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Hammer rebound index as an overall-mechanical-quality indicator of self-compacting concrete containing recycled concrete aggregate

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ABSTRACT

The hammer rebound index has traditionally been solely and exclusively used to estimate the compressive strength of vibrated concrete. Its use has recently been extended to the prediction of the compressive strength of Self-Compacting Concrete (SCC) and concrete produced with Recycled Concrete Aggregate (RCA). The conventional use of the hammer-rebound test is further developed in this paper, by demonstrating how it can be used to estimate the overall mechanical behavior of SCC containing RCA. To do so, nine SCC mixes with different contents and fractions (coarse, fine, and powder) of RCA are analyzed. Following a simple-linear-regression validation and property standardization procedure, the hammer rebound index is then expressed as a linear combination of four mechanical properties, adjusted through a multiple regression. The hammer rebound index is therefore expressed as a weighting of both the mean value of compressive behavior (arithmetic mean of compressive strength and modulus of elasticity) amounting to a weight of 72.8%, and the mean value of bending-tensile behavior (arithmetic mean of splitting tensile strength and flexural strength) amounting to a weight of 27.2%. The hammer rebound index can therefore be construed as an overall-mechanical-quality performance indicator of the SCC containing RCA, which can also yield predictions of every mechanical property. In this way, the application of the hammer rebound index could likewise be of use in rehabilitation, pathology, and health-monitoring works where a full characterization of the mechanical performance of SCC with RCA is required, facilitating the use of SCC with RCA in real structures.

1. Introduction

Quality control of concrete laid in place is a fundamental step during civil-work constructions. These regular tests are used to verify the performance specifications of a concrete and its compliance with the design criteria, regardless of whether a pavement or a singular structure is built [1]. Quality control has traditionally consisted of direct mechanical tests on concrete specimens at a certified laboratory [2]. However, large-scale structures may make this procedure unfeasible or extremely costly [3]. In those cases, indirect control of the mechanical behavior of concrete is a simple economic alternative that can be easily-performed [4]. Indirect control of concrete is also essential for rehabilitation and health-monitoring of aging constructions where separate concrete specimens of the same material may no longer be produced [5,6]. The exceptions are core-drilling and penetration-resistance tests, yielding semi-direct analyses of mechanical behavior, though any damage to the concrete component during their implementation requires careful evaluation [7,8].

Indirect control of concrete consists of measuring a physical magnitude that can be precisely correlated with its mechanical properties [4]. There are at present three conventional procedures of proven usefulness dating back to the mid-20th century [9,10]. On the one hand, ultrasonic pulse velocity is used to measure the propagation velocity of an ultrasonic wave that passes through a concrete object [11]. The higher the wave velocity, the lower the porosity and the higher the specific weight of the concrete, which generally implies higher elastic stiffness [12]. Ultrasonic pulse velocity therefore yields an estimate of the modulus of elasticity of concrete, although in recent times its results have also been adapted to predict compressive strength [13]. On the other hand, although less widely used, there is the electrical-resistivity

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test that measures the flow of an electric current through a concrete object and correlates it with the mechanical behavior of the object and any reinforcement corrosion [14,15]. Both methodologies require the use of specific electronic devices, powered by electricity, whose use in the field can sometimes be difficult. However, as an indirect-control method the hammer rebound index uses a mechanical device, so it can be used in almost all situations [16].

The hammer rebound index is a dimensionless number that indicates the rebound height reached by a calibrated mass connected to a spring that, moving under a predefined force, rebounds after hitting a concrete surface [18]. A sclerometer or Schmidt hammer is often used for its determination, the operation of which is depicted in Fig. 1 [17]. The hammer rebound index, which is conditioned by the surface hardness of concrete, is commonly used as an indirect test of its compressive strength [19,20]. There are models that correlate the compressive strength and the hammer rebound index of vibrated concrete, through statistical adjustments of repeated experimental results [21], because such aspects as the nature and the origin of the aggregate and the cement type determine the hammer rebound index [22].

Self-Compacting Concrete (SCC) is characterized by its high proportion of fine-aggregate particles, less than 4 mm, and aggregate powder, with a maximum particle size of about 0.5 mm [23]. Along with the use of an adequate amount of superplasticizer, it means that the fresh concrete fills the formwork under its own weight, without any need for vibration [24,25]. However, the large quantities of aggregate fines required in the design of SCC entail a lower surface hardness in this concrete type than in a vibrated one [26]. The hammer rebound index and the compressive strength relationship is therefore modified, which in turn means that conventional formulas are invalid for SCC [27]. Nevertheless, some research has been focused on the extent to which varying proportions of fine aggregate and flowability in the fresh state can affect the hammer rebound index of SCC [28], from which models have been developed that relate it to compressive strength [29].

The use of Recycled Concrete Aggregate (RCA) in concrete falls within the current trend of increasing the sustainability of this construction material through the use of by-products as aggregates and binders [30–32]. As rejected concrete components are crushed to obtain RCA [33], the coarse fraction is Natural Aggregate (NA), generally siliceous, with adhered mortar [34], while the fine fraction is a mixture of NA particles and mortar [35]. The workability of concrete containing RCA rather than NA decreases, because the water absorption levels of the former are higher [36]. Moreover, the increased porosity and adhesion problems caused by RCA in the interfacial transition zones of concrete [37] worsen its mechanical behavior [38] and increase concrete deformability [39]. Despite these aspects, adequate concrete-mix designs have shown that this alternative aggregate can be used in structural elements such as beams and columns [40], the key parameter for its proper performance being sufficient compressive strength [41].

Regarding the hammer rebound index, the presence of mortar within both RCA fractions reduces the surface hardness of the concrete [42]. Coupled with the compressive-strength reduction usually caused by RCA, the relationship between both properties, compressive strength and hammer rebound index, is never the same as when NA is used [2]. Consequently, the influence of both RCA content and fraction on the aforementioned relationship has been evaluated, prior to the development of specific hammer-rebound-index models that are valid for estimating the compressive strength of concrete with RCA [16].

Although several models can be found in the literature for estimating different mechanical properties of vibrated concrete with RCA [38,43], there are few studies on hammer-rebound-index predictions of compressive strength applied to SCC with NA and vibrated concrete containing RCA, although such predictions are key to achieve the widespread use of RCA concrete in real civil works [44]. Whenever SCC contains RCA, all the aspects discussed above can be simultaneously found in the same concrete mix, which further affects the validity of conventional strength-prediction models using the hammer rebound index [45]. Research works addressing this aspect are even scarcer and have been limited to demonstrations of clear dependencies between both properties [44]. However, the development of these specific sorts of statistical models that correlate both properties in SCC with RCA has only recently been advanced [27].

In this study, the conventional understanding of the hammer

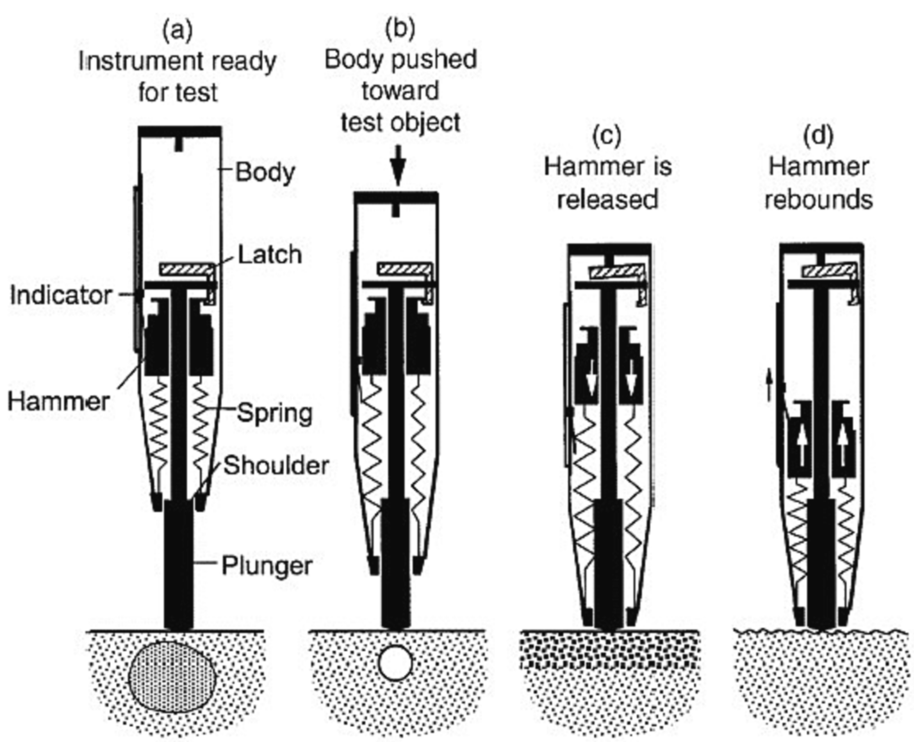

Fig. 1. Operation of a sclerometer [17].

rebound index as a measure of nothing other than the compressive strength of concrete is challenged, in so far as its utility is demonstrated for evaluations of the overall mechanical quality of SCC containing RCA. Using nine SCC mixes produced with different RCA contents and fractions, it is shown how the hammer rebound index can also be understood in this concrete type as an indicator and predictor not only of its compressive strength, but also of its overall mechanical quality, *i.e.*, as a weighting of compressive strength, modulus of elasticity, splitting tensile strength, and flexural strength. This novel approach to the hammer rebound index is intended to extend its field of application, so that SCC containing RCA may be easily validated for use in real structures through a simple and economical procedure that provides an overall estimation of its mechanical behavior.

2. Materials and methods

2.1. Raw materials

All the mixes in this study were made with the same cement, water, and admixtures:

- Ordinary Portland cement CEM I 52.5 R (EN 197–1 [46]), with a specific weight of 3.12 Mg/m^3.
- Mains water with no harmful compounds that might affect SCC behavior.
- A modified-polycarboxylate superplasticizing admixture to ensure adequate self-compactability levels of the mixes.
- A viscosity-regulating admixture that reduces the amount of water needed for adequate flowability levels.

Two aggregate types, Natural Aggregate (NA) and Recycled Concrete Aggregate (RCA), were used in the coarse and fine fractions for mix preparation:

- In all the mixes, 100 % coarse RCA 4/12.5 mm was used. The RCA was obtained from the crushing of rejected precast components at least 3 years old. The minimum compressive strength of the concrete used in those components was 45 MPa and, due to its advanced age, showed no signs of shrinkage that could affect SCC behavior. Its specific weight was 2.42 Mg/m^3, and its water absorption levels within 15 min and 24 h were 4.90 % and 6.25 %, respectively.
- The fine aggregate 0/4 mm fraction consisted of siliceous sand combined with fine RCA. The siliceous sand showed common characteristics for manufacturing SCC, *i.e.*, a rounded shape, water absorption levels in 15 min and in 24 h of 0.18 % and 0.25 %, respectively, and a specific weight of 2.58 Mg/m^3. The source of the fine RCA was the same as that of the coarse fraction, also presenting usual specific weight values (2.37 Mg/m^3) and water absorption levels (5.77 % within 15 min and 7.36 % within 24 h) [47].

An aggregate powder was added to compensate for the insufficient fines content of siliceous sand and fine RCA to achieve an optimum SCC. Three types of aggregate powder were considered:

- Limestone filler less than 0.063 mm, with a specific weight of 2.77 Mg/m^3, and water absorption levels within 15 min and within 24 h of 0.37 % and 0.54 %, respectively. This aggregate powder is commonly used in the industrial manufacturing of SCC [48].
- Limestone powder 0/0.5 mm, with a specific weight of 2.60 Mg/m^3, and water absorption levels in 15 min and in 24 h of 1.95 % and 2.57 %, respectively. This aggregate powder was considered to evaluate the effect of the aggregate-powder size on SCC behavior.
- RCA powder 0/0.5 mm, of lower specific weight (2.31 Mg/m^3) and higher water absorption levels (6.32 % in 15 min and 7.95 % in 24 h) than limestone powder. This RCA powder was considered, so that its effects could be analyzed.

The continuous granulometry of all the aggregates, shown in Fig. 2, was suitable for use in concrete production [49].

2.2. Mix design

The design objective of all the mixes was an SF3 slump-flow class. This slump-flow class is the highest possible according to the relevant standard (EN 206 [46]) and occurs when the SCC has a slump flow of 800 ± 50 mm. The composition of the SCC was adjusted accordingly, to maintain this slump-flow class when the content or nature of any component was modified. It was therefore possible to show that the use of large amounts of RCA was no impediment to obtaining high levels of self-compactability [50].

The first step was to produce an SCC mix with limestone filler, 100 % siliceous sand, and 100 % coarse RCA. The coarse RCA amount was defined to maximize concrete sustainability as per a previous study [45]. In the first instance, the proportion of the different components was defined in line with the specifications of Eurocode 2 [49]. Subsequently, the amount of water (effective water-to-cement ratio of 0.40) and the proportions of aggregate powder, fine aggregate, and coarse aggregate were adjusted through different trial mixes, to achieve the desired slump-flow class.

Then, two mixes, identical to the previous one, were prepared, in which 50 % and 100 % siliceous sand were replaced with fine RCA, using the volume-correction method. Those substitution ratios were also taken from the above-mentioned previous study [45]. Adjustments to the water content were required, due to the high water absorption levels of fine RCA, so the effective water-to-cement ratio and the slump-flow class remained unchanged.

Finally, six other mixes were prepared with the same contents of both RCA fractions, although limestone filler was substituted with limestone powder (3 mixes) and RCA powder (3 mixes). In these mixes, besides adjustments to the water content, so that the effective water-to-cement ratio and the slump-flow class remained unchanged, the use of aggregate powder with larger sized particles meant that the ratio between both the aggregate powder and the fine aggregate had to be balanced.

Nine SCC mixes were produced, the composition of which is shown in Table 1. They were labelled with the code *AP*, where *A* stands for aggregate powder (*F*, limestone filler; *L*, limestone powder; *R*, RCA powder) and *P* stands for the addition ratio of fine RCA (*0*, *50* or *100*).

2.3. Experimental tests

Once the composition of the SCC mixes had been defined, they were prepared by mechanical mixing for 15 min, after which it was verified with the slump-flow test (EN 12350–8 [46]) that all of them had an SF3 slump-flow class. Subsequently, as detailed in Table 2, different types of specimens were prepared to measure the mechanical properties of the mixes and their hammer rebound indexes. These specimens were stored in a humid chamber (humidity of 95 ± 5 % and temperature of 20 ± 2 °C) until the concrete was 28 days old, at which age the tests were performed. All the hardened-state tests were conducted following standard procedures [46], although it was necessary to place the specimens in a test press under a load of 30 kN (Fig. 3), in order to perform the hammer-rebound-index test, as described in other similar studies [27].

3. Results and discussion: Experimental tests

This section presents the experimental results necessary to analyze the relationship between the mechanical properties and the hammer rebound index in SCC mixes made with different RCA contents and fractions.

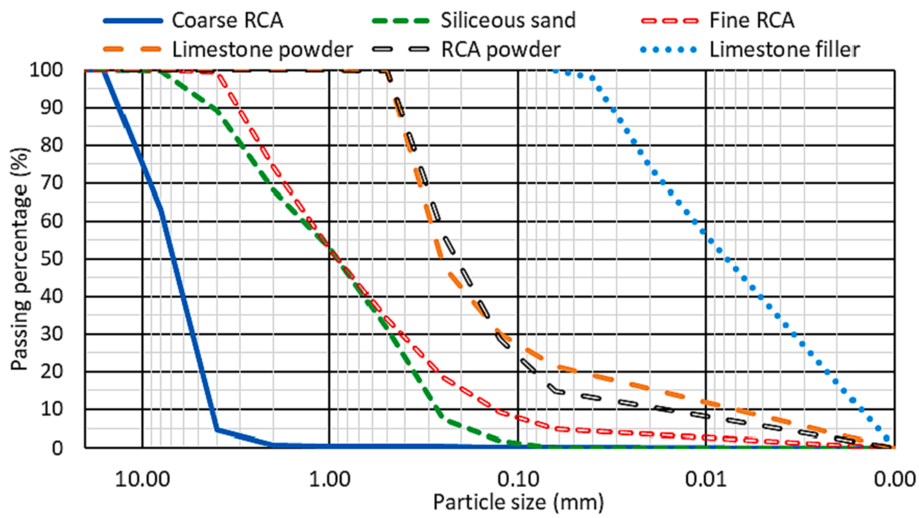

Fig. 2. Granulometry of the aggregates.

Table 1
Composition of the SCC mixes.

Component	F0	F50	F100	L0	L50	L100	R0	R50	R100
Cement CEM I 52.5 R	300	300	300	300	300	300	300	300	300
Water	185	210	235	185	210	235	200	220	245
Superplasticizer	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
Viscosity regulator	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30
Coarse RCA	530	530	530	530	530	530	530	530	530
Fine RCA	0	505	1010	0	435	865	0	435	865
Siliceous sand	1100	550	0	940	475	0	940	475	0
Limestone filler	165	165	165	0	0	0	0	0	0
Limestone powder	0	0	0	335	335	335	0	0	0
RCA powder	0	0	0	0	0	0	305	305	305

Table 2
Hardened-state tests.

Property	Compressive strength	Modulus of elasticity	Splitting tensile strength	Flexural strength	Hammer rebound index
Standard [46]	EN 12390-3	EN 12390-13	EN 12390-6	EN 12390-5	EN 12504-2
Specimen shape	Cylindrical	Cylindrical	Cylindrical	Prismatic	Cubic
Specimen dimensions (cm)	10x20	10x20	10x20	7.5x7.5x27.5	10x10x10
Number of specimens	2	2	2	2	3

3.1. Filling ability

The slump flow (EN 12350–8 [46]) of SCC was evaluated immediately after mixing, yielding the results shown in Fig. 4. In all cases, SCC had a slump-flow class SF3, *i.e.*, a slump flow of 800 ± 50 mm (EN 206 [46]). None of the RCA fractions, including 100 % initial coarse RCA, hindered such high flowability levels, thanks to careful dosing of the SCC. This good fresh performance was also supported by the results of viscosity, passing ability, and segregation resistance reported elsewhere [50].

Although the high water absorption levels of fine RCA are compensated, SCC slump flow usually decreases due to the angular shape of fine RCA [51], which causes an increase in both the friction between the mix components and the opposition of the fine aggregate to be dragged by the cement paste [52]. Nevertheless, the slump flow increased following the addition of fine RCA, because of its higher content of fines compared to siliceous sand (Fig. 2) and the replacement of the entire 0/4 mm aggregate fraction simultaneously, rather than sieve by sieve. Thus, slump flows of up to 840 mm were reached (mix F100).

Concerning the aggregate powder, the limestone filler provided higher initial flowability, possibly due to its smaller particle size, so the SCC spread more easily [48]. The limestone powder reduced the spread of the SCC, due to the higher amount of particles between 0.25 mm and 0.50 mm in size that are dragged within the cement paste with greater difficulty when using this aggregate powder [25]. However, RCA powder caused the highest loss of slump flow, because of its very angular and irregular shape [50]. This trend was noted when comparing mixes with the same amount of fine RCA. For instance, mixes F50, L50, and R50 showed slump flows of 810 mm, 785 mm, and 755 mm, respectively.

3.2. Mechanical properties

The mechanical properties of the mixes (compressive strength, modulus of elasticity, splitting tensile strength and flexural strength) were determined at 28 days, although a more detailed analysis of the mechanical performance of similar mixes can be found in another paper of the authors [53]. The type and number of specimens used are shown in Table 2. All the results are detailed in Fig. 5 and Table 3.

First of all, it should be noted that the use of 100 % coarse RCA in combination with a limestone aggregate powder, achieved mechanical properties suitable for structural concrete [49]. Thus, compressive strengths and elastic moduli higher than 40 MPa and 35 GPa,

Fig. 3. Hammer-rebound-index test.

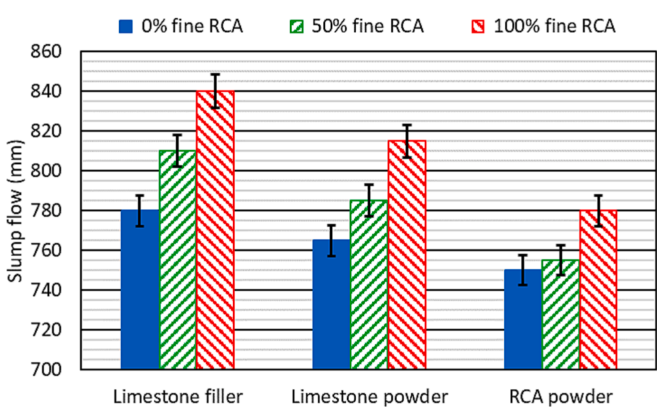

Fig. 4. Slump flow.

respectively, were obtained, as well as splitting tensile and flexural strengths within the range of 3–5 MPa.

The addition of fine RCA worsened the mechanical properties, because its use caused, on the one hand, a porosity increase [23] and, on the other, worse adhesion between the cementitious matrix and the aggregate [30]. Moreover, these problems are generally aggravated when fine RCA is combined with large amounts of coarse RCA [45]. Regardless of the mechanical property and aggregate powder, the worst-performing mix had 100 % fine RCA. However, the effect of 50 % fine RCA differed in each property: the decrease in compressive strength after adding 50 % fine RCA was less than half the decrease after adding 100 % fine RCA, while the reductions in splitting tensile strength and flexural strength were higher. These results showed that the effects of fine RCA were especially harmful when the SCC was subjected to tensile stresses.

Limestone aggregate powders showed a similar behavior in the mixes with 0 % fine RCA, demonstrating practically the same compressive strength and flexural strength, although the limestone filler yielded a slightly higher modulus of elasticity and the limestone powder a higher splitting tensile strength. Therefore, both aggregate powders contributed to a good quality cementitious matrix [48]. However, the interaction between limestone filler and fine RCA was worse than between this waste and limestone powder, as shown by the reductions in the modulus of elasticity (20 GPa vs 15 GPa) and flexural strength (2 MPa vs 1 MPa) when 100 % fine RCA was used. RCA powder caused the worst mechanical behavior, regardless of the fine RCA amount, with mix R100 showing a compressive strength of only 16 MPa and an elastic modulus of 15 GPa. However, the flexural and splitting tensile strength values were very similar in mixes F100 and R100, once again revealing the poor interaction between the limestone filler and the large contents of fine RCA.

3.3. Hammer rebound index

The hammer rebound index (Fig. 6 and Table 3) of each mixture was the arithmetic mean of the indexes measured on three different cubic specimens. As specified in EN 12504–2 [46], the hammer rebound index of each specimen was the median of nine test results. A more detailed analysis of this indirect measurement for these mixes can be found in a previously published paper of the authors [27].

The hammer rebound indexes were 5–10 units lower than expected, in view of the compressive strength of the mixes and the existing models for vibrated concrete [27]. Primarily, this lower than expected result was due to the high amount of aggregate powder and fine aggregate in SCC, which reduces its surface hardness without affecting its compressive strength [26]. Furthermore, the use of 100 % coarse RCA in all mixes also favored this behavior, because of the adhered mortar that was not as hard as NA [16].

The addition of fine RCA led to a decrease of the surface hardness of SCC, mainly because of the mortar presence [44], although the increase in porosity that it caused might also favor this behavior [23]. The increase of fine RCA and the decrease of the hammer rebound index were not proportional, as this decrease was lower between fine RCA contents of 0 % and 50 % than between 50 % and 100 %. Thus, a similar trend to compressive strength was found (Fig. 5a), which reveals the great dependence that has traditionally been established between both properties [4].

Although it had no effect on the trend of the hammer rebound index, the type of aggregate powder did affect its value. Thus, the hammer rebound indexes of the mixes with limestone powder were the highest, exceeding an index of 40 units in mix L0, closely followed by the mixes with limestone filler. The high mortar content in the RCA powder [27] and its potential to increase porosity [54], led to low hammer rebound indexes, with a value of only 18 units in mix R100.

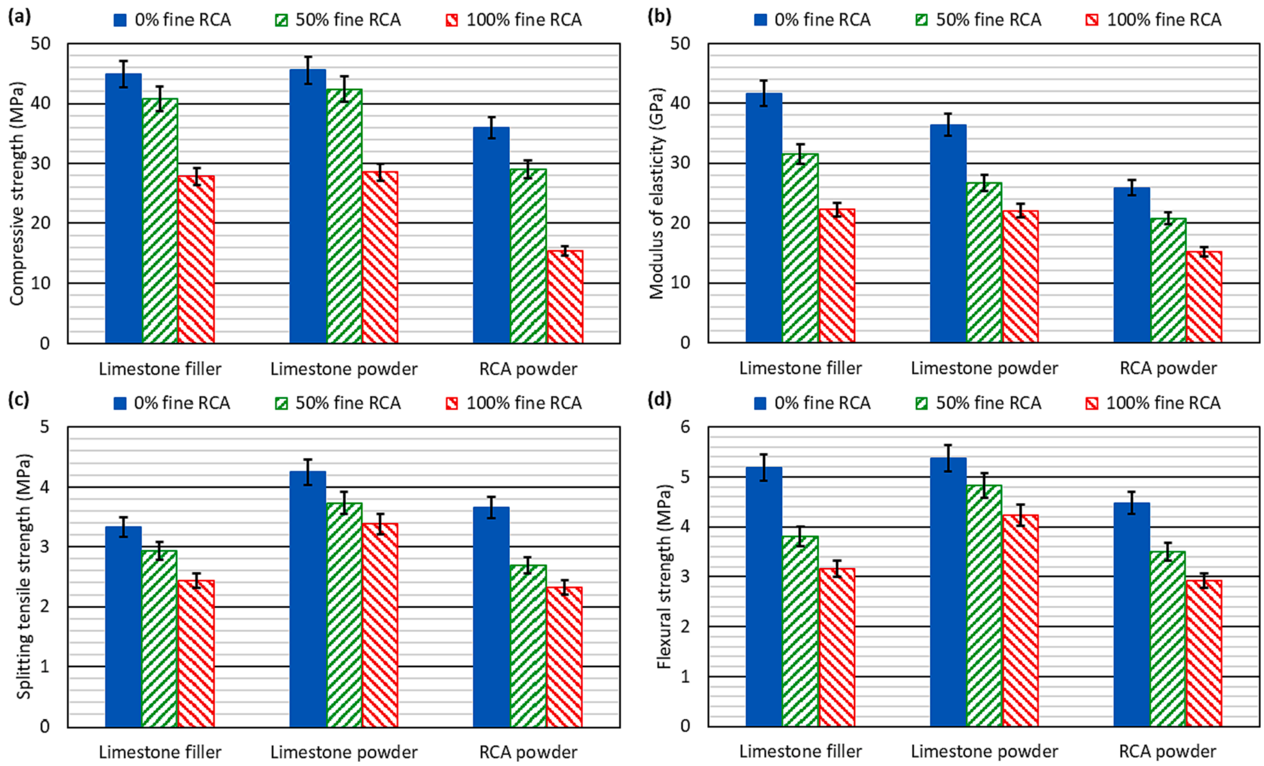

Fig. 5. Mechanical properties: (a) compressive strength; (b) modulus of elasticity; (c) splitting tensile strength; (d) flexural strength.

Table 3
Average values of mechanical properties and hammer rebound index.

Mix	Compressive strength (MPa)	Modulus of elasticity (GPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Hammer rebound index
F0	44.9	41.6	3.3	5.2	39
F50	40.8	29.5	2.9	3.8	34
F100	27.8	23.2	2.4	3.2	28
L0	45.6	36.4	4.3	5.4	41
L50	42.4	26.7	3.7	4.8	40
L100	28.5	22.1	3.4	4.2	29
R0	36.0	25.9	3.7	4.5	29
R50	29.0	22.8	2.7	3.5	26
R100	15.4	15.2	2.3	2.9	18

4. Results and discussion: overall-mechanical-quality indicator

Based on the experimental results presented previously, this section evaluates the relationship between the mechanical properties and the hammer rebound index in SCC mixes produced with different amounts and fractions of RCA. It is demonstrated that this indirect measure can serve as an indicator of the overall mechanical quality of these sorts of concrete mixes.

4.1. Simple regression between the hammer rebound index and the mechanical properties

Traditionally, the hammer rebound index has been used for predicting the compressive strength of concrete, and its use has not been extended to the prediction of other mechanical properties [10]. Regarding SCC made with RCA, recent studies have shown that its compressive strength can be accurately estimated with this indirect measure [27]. Some studies have gone even further, showing that any mechanical property can be accurately related to the hammer rebound index in this type of concrete [44].

The validity of separate estimations of any mechanical property based on the hammer rebound index have first to be confirmed before this index can be proven to be a simultaneous estimator of all four mechanical properties of SCC with RCA, *i.e.*, as an overall-mechanical-quality indicator expressed as a function whose independent variables are the four mechanical properties of SCC containing RCA. This point can be evaluated by a simple regression, but considering this indirect measurement as the dependent variable, which allows showing that the statistical value of the hammer rebound index is a function of any individual mechanical property of concrete. Simple-regression models can also be used with this approach to provide estimates of any mechanical property from the hammer rebound index, rather than the conventional procedure of estimating the modulus of elasticity and the bending-tensile properties from the compressive strength, procedure that is shown in the literature [43,53]. In this case, a compressive strength value obtained from the hammer rebound index should be used to estimate those properties through that conventional procedure, which could in turn reduce the precision of the estimation.

In accordance with the previous paragraph, a simple regression was performed between each mechanical property (*CS*, compressive strength in MPa; *ME*, modulus of elasticity in GPa; *STS*, splitting tensile strength in MPa; *FS*, flexural strength in MPa) and the hammer rebound index (*HRI*, dimensionless). For that purpose, each mechanical property was considered as the independent variable and the hammer rebound index as the dependent variable. The same values of the hammer rebound index were considered for all the mechanical properties when performing the simple regression. Two conclusions were obtained from this regression analysis:

- On the one hand, the hammer rebound index could be accurately related to all mechanical properties as the coefficients R^2 were high, as shown in the fourth and fifth columns of Table 4.
- On the other hand, the simple linear regression model (Equation (1); *y*, independent variable, every mechanical property; *z*, dependent variable, the hammer rebound index; *A* and *B*, fitting coefficients)

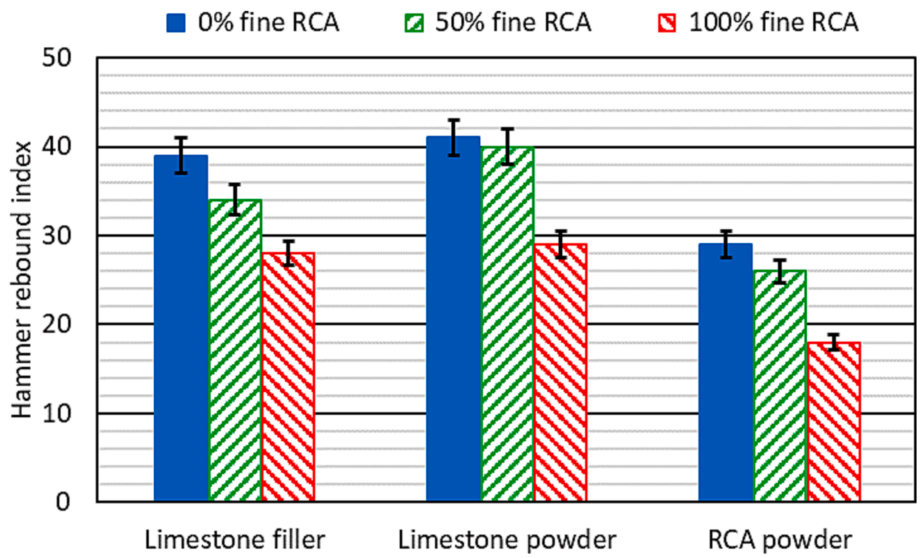

Fig. 6. Hammer rebound index.

Table 4
Simple linear regression between the hammer rebound index and the mechanical properties.

Mechanical property (independent variable)	Linear-model fitting coefficients		Linear-model coefficient R^2 (%)	Best-fit model coefficient R^2 (%)
	A	*B*		
Compressive strength	6.499	0.727	92.57	95.27
Modulus of elasticity	10.283	0.790	85.98	88.26
Splitting tensile strength	2.296	9.167	80.49	83.82
Flexural strength	−0.143	7.609	87.13	88.63

was not the model with the best fit in any case. Nevertheless, the small difference between its coefficient R^2 and that of the best-fit model showed that the linear model was always adequate (Table 4). A relationship of linear dependence between the mechanical properties and the hammer rebound index was also found in the Pearson correlations, which were greater than 0.75 in all cases (Fig. 7).

$$z = A + B \times y \quad (1)$$

In view of the above results, a strong linear relationship can be observed between each of the four mechanical properties and the hammer rebound index of the SCC containing RCA. The hammer rebound index can therefore be expressed in terms of the linear dependence of all four mechanical properties as a combination of their values. The high goodness of fit of the results suggests that this sort of model could be further developed through multiple-regression models.

4.2. Multiple regression: Hammer rebound index as an overall-mechanical-quality indicator

Having defined in the previous section the hammer rebound index as a linear combination of four mechanical properties, the multiple-regression-based determination of the best-fit linear combination, whose results are more directly interpretable, is shown in this section. The multiple regression showed simultaneous relations between the hammer rebound index and all the mechanical properties of SCC containing RCA, which supports its validity as an overall-mechanical-quality indicator.

4.2.1. Property standardization

Developing multiple-regression models between the hammer rebound index and a linear combination of the four mechanical

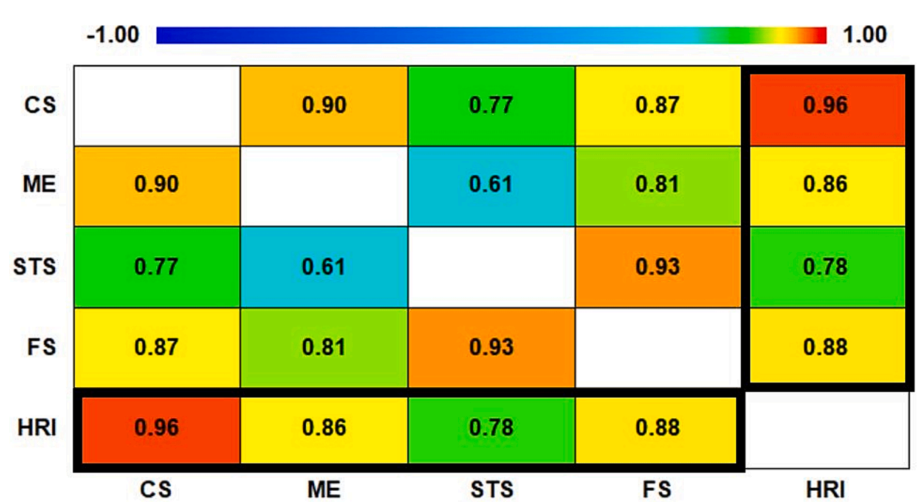

Fig. 7. Pearson correlations matrix (correlations between the hammer rebound index and the mechanical properties marked with a thick border).

properties using absolute values is an inappropriate method. The use of absolute values in the mechanical properties implies that some mechanical properties will, inevitably, have a greater influence on the regression, not because of their statistical trends, but because of their values [16,27]. It is therefore necessary to use standardized values for the mechanical properties, *i.e.*, expressing them in relative dimensionless terms [55]. If this standardization is also performed for the hammer rebound index, the weights of the linear combination will approximately show the contribution of each mechanical property to this indirect measure.

The standardization of a variable consists of its expression on a dimensionless scale, so that it can be compared in relative terms with other variables. Furthermore, statistical normalization is the standardization of a variable, in such a way that it can be expressed on a scale with clear upper and lower limits, between 0 and 1 [55]. In this case, normalization could not be adequately conducted, since there were no clear upper and lower limits for either the mechanical properties or the hammer rebound index. A standardization was therefore performed, so that each value of each variable was subtracted from the mean and divided by the width of its 95 % confidence interval. Equation (2) was applied in the standardization, in which X_s is the standardized value of the variable (mechanical property or hammer rebound index); X_{exp}, the experimental value of the variable; X_m, the mean value of the variable considering the values of that variable for all the concrete mixes under study; $X_{u\text{-}95}$, the upper limit of the 95 % confidence interval for the variable, considering the values of that variable for all the mixes under study; and $X_{l\text{-}95}$, the lower limit of the 95 % confidence interval. The values of X_m, $X_{u\text{-}95}$ and $X_{l\text{-}95}$ for the mechanical properties and the hammer rebound index are shown in Table 5.

$$X_s = \frac{X_{exp} - X_m}{X_{u-95} - X_{l-95}} \tag{2}$$

This standardization method, unlike the normal method in which the divisor is the standard deviation, was used for two reasons. On the one hand, the standardization procedure yielded high precision when performing the multiple regression. On the other, the standardization method provided plenty of information:

- The sign of the standardized variable indicated whether the experimental value of the variable was greater (positive sign) or less (negative sign) than the mean value of that variable.
- If the standardized variable is between −0.5 and 0.5, it means that the experimental value is within the 95 % confidence interval for that variable, so it conformed to the expected statistical dispersion. If the value of the standardized variable is less than −0.5 or greater than 0.5, then the experimental value is outside the confidence interval.

These aspects are shown for the mechanical properties and the hammer rebound index in Fig. 8 and Table 6. Although many different situations were detected, in general the experimental values for the mixes with 0 % fine RCA were always greater than the mean value (positive standardized value), generally exceeding the upper limit of the 95 % confidence interval (standardized value greater than 0.5). On the contrary, mixtures with 100 % fine RCA presented experimental values that were, in most cases, lower than the mean value (negative standardized value) and that were under the lower limit of the 95 % confidence interval (standardized value lower than −0.5). The mixes with 50 % fine RCA showed intermediate behaviors.

Table 5
Standardization parameters for the mechanical properties and the hammer rebound index.

Variable/Property	X_m	$X_{u\text{-}95}$	$X_{l\text{-}95}$
Compressive strength (MPa)	34.49	42.23	26.75
Modulus of elasticity (GPa)	27.01	33.31	20.58
Splitting tensile strength (MPa)	3.20	3.69	2.70
Flexural strength (MPa)	4.17	4.84	3.49
Hammer rebound index (dimensionless)	31.56	37.40	25.71

4.2.2. Model development

Once the variables have been standardized, the simplest method of performing a linear combination of different variables is to multiply each of them by a coefficient and then to add them all together [56]. Equation (3) (CS_s, standardized compressive strength; ME_s, standardized modulus of elasticity; STS_s, standardized splitting tensile strength; FS_s, standardized flexural strength; HRI_s, standardized hammer rebound index; all of them dimensionless) consists of the linear combination of the four standardized mechanical properties using variable coefficients, which is then equated with the standardized hammer rebound index, so that coefficients may be calculated through multiple regression. Two main points may be derived from this adjustment, with a coefficient R^2 of 93.89 %:

- First, the hammer rebound index can indeed be successfully expressed as a linear combination of the four mechanical properties. Furthermore, the coefficients (weights) show that the percentage contribution of each mechanical property to the hammer rebound index amounts to approximately 1.
- Secondly, if the mechanical properties are individually considered when the linear combination is performed, then there are two mechanical properties whose adjustment coefficients have negative signs. Thus, the modulus of elasticity partially compensates the influence of compressive strength, in terms of compressive behavior. Similarly, the splitting tensile strength of the concrete partially compensates the contribution of flexural strength in the hammer rebound index in terms of bending-tensile behavior.

$$HRI_s = 0.951 \times CS_s - 0.230 \times ME_s - 0.244 \times STS_s + 0.470 \times FS_s \tag{3}$$

It can therefore be noted in Equation (3) that the adjustment of the hammer rebound index as a linear combination of the four mechanical properties in no way meant that each individual mechanical property could be distinguished. Instead, it represented an “average” between the mechanical properties in relation to both compressive and bending-tensile stresses. No individual values could be identified, because one of the mechanical properties for each stress type has a positive sign and the other a negative one. This interpretation is valid because all the properties were standardized, which means that the values of the properties are not affected by units and have no physical meaning, but are just numbers. The same was true when considering the values of the mechanical properties related to the compressive behavior of different sign than the bending-tensile-related properties. Various adjustments were then introduced on the basis of this hypothesis, the most accurate of which with the most direct interpretation is shown in Equation (4) (CS_s, standardized compressive strength; ME_s, standardized modulus of elasticity; STS_s, standardized splitting tensile strength; FS_s, standardized flexural strength; HRI_s, standardized hammer rebound index; CB_s, standardized compressive behavior, *i.e.*, average of standardized compressive strength and standardized modulus of elasticity; BTB_s, standardized bending-tensile behavior, *i.e.*, average of standardized splitting tensile strength and standardized flexural strength; all the variables dimensionless). The adjustment coefficients of this model were determined by multiple least-squares regression. This model consists of averaging the values of the mechanical properties related to compressive behavior on the one hand and those related to bending-tensile behavior on the other. This averaging is a statistical artifice to show that the field of application of the hammer rebound index is larger than traditionally considered, whose development was possible thanks to standardization, which enabled the elimination of the units and the physical meaning of all the properties. The model of Equation (4) was validated in terms of statistical uncertainty by the high coefficient R^2 of 91.94 %, the low standard error, equal to 0.221, and the uncorrelated random

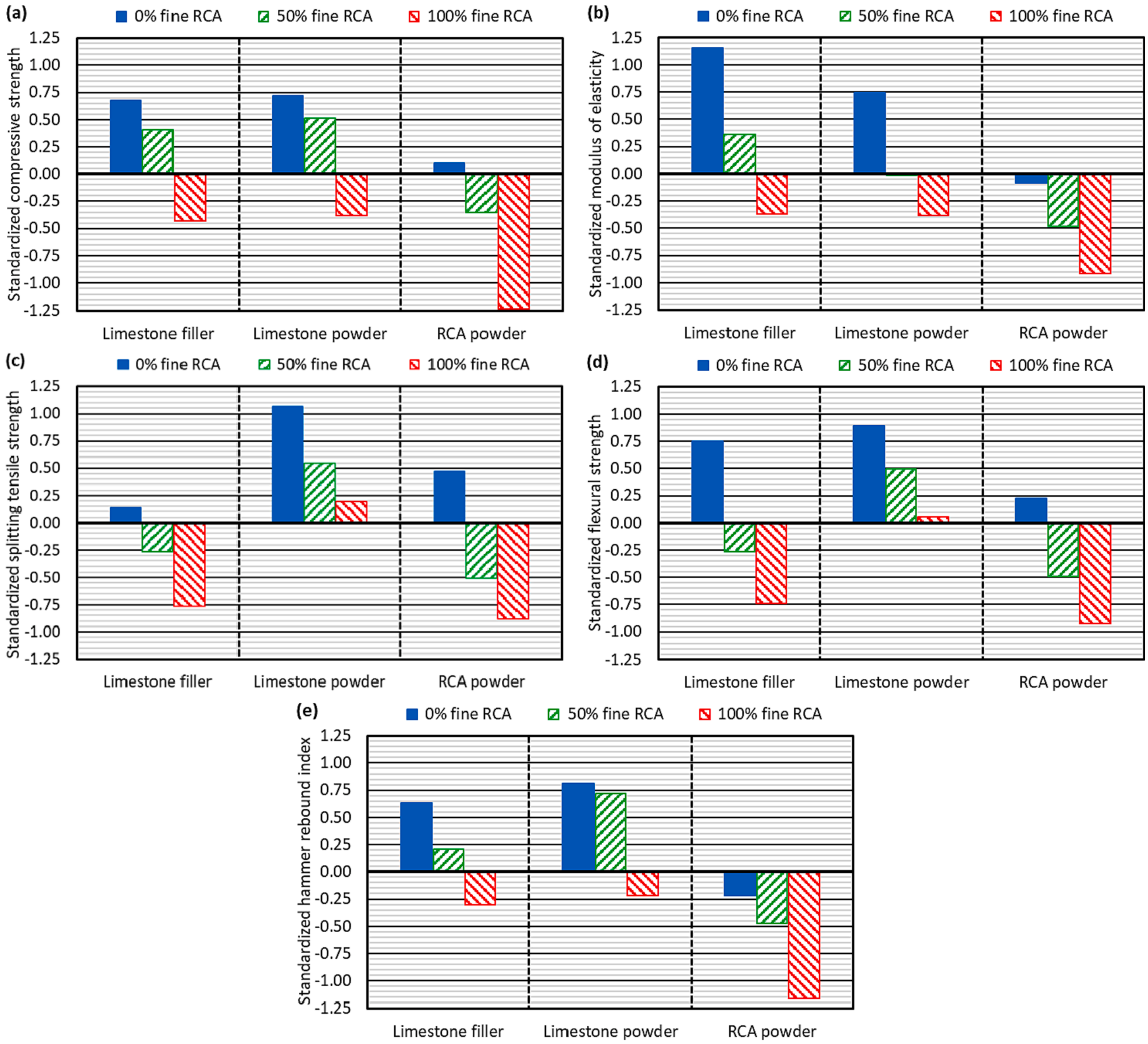

Fig. 8. Standardized properties: (a) compressive strength; (b) modulus of elasticity; (c) splitting tensile strength; (d) flexural strength; (e) hammer rebound index.

Table 6
Values of standardized properties.

Mix	Compressive strength (MPa)	Modulus of elasticity (GPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Hammer rebound index
F0	0.67	1.15	0.14	0.75	0.64
F50	0.41	0.36	−0.26	−0.27	0.21
F100	−0.43	−0.37	−0.76	−0.74	−0.30
L0	0.72	0.74	1.07	0.89	0.81
L50	0.51	−0.02	0.54	0.49	0.72
L100	−0.38	−0.38	0.19	0.05	−0.22
R0	0.10	−0.09	0.47	0.23	−0.22
R50	−0.36	−0.48	−0.51	−0.49	−0.48
R100	−1.23	−0.92	−0.88	−0.92	−1.16

distribution of the fit residuals, with a Durbin-Watson statistic equal to 1.797, higher than the requested limit value.

$$HRI_s = 0.737 \times \left(\frac{CS_s + ME_s}{2}\right) + 0.275 \times \left(\frac{STS_s + FS_s}{2}\right) = 0.737 \times CB_s + 0.275 \times BTB_s \quad (4)$$

The validation of the model was performed by alternately considering only 6 of the 9 mixes, as no studies on similar SCC mixes, fully characterized in terms of their four mechanical properties and hammer rebound index, had been found in the literature. In each of these validation adjustments, 6 mixes were considered, 2 for each type of aggregate powder, to represent all the aggregate powders in use, and at all times considering the mixes containing 0 % and 100 % fine RCA for at least one aggregate powder, so that all the RCA fractions were taken into consideration. In all cases, very similar fitting coefficients were found.

4.2.3. *Utility of the model*

There is a direct interpretation of the fit of Equation (4). It shows that the hammer rebound index is not only an indirect measurement valid for estimating the compressive strength [16], but that it can also be used to evaluate the other mechanical properties of SCC with RCA in average terms. To do so, on the one hand, it considers the arithmetic mean of the mechanical properties related to compressive behavior, the modulus of elasticity and the compressive strength and, on the other hand, the arithmetic mean of the mechanical properties related to bending-tensile behavior. Moreover, if the weights (adjustment coefficients) are considered, it can be noted that the compressive behavior represents 72.8 % of the hammer rebound index while the bending-tensile behavior accounts for 27.2 %. Although compressive behavior continues to be the predominant value, as it always has been in conventional formulas [10], the model shows that around a quarter of the value of this indirect measure in SCC containing RCA is due to the influence of bending-tensile behavior.

In line with the above, it can be stated that the hammer rebound index is not only an indicator of compressive strength, but also of the overall mechanical performance of SCC with RCA. Its use can provide an overview of the mechanical performance of SCC with RCA and not only of its compressive strength. Furthermore, the utility of Equation (4) is even broader, as four different approaches can be considered for its use:

- First, if the mechanical properties of the SCC mix are known, then the hammer rebound index of SCC with RCA can be accurately estimated, as shown in Fig. 9 (maximum deviations of ± 10 %).
- Secondly, if three mechanical properties are known for an SCC mix with RCA, apart from its hammer rebound index, then the properties can be standardized (Equation (2) and Table 5) and the unknown mechanical property can be determined with Equation (4).
- Thirdly, if the hammer rebound index is known and Equation (4) is used in reverse, then the mean value of the behavior under compression or bending-tensile stress forces can also be determined when the mean value of the other mechanical behavior is known. In other words, if the value of the hammer rebound index and the mechanical properties related to compressive behavior are experimentally determined and subsequently standardized (Equation (2) and Table 5), then the mean value of the mechanical properties linked to the bending-tensile behavior can be estimated. Or *vice versa*, if the hammer rebound index and the bending-tensile mechanical properties are experimentally known and then standardized, then the mean value of the properties related to the compressive behavior can be calculated.
- Finally, Equation (4) can be used in reverse to estimate the mean bending-tensile behavior in the same way as described in the previous bullet point. In this way, the mechanical properties related to the compressive behavior of SCC with RCA are estimated with models available in the literature [27], although it can also be assumed that, as can be seen in Table 3, the average difference between the compressive strength and the modulus of elasticity in this type of concrete, considering both MPa and GPa, is 7 units [53].

Rather than giving a precise estimation, the calculation of the mean values of the mechanical properties related to both compressive and bending-tensile stresses, as described in the last two bullet points, yields a quick and easy picture of the overall mechanical behavior of SCC with RCA. Any interpretation of the values, which are standardized, should bear in mind the points mentioned in section 4.2.1. Furthermore, considering a mean value for the mechanical properties related to the bending-tensile behavior is a valid approximation. For example, flexural strength is estimated from the splitting tensile strength in current standards [49,53], the values of both properties often coincide. Table 7 shows an example of how this calculation should be performed, considering mix L0.

In view of all the above points, it can be stated that all four types of mechanical behavior of the SCC with RCA can be predicted through the use of the hammer rebound index as single indirect measure. This

Table 7
Equation (4) applied to calculate the mean value of the bending-tensile mechanical properties for mix L0.

Starting properties	Compressive strength (MPa) [1]	45.6
	Modulus of elasticity (GPa) [1]	36.4
	Hammer rebound index	41
Standardized properties (Equation (2) and Table 5)	Compressive strength CS_S	0.7177
	Modulus of elasticity ME_S	0.7423
	Hammer rebound index HRI_S	0.8075
Standardized compressive behavior $\left(\frac{CS_s + ME_s}{2}\right)$		0.7300
Standardized mean value of bending-tensile mechanical properties $\left(\frac{STS_s + FS_s}{2}\right) = \frac{1}{0.275} \times \left[HRI_s - 0.737 \times \left(\frac{CS_s + ME_s}{2}\right)\right]$		0.9800
Interpretation of the mean value of bending-tensile mechanical properties (section 4.2.1)		1. Positive sign: higher than the expected mean value 2. Higher than 0.5: above the upper limit of the expected confidence interval Expected mean values and confidence intervals shown in Table 5.

[1] Properties determined experimentally or through the hammer rebound index using models available in the literature [27].

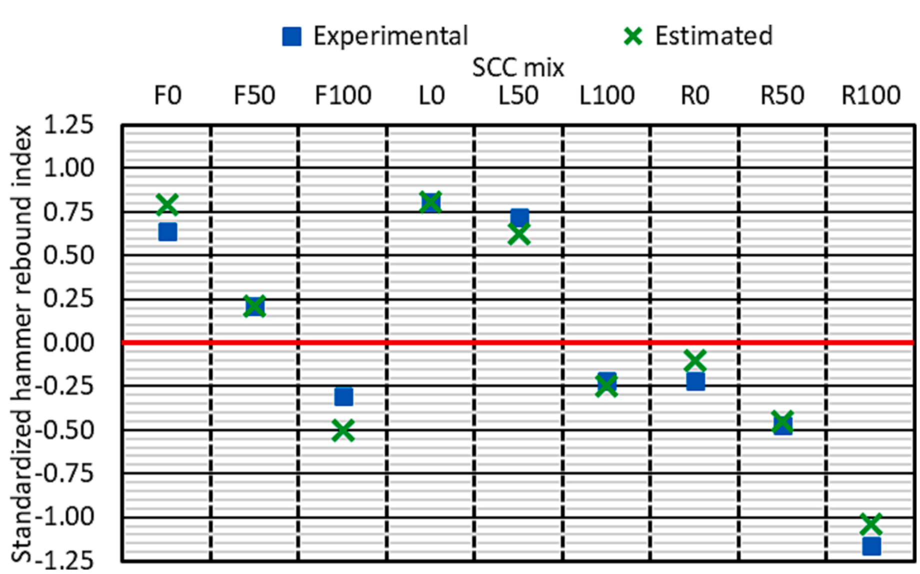

Fig. 9. Comparison of experimental and estimated standardized hammer rebound index.

prediction can be performed with the multiple-regression model (Equation (4)) for an SCC with at least 100 % coarse RCA with medium mechanical behavior, *i.e.*, with mechanical-property confidence intervals of 34.5 ± 7.7 MPa for compressive strength, 27.0 ± 6.4 GPa for modulus of elasticity, 3.2 ± 0.5 MPa for splitting tensile strength, and 4.2 ± 0.7 MPa for flexural strength.

5. Conclusions

In this article, the behavior of Self-Compacting Concrete (SCC) manufactured with different contents and fractions (coarse, fine and powder) of Recycled Concrete Aggregate (RCA) has been evaluated. In the first instance, its mechanical behavior has been assessed, and it has been found that the simultaneous use of 100 % coarse RCA, natural sand, and limestone aggregate powders can achieve adequate mechanical properties for structural use. However, the strength and elastic stiffness decreased when increasing the amount of fine RCA and, especially, RCA powder. Subsequently, the relationship between the mechanical behavior of this type of concrete and its hammer rebound index has been statistically analyzed. This analysis moves beyond the conventional usage of the hammer rebound index solely and exclusively to estimate compressive strength. Thus, all four mechanical properties (compressive strength, modulus of elasticity, splitting tensile strength and flexural strength) were included in the analysis. From the relationship between this indirect measurement and the mechanical properties, the following conclusions can be drawn for SCC containing RCA:

- There is an accurate linear-regression relationship (coefficient R^2 higher than 80 %) between any mechanical property and the hammer rebound index used as the dependent variable. Hence, the hammer rebound index can be expressed as a linear combination of the values of the four mechanical properties.
- The multiple-regression fit of the hammer rebound index as a linear combination of the four mechanical properties, using standardized values for all the magnitudes, showed that the value of this indirect measure is a weighting between the mean value of the compressive mechanical behavior (arithmetic mean of the modulus of elasticity and compressive strength) and the mean value of the bending-tensile mechanical behavior (arithmetic mean of the splitting tensile strength and flexural strength). The weights in this fitting indicate that the compressive behavior represents 72.8 % of the value of this indirect measurement and the bending-tensile behavior, 27.2 % (Equation (4)). Considering all mechanical properties individually in the statistical adjustment led to the appearance of coefficients with a negative sign that hindered easy interpretation of the model.
- The hammer rebound index yields accurate estimates of the overall mechanical performance of SCC with RCA. First, the mechanical behavior under compression can either be experimentally determined or can be estimated with existing models [27]. Once it and the hammer rebound index are known, the standardized mean value of the bending-tensile behavior can be determined using Equation (4). In this way, the use of a single indirect measure provides an overview of the mechanical behavior of the SCC with RCA in a non-invasive manner without damaging the concrete element that is tested.

As set out above, the hammer rebound index can be interpreted as an indicator of the overall mechanical behavior of SCC with RCA, at all times considering the weighting that is fixed between the compressive and bending-tensile behaviors. Its utility for building health and rehabilitation monitoring work is therefore clear, enabling a complete assessment of the mechanical performance of the SCC with RCA without any damage to the structure. This broad scope of application of the hammer rebound index to SCC containing RCA will hopefully further the use of RCA in real structures, although complementary studies are advisable on the statistical method, in order to verify the reliability of the model with a wider range of concrete mixes.

CRediT authorship contribution statement

Víctor Revilla-Cuesta: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review & editing. **Vanesa Ortega-López:** Conceptualization, Supervision, Writing – review & editing, Project administration, Funding acquisition. **Flora Faleschini:** Methodology, Writing – review & editing, Supervision, Project administration. **Ana B. Espinosa:** Methodology, Formal analysis, Writing – review & editing. **Roberto Serrano-López:** Formal analysis, Data curation, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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