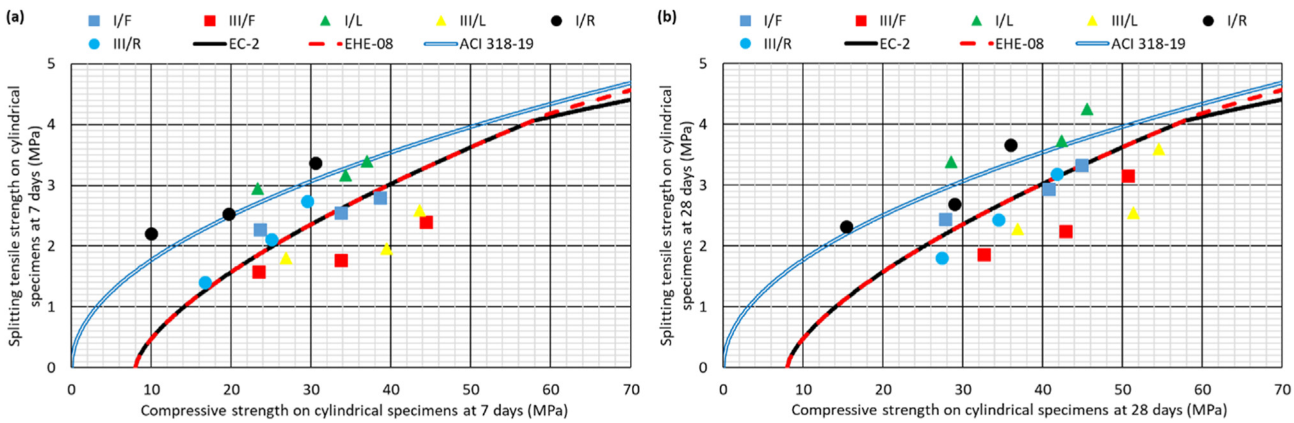

Fig. 16 – Comparison between experimental and theoretical splitting tensile strength calculated from the compressive strength of cylindrical specimens: (a) 7 days; (b) 28 days.

factors (fine RCA amount, cement type and aggregate-powder nature) at 28 days.

The use of 100% coarse RCA reached adequate flexural strength values [52,53]. In contrast, any increase of the fine RCA content decreased the flexural strength, as in similar studies [64], so that 100% fine RCA caused a reduction of the flexural strength of around 1–2.5 MPa (Fig. 19(a)). In addition, it also reduced the strength increase between 7 and 28 days (Fig. 17).

Unlike the splitting tensile strength, the CEM III/A mixes showed slightly higher flexural strength than the CEM I mixes (Fig. 18(b)). In fact, the mix with the highest flexural strength was mix III-0/L (CEM III/A, 0% fine RCA and limestone powder), 5.9 MPa, compared to 5.4 MPa for mix I-0/L. This behavior was more in line with expectations, due to its higher cement content and higher compressive strength [52]. It also reflects that, under bending stresses, the response of the mixes was mainly conditioned by the compression zone [8], since the poor tensile behavior of the mixes with CEM III/A hardly appeared to influence performance in this test.

Limestone powder performed better than limestone filler (Fig. 18(c)), as other studies have shown [26]. As expected, the mixes prepared with RCA powder had the lowest strength, due to its detrimental properties [36], as mix I-100/R (CEM I, 100% fine RCA and RCA powder) only reached a flexural strength of 2.9 MPa. Nevertheless, when adding 50–100% fine RCA bearing CEM III/A, RCA powder provided higher flexural strength than limestone filler. Regarding the interaction between fine RCA and aggregate powder, fine RCA exhibited the most detrimental effect in the mixes with limestone filler. Thus, adding 50% fine RCA decreased the flexural strength of these mixes by 1.4–1.6 MPa, while this decrease in the other mixes was only 0.4–0.7 MPa.

3.6.1. *Estimation of flexural strength as per the standards*

A comparison of the theoretical (Table 4) and the experimental results for both flexural strength and splitting tensile strength showed similar trends, as reflected in Fig. 19 and Fig. 20. A result that was due to the low flexural strength of the

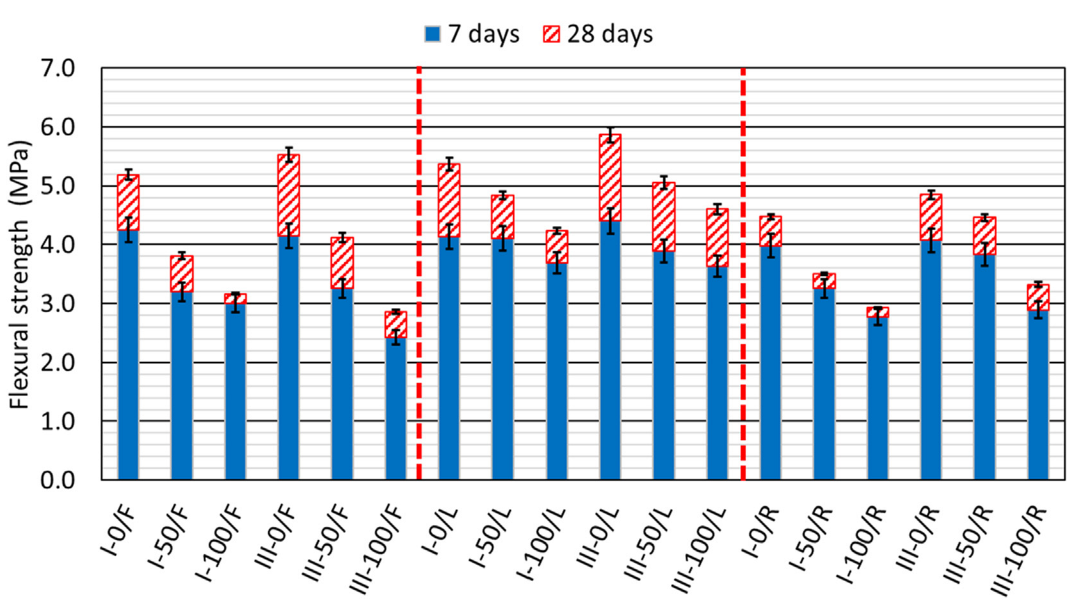

Fig. 17 – Flexural strength at 7 and at 28 days (7.5 × 7.5 × 27.5-cm prismatic specimens).

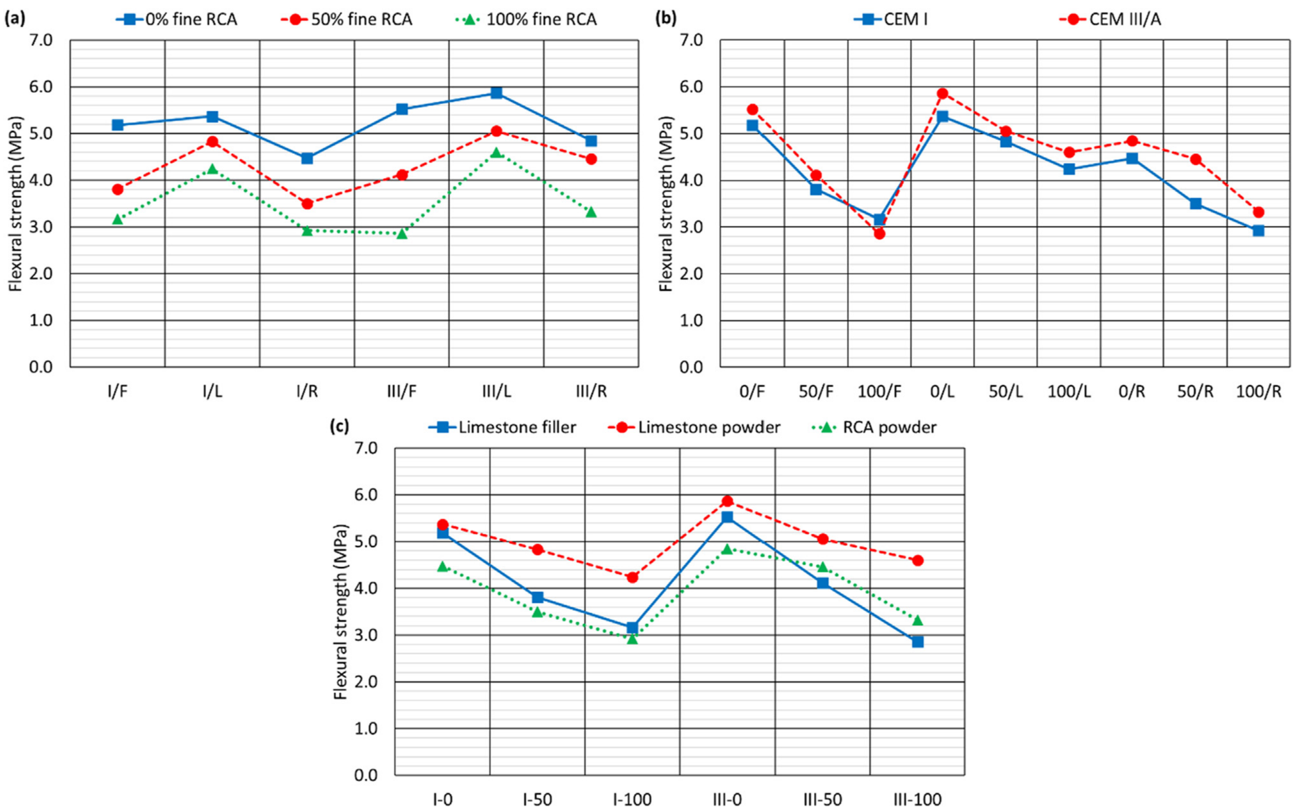

Fig. 18 – Effect of the factors on 28-day flexural strength: (a) content of fine RCA; (b) cement type; (c) nature of aggregate powder.

SCC mixes under development, due to their high fines content [14].

The best estimation (lower overestimation) was obtained using the formulas of the European standard, in this case EC2 [53], at advanced ages (28 days) and with the use of the compressive strength on cylindrical specimens. Again, the III/F mixes (CEM III/A and limestone filler) were the ones that presented the worst fit, while the best estimation was for the mixes with RCA powder. It is also noteworthy that the ACI 318-19 [52] formulation overestimated the flexural strength of all the mixtures, regardless of the age and the type of specimen under consideration in relation to compressive strengths.

3.7. *Statistical approach*

3.7.1. *Effect of the factors: one-way ANOVA*

One-way ANOVA was used to determine whether each change in the SCC composition had a significant effect on a property (in this study, the different mechanical properties of concrete) [58]. Furthermore, it revealed homogenous groups, *i.e.*, groups of factors that have the same statistical effect on the property

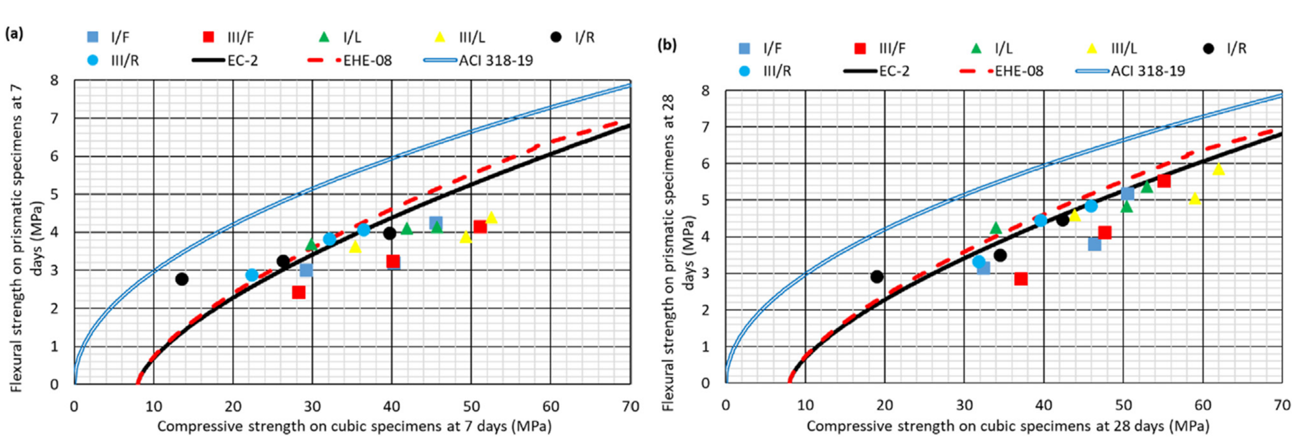

Fig. 19 – Relation between experimental and theoretical flexural strength calculated from the compressive strength of the cubic specimens: (a) 7 days; (b) 28 days.

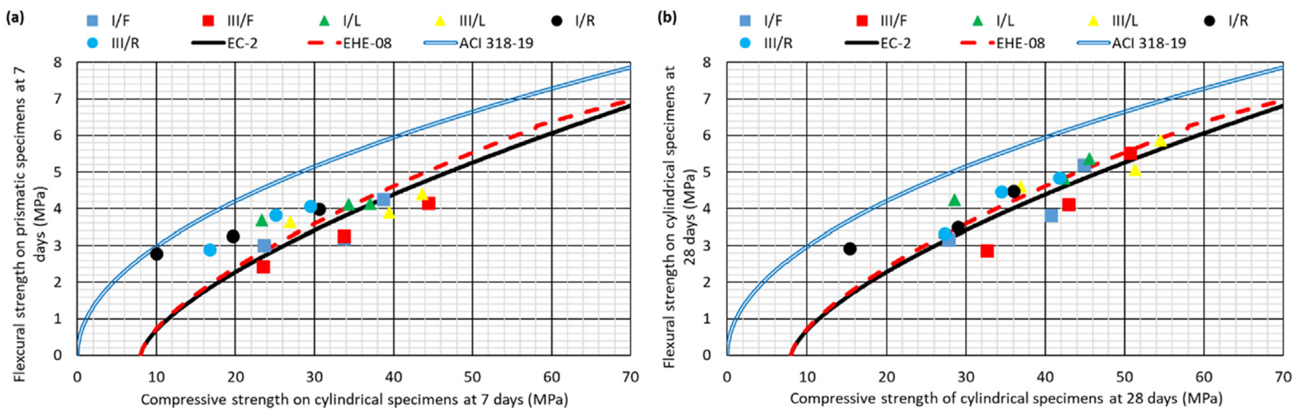

Fig. 20 – Relation between experimental and theoretical flexural strength calculated from the compressive strength of the cylindrical specimens: (a) 7 days; (b) 28 days.

Table 6 – One-way ANOVA ($\alpha = 0.05$).

Property	Factor	*p*-value		Homogeneous groups: 28-day mechanical properties
		7 days	28 days	
Compressive strength	Aggregate powder	0.0305	0.0037	L and F
	Fine RCA content	0.0002	0.0003	0% and 50%
	Cement type	0.2889	0.0373	None
Modulus of elasticity	Aggregate powder	0.0041	0.0058	L and F
	Fine RCA content	0.0000	0.0000	None
	Cement type	0.4558	0.2731	CEM I and CEM III/A
Splitting tensile strength	Aggregate powder	0.6276	0.0408	F and R
	Fine RCA content	0.0021	0.0000	None
	Cement type	0.0017	0.0033	None
Flexural strength	Aggregate powder	0.0156	0.0047	F and R
	Fine RCA content	0.0001	0.0001	None
	Cement type	0.9440	0.3430	CEM I and CEM III/A

that is analyzed [65]. For example, the percentages of fine RCA or the different aggregate powders that affect a mechanical property in the same way. The results obtained through this analysis on the mixes produced at 7 and 28 days are shown in Table 6.

Considering a significance level of 5%, the results provided by the one-way ANOVA confirmed the points highlighted in previous sections:

- The compressive strength of the mixes was fundamentally conditioned by the fine RCA percentage [36], although its effect was not significant up to RCA contents of 50%. The effect of the other factors (cement type and nature of aggregate powder) was also significant, especially at later ages. The use of GGBFS had no detrimental effect on the 7-day compressive strength due to the mix design. The compressive strength behavior of the limestone powder was statistically the same as the limestone filler.
- The effect of the factors in relation to both the modulus of elasticity and compressive strength was similar, with two exceptions. On the one hand, every content of fine RCA affected the modulus of elasticity in a different way (*i.e.*, no homogenous groups). On the other hand, the effect of the GGBFS additions as a binder was not significant at any age.
- Both the fine RCA content and the cement type significantly affected the splitting tensile strength. The addition

Table 7 – Coefficients *a*; *b* of the model (Equation (2)).

		/F	/L	/R
Modulus of elasticity	CEM I	$0.0581; -1.6497 \times 10^{-5}$	$0.0563; -1.2552 \times 10^{-5}$	$0.0711; -2.5650 \times 10^{-5}$
	CEM III/A	$0.0583; -1.5056 \times 10^{-5}$	$0.0626; -1.2791 \times 10^{-5}$	$0.0777; -2.7127 \times 10^{-5}$
Splitting tensile strength	CEM I	$0.4784; -8.6100 \times 10^{-5}$	$0.3329; -4.2570 \times 10^{-5}$	$0.4743; -1.4617 \times 10^{-4}$
	CEM III/A	$0.7014; -1.4651 \times 10^{-4}$	$0.5600; -8.1770 \times 10^{-5}$	$0.7205; -2.3896 \times 10^{-4}$
Flexural strength	CEM I	$0.3933; -9.1732 \times 10^{-5}$	$0.2671; -3.6750 \times 10^{-5}$	$0.3717; -1.1115 \times 10^{-4}$
	CEM III/A	$0.4636; -1.1263 \times 10^{-4}$	$0.2537; -2.5179 \times 10^{-5}$	$0.3567; -9.1937 \times 10^{-5}$

of CEM III/A significantly decreased the splitting tensile strength of SCC, despite the higher cement content of SCC when the by-product was added [40]. The nature of the aggregate powder was also significant (with the exception of the homogeneous group of the mixes manufactured with limestone filler or RCA powder).

- The results obtained for flexural strength were significantly conditioned by both the aggregate powder and the fine RCA content. The cement type did not condition this strength.

3.7.2. *Estimation of mechanical properties through the compressive strength*

In previous sections, it has been demonstrated that the formulations of current standards in both the USA and Europe overestimate the values of the mechanical properties of the mixes that are evaluated in this study. The explanation is that those expressions were developed for vibrated, not self-compacting, concretes [52,53]. Furthermore, the presence of by-products, such as RCA or GGBFS, modified the behavior of concrete with conventional materials (NA and cement clinker)

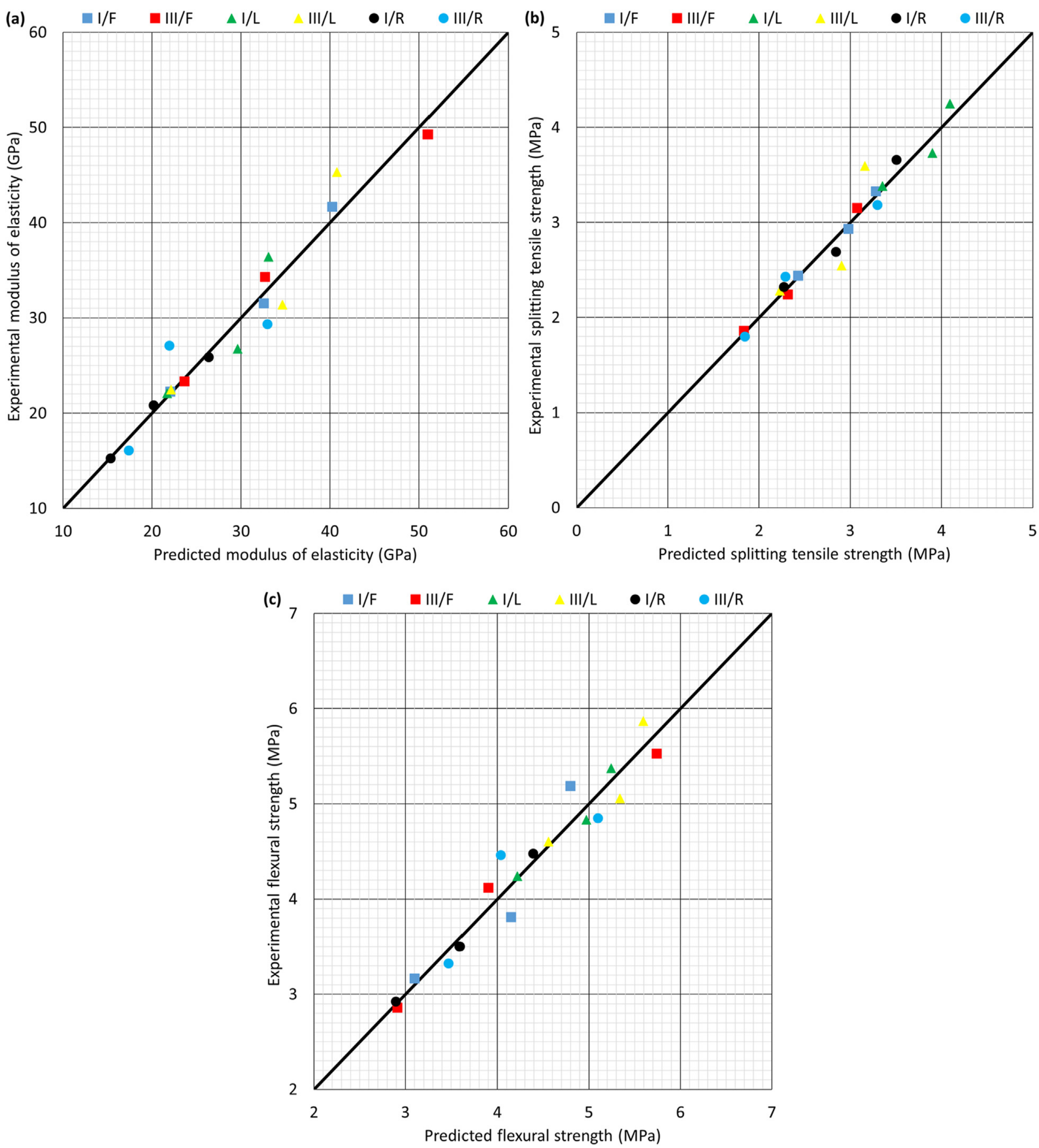

Fig. 21 – Comparison between predicted and experimental values, according to Equation (2): (a) elastic modulus; (b) splitting tensile strength; (c) flexural strength.

[14]. It was therefore considered necessary to develop a simple model that could be used to produce accurate estimations of all the mechanical properties.

According to the previous section, the most significant factor in compressive strength was the fine RCA content. Maximization of the correlation coefficient R^2 for all the mixes containing the same cement type and aggregate powder (groups of three mixtures whose only difference was the fine RCA content) was therefore studied. It was found that all the mechanical properties of the mixtures followed the same simple-regression trend, thus obtaining Equation (2).

$$Property = \frac{1}{a + b \times CS^2} \tag{2}$$

In Equation (2), the variables that appear are:

- *Property* refers to the mechanical property to be estimated at 28 days: splitting tensile strength (in MPa), flexural strength (in MPa) or modulus of elasticity (in GPa).
- CS is the compressive strength in MPa of the cylindrical specimens at 28 days.
- a and b are the adjustment coefficients, which vary according to the mechanical property to be estimated and the cement and aggregate powder used in the mix. Their values are given in Table 7.

This model presented an average R^2 coefficient of 0.951 for the estimation of the modulus of elasticity, 0.923 when estimating the splitting tensile strength and 0.955 for the flexural strength. The estimation of all mechanical properties was, in general, very accurate, as the largest overestimation never exceeded 10% of the real value, as shown in Fig. 21. Therefore, those values would be valid for structural design with those mixtures [66,67] taking into account the traditional safety coefficients of both the US [52] and European [53,54] standards. No clear influence of the mixtures on the estimation accuracy of the model was observed.

4. Conclusions

The production of a Self-Compacting Concrete (SCC) of adequate flowability requires a high content of fine particles that are provided by both the cement and the aggregate. The behavior of SCC is therefore very sensitive to the addition of by-products in these fractions. For this reason, throughout this article, the mechanical properties of 18 SCC mixtures of slump-flow class SF3 according to EN 206 [51] were analyzed. The coarse natural aggregate of these SCC mixes was fully replaced with Recycled Concrete Aggregate (RCA). In addition, several fine RCA contents (0%, 50% and 100%), and aggregate powders of different nature (limestone filler, limestone powder or RCA powder) were also considered. Finally, in half of the mixes CEM I was replaced with CEM III/A, which has a content of 45% Ground Granulated Blast Furnace Slag (GGBFS) in substitution of Portland clinker. The following conclusions can be drawn from this research work:

- The flowability of SCC could be improved when adding alternative materials through a specific composition adjusted according to the properties of those materials. First, to compensate the high levels of water absorption of RCA, as well as the irregular shape of its particles, the water content and the fine-aggregate-particles proportion of the mix had to be increased. Second, the low grinding fineness of GGBFS meant that the ratio of coarse aggregate to cement had to be adjusted when using it. This optimal fresh state performance of SCC was also obtained by the implementation of a three-stage mixing process. Despite the adjustment of the mix composition, the viscosity of SCC increased when adding fine RCA.
- All the mechanical properties under evaluation significantly worsened when using fine RCA. Thus, increasing the fine RCA content always reduced every mechanical property, except for compressive strength, which showed statistically equal behavior for 0% and 50% fine RCA.
- The increase of the binder content when adding GGBFS to SCC resulted in this by-product having no significant effect on 7-day compressive strength, modulus of elasticity and flexural strength, so that the mixes presented the same behavior as those made with conventional cement. The most significant effect of the use of this alternative binder was found in the splitting tensile strength, which decreased notably, thus showing a poor behavior of this by-product under tensile stresses.
- Under compressive stresses (compressive strength and elastic modulus), both limestone filler <0.063 mm and limestone powder 0/0.5 mm had the same effect on the mechanical behavior of SCC. The application of tensile stress showed that the performance of limestone powder was better and that sometimes limestone filler and RCA powder gave the SCC the same splitting tensile strength and flexural strength from a statistical approach.
- In the mixes incorporating RCA and GGBFS, all the mechanical properties were lower than predicted by the formulas of the current standards through their compressive strength. The lowest overestimation was obtained at advanced ages (28 days) using the European standard formulation [53,54] calculated with the compressive strength of the cylindrical specimens. The estimation of the modulus of elasticity showed greater accuracy when the density correction was introduced. Nevertheless, the experimental results were used to develop a simple-regression model that can accurately estimate all these properties, as all the mechanical properties followed the same simple-regression trend.

Overall, the addition of CEM III/A (45% GGBFS), natural aggregate powder (0/0.5 mm), 100% coarse RCA, and 50% fine RCA, yielded concrete of high self-compactability, sustainability and strength. Therefore, the simultaneous use of large quantities of waste or industrial by-products in SCC is feasible in terms of its mechanical behavior.

Availability of data and materials

The "Experimental and Numerical Research" data used to support the findings of this study are available from the corresponding author upon request.

Declaration of Competing Interest

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

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