Compressive-strength evaluation of recycled aggregate self-compacting concrete through hammer rebound index

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Abstract. Hammer rebound index is an indirect measure that has traditionally been used to estimate the compressive strength of concrete through the use of statistical models. It is especially useful in the quality control performed during the construction of a concrete structure, as well as in rehabilitation works. The high content of fine aggregate and aggregate powder of Self-Compacting Concrete (SCC) reduces its surface hardness and causes that the models traditionally used to estimate the compressive strength through this indirect measure in conventional concrete are not valid. On the other hand, Recycled Concrete Aggregate (RCA) has a lower surface hardness than Natural Aggregate (NA) due to the presence of adhered mortar, which causes that its addition prevents of using the currently existing models. Therefore, this paper aims to prove the validity of this indirect measure for the in-situ estimation of compressive strength of recycled aggregate SCC. Furthermore, it is also analyzed how the relationship between this indirect measure and the compressive strength of SCC is affected by the modification of the fine RCA content or the nature of the aggregate powder, two aspects that remarkably condition the design and behavior of SCC. The final objective is to provide a useful tool/model that promotes the use of SCC with RCA in real structures.

Keywords: Hammer rebound index, Quality control, Recycled concrete aggregate, Self-compacting concrete, Statistical modelling.

1 Introduction

Indirect control of concrete's compressive strength is a very useful feature during both the construction stage and the service life of any structure [1]. During the construction stage, it is necessary to verify that the concrete reaches the required compressive strength. Since it is not always possible to perform this verification directly by testing specimens, estimating it indirectly is a cheap, simple, and quick alternative [2]. On the other hand, for many rehabilitation works, it is essential to determine the compressive strength of the concrete with which the structure has been built. In this case, core drilling is a suitable option [3], although its indirect estimation can be more time and cost efficient [4].

Among the different indirect measures that can be used for this estimation, the present study focuses on the hammer rebound index determined using a sclerometer [5], apparatus shown in Fig. 1. This indirect measure relates the surface hardness of concrete to its compressive strength. For this purpose, a calibrated mass is pushed with a standardized force against the surface of the concrete by placing the sclerometer in a horizontal position. This mass rebounds with the concrete and separates from its surface a specific distance. This distance is known as hammer rebound index and is measured dimensionless by the sclerometer [6]. The relationship between this rebound index and the compressive strength of concrete is established by statistical models obtained from numerous laboratory tests [7]. There are models that relate these two variables for conventional concrete, i.e., vibrated concrete made with conventional materials (natural aggregate, NA, and ordinary Portland cement) [8].

Fig. 1. N-type sclerometer.

Self-Compacting Concrete (SCC) does not require any type of vibration to adapt to the formwork shape during its placement [9]. This property, called self-compactability, is achieved thanks to two different aspects. Firstly, adding a large amount of fine aggregate particles, smaller than 0.25-0.50 mm, thanks to the use of an aggregate powder, the most common of which is limestone filler [10]. Secondly, through an adequate ratio between coarse and fine aggregate. In this type of concrete, the coarse aggregate content is generally lower than the fine aggregate content, unlike in conventional concrete [11]. These two aspects finally result in SCC having a lower surface hardness than conventional concrete [12], although not necessarily in a lower strength, since the addition of aggregate powder can compensate the negative effect of the reduction of the content of coarse aggregate [13]. Therefore, the models that relate compressive strength and hammer rebound index for conventional concrete seem not to be valid for SCC.

Recycled Concrete Aggregate (RCA) is a waste that can be used to replace NA in the production of concrete [14]. This aggregate is obtained from the crushing of concrete elements and is mainly characterized by the presence of mortar adhered to the NA in the coarse fraction [10], as well as by the presence of mortar particles in the fine fraction [15]. These aspects cause the surface hardness of RCA compared to that of NA to be lower [16], which in turn also affects the surface hardness of the concrete produced with it [17]. Therefore, the existing models are also invalid for concrete incorporating this type of aggregate.

The purpose of this paper is to present a preliminary analysis of the validity of the hammer rebound index for the *in situ* estimation of the compressive strength of SCC produced with RCA. For this purpose, six SCC mixes were prepared with ordinary Portland cement, 100 % coarse RCA, three different contents of fine RCA (0 %, 50 %, and 100 %) and two different aggregate powders, limestone filler and limestone fines 0/0.5 mm. Models that would be valid for predicting the compressive strength of the developed SCC were proposed.

2 Materials and methods

2.1 Materials

Ordinary Portland cement CEM I 52.5 R (EN 197 [18]) available in the region where the study was carried out was used. It had a specific weight of 3.12 Mg/m^3 and a clinker content of 95-98 %. Drinking water from the city of Burgos, Spain, was added to the SCC. In addition, two admixtures were used to achieve self-compactability: a plasticizer and a viscosity regulator.

Two aggregate powders were employed to provide the content of fine aggregate particles (less than 0.25-0.50 mm) necessary to achieve self-compactability [9]. Limestone filler <0.063 mm (density of 2.77 Mg/m^3 and purity of 98 %) was added to half of the mixes, while limestone fines 0/0.5 mm (density of 2.60 Mg/m^3, 24-h water absorption of 2.57 %, and fineness modulus of 1.22 units) were added to the other half.

Since the mixes incorporated 100 % coarse Recycled Concrete Aggregate (RCA), only fine Natural Aggregate (NA) was added. This aggregate was siliceous sand 0/4 mm with a density of 2.58 Mg/m^3, a 24-h water absorption of 0.25 %, and a fineness modulus of 3.49 units.

The RCA used came from precast concrete elements with a compressive strength higher than 45 MPa. Its crushing allowed obtaining RCA with a continuous grain size of 0/31.5 mm, which was subsequently sieved to obtain the fine fraction 0/4 mm (density of 2.37 Mg/m^3, 24-h water absorption of 7.36 %, and fineness modulus of 3.11 units) and the coarse fraction 4/12.5 mm (density of 2.42 Mg/m^3, 24-h water absorption of 6.25 %, and fineness modulus of 6.30 units).

2.2 Mix design

Six mixtures were prepared with 100 % coarse RCA, three different fine RCA contents (0 %, 50 %, and 100 %), and two different aggregate powders (limestone filler, and limestone fines 0/0.5 mm). The mixtures were referred to as *A/P*, in which *A* referred to the aggregate powder added to SCC, F (limestone filler <0.063 mm) or L (limestone fines 0/0.5 mm), while *P* referred to the percentage of fine RCA added to the mix, 0 %, 50 %, or 100 %.

Firstly, the composition of the F/0 mix was defined. The proportion of its components was obtained according to Eurocode 2 (EC2) [19], which subsequently were adjusted empirically to achieve a SF3 slump-flow class (slump flow between 750 mm and 850 mm) according to EFNARC recommendations [20]. Later on, the fine NA was replaced by fine RCA in the mentioned quantities by volume correction. Finally, limestone filler was replaced by limestone fines 0/0.5 mm. In each mix, the content of water and aggregate powder was adjusted so that the flowability remained constant (same slump-flow class). The composition of the different mixtures is shown in Table 1.

Table 1. Mix design (kg/m^3).

Component	F/0	F/50	F/100	L/0	L/50	L/100
CEM I 52.5 R	300					
Plasticizer	4.50					
Viscosity regulator	2.30					
Coarse RCA 4/12.5 mm	530					
Fine RCA 0/4 mm	0	505	1010	0	435	865
Siliceous sand 0/4 mm	1100	550	0	940	475	0
Limestone filler <0.063 mm		165			0	
Limestone fines 0/0.5 mm		0			335	
Water	185	210	235	185	210	235

2.3 Experimental plan

After the preparation of each mix, the slump-flow test (EN 12350-8 [18]) was carried out to check that they all had a slump flow between 750 and 850 mm (SF3 slump-flow class) and six 10x10x10-cm cubic specimens were produced for testing in the hardened state: measurement of compressive strength as per EN 12390-3 [18] and determination of hammer rebound index according to EN 12504-2 [18].

Both hardened-state tests were performed at 7 and 28 days (3 specimens at each age). Until the moment of testing, the specimens were kept in a moist room (humidity of around 95 % and temperature of 20 ºC). The values of compressive strength and hammer rebound index were related to each other, and the effect of the mix composition was analyzed.

3 Results and discussion

3.1 Slump flow

All SCC mixes reached an SF3 slump-flow class (Fig. 2): slump flow between 750 mm and 850 mm [20]. According to these results, the use of RCA did not hinder the achievement of high self-compactability if the composition of the mixture was adjusted according to the particular characteristics of this waste.

All changes in the mix composition modified the slump flow obtained. On the one hand, despite the higher water absorption levels of RCA compared to NA, the adjustment of the water content showed that it is possible to increase the flowability of SCC by adding RCA [14]. This phenomenon could also be favored by the higher proportion of fine particles of this waste, as shown by the fineness moduli (3.49 units for siliceous sand 0/4 mm, and 3.11 units for fine RCA 0/4 mm). On the other, the use of limestone fines 0/0.5 mm produced a cement paste with a higher content of particles with a size between 0.25 and 0.50 mm [11]. Although it allowed obtaining adequate slump flow, its use resulted in lower values of slump flow than when using limestone filler.

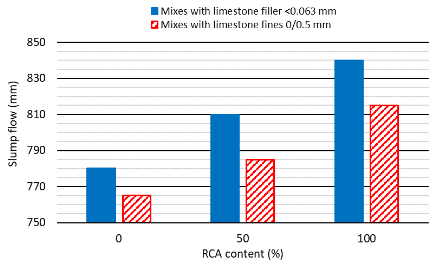

Fig. 2. Slump flow of the mixes.

3.2 Compressive strength

Fig. 3 shows the results of the compressive strength of the mixes at 7 and 28 days. The compressive strengths obtained were adequate for the structural use of the mixes [19]. The increase of the fine RCA content led to an approximately linear decrease of the compressive strength. The increased porosity associated with the use of fine RCA may explain this phenomenon [15]. On the other hand, the use of limestone fines 0/0.5 mm resulted in a higher compressive strength, especially in the long term. The higher water absorption of this aggregate powder compared to the limestone filler may have led to a more noticeable internal curing [11], which resulted in a greater increase of strength between 7 and 28 days.

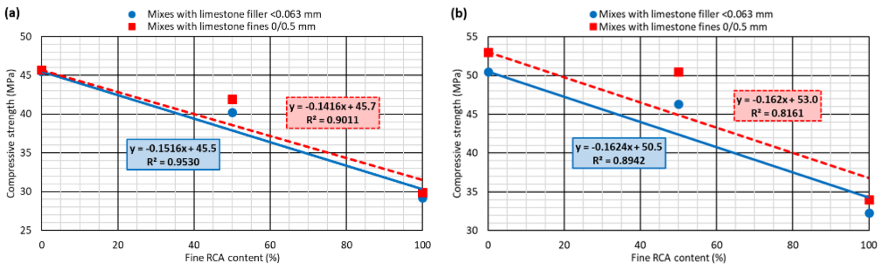

Fig. 3. Compressive strength at: (a) 7 days; (b) 28 days.

3.3 Hammer rebound index

Hammer rebound index was determined at 7 and 28 days on the same specimens that were subsequently tested to compressive strength. The results obtained are shown in Fig. 4, which exhibited the same trends than the compressive strength. Firstly, hammer rebound index increased with the age of the SCC due to the surface-hardness development [17]. Secondly, the use of fine RCA, with a lower surface hardness than fine NA due to the presence of mortar particles [13], caused a decrease of the hammer rebound index approximately linear with the amount of fine RCA. Finally, the use of limestone fines 0/0.5 mm increased the surface hardness of the SCC and, therefore, the hammer rebound index. This trend is clearly observed at 28 days, as at 7 days the effect of aggregate powder was not clear due to the variability of this indirect measure. The similarity of the trends shown by the compressive strength and hammer rebound index reflects the suitability of this indirect measure for estimating the compressive strength of recycled aggregate SCC.

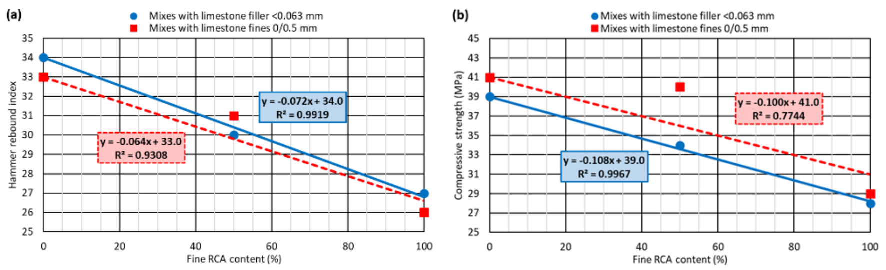

Fig. 4. Hammer rebound index at: (a) 7 days; (b) 28 days.

3.4 Models for compressive strength prediction of recycled aggregate SCC

Models for estimating compressive strength from the hammer rebound index may be obtained by least squares fitting. The 7-day compressive strength of the developed mixes can be estimated from the hammer rebound index through equation 1 (R^2 coefficient of 96.7 %), while the 28-day strength can be estimated from equation 2 (R^2 coefficient of 98.5 %). Finally, equation 3 allows estimating the compressive strength of concrete regardless of its age (R^2 coefficient of 97.0 %). In order to give these expressions a general character, no differentiation was made between the modifications made in the composition of the SCC (fine RCA content and nature of the aggregate powder). The high R^2 coefficients obtained show that the hammer rebound index is a valid measure for the estimation of compressive strength of SCC, although the development of specific models for this purpose is necessary. In addition, two relevant aspects can be noted. Firstly, the formulation of the model was robust. In each case, the model with the best fit was chosen, which always resulted in an equation with the same formulation, but with different constants. This reflects the fact that the models for this estimation can be easily standardized. Secondly, since the surface hardness of SCC is highly dependent on its strength development due to its low proportion of coarse aggregate [17], it is possible to develop models that allow estimating the compressive strength regardless of age. This situation is opposite to that used in conventional vibrated concrete [8].

$$CS_7 = \sqrt{6562 - \frac{149894}{HRI_7}} \quad (1)$$

$$CS_{28} = \sqrt{6462 - \frac{151866}{HRI_{28}}} \quad (2)$$

$$CS = \sqrt{6253 - \frac{142511}{HRI}} \quad (3)$$

4 Conclusions

In this paper, the validity of the hammer rebound index to predict the compressive strength of Self-Compacting Concrete (SCC) has been evaluated. In addition, the effect of some changes in the mix composition, concerning fine Recycled Concrete Aggregate (RCA) and aggregate powders, has been studied. These conclusions can be drawn:

(1) Using the hammer rebound index for compressive-strength estimation must be subjected to statistical adjustment. The variability of the measurements of this parameter, increased by changing the SCC composition, makes this type of study essential.

(2) Existing models for conventional concrete underestimate the compressive strength of SCC. This is due to the lower surface hardness of SCC because of its reduced coarse aggregate content, as well as its high amount of fine aggregate particles. The use of RCA and limestone filler also promotes this phenomenon.

(3) It is possible to develop models that allow accurate estimation of the compressive strength of SCC from the hammer rebound index regardless of the age of the SCC. For it, modification of the mix composition allows obtaining more general models.

Despite all this, further research is needed, as the number of tests performed was not enough to evaluate the uncertainty of the indirect measurements studied.

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References

1. Aseem, A., Latif Baloch, W., Khushnood, R.A., Mushtaq, A.: Structural health assessment of fire damaged building using non-destructive testing and micro-graphical forensic analysis: A case study. Case Studies in Construction Materials. 11, e00258 (2019).

2. Dolinar, U., Trtnik, G., Turk, G., Hozjan, T.: The feasibility of estimation of mechanical properties of limestone concrete after fire using nondestructive methods. Construction and Building Materials 228, 116786 (2019).
3. Qasrawi, H.: Effect of the position of core on the strength of concrete of columns in existing structures. Journal of Building Engineering 25, 100812 (2019).
4. Hover, K.C.: Case studies of non-destructive test results and core strengths at age of 3-days. Construction and Building Materials 227, 116672 (2019).
5. Greene, G.W.: Test hammer provides new method of evaluating hardened concrete. ACI Journal of Proceedings 51(11), 249-256 (1954).
6. ACI-228.1R-19: In-place methods to estimate concrete strength. ACI Committee 228, American Concrete Institute (2019).
7. Jones, R.: The non-destructive testing of concrete. Magazine of Concrete Reasearch 1(2), 67-78 (1949).
8. Proceq: Sclerometer types N and NR: instructions for use (2020).
9. Okamura, H., Ouchi, M.: Self-compacting concrete. Journal of Advanced Concrete Technology. 1, 5-15 (2003).
10. Fiol, F., Thomas, C., Muñoz, C., Ortega-López, V., Manso, J.M.: The influence of recycled aggregates from precast elements on the mechanical properties of structural self-compacting concrete. Construction and Building Materials 182, 309-323 (2018).
11. Santamaría, A., González, J.J., Losáñez, M.M., Skaf, M., Ortega-López, V.: The design of self-compacting structural mortar containing steelmaking slags as aggregate. Cement and Concrete Composites 111, 103627 (2020).
12. Revilla-Cuesta, V., Skaf, M., Faleschini, F., Manso, J.M., Ortega-López, V.: Self-compacting concrete manufactured with recycled concrete aggregate: An overview. Journal of Cleaner Production 262, 121362 (2020).
13. Santos, S., da Silva, P.R., de Brito, J.: Self-compacting concrete with recycled aggregates – A literature review. Journal of Building Engineering 22, 349-371 (2019).
14. Revilla-Cuesta, V., Ortega-López, V., Skaf, M., Manso, J.M.: Effect of fine recycled concrete aggregate on the mechanical behavior of self-compacting concrete. Construction and Building Materials 263, 120671 (2020).
15. Faleschini, F., Jiménez, C., Barra, M., Aponte, D., Vázquez, E., Pellegrino, C.: Rheology of fresh concretes with recycled aggregates. Construction and Building Materials 73, 407-416 (2014).
16. San-José, J.T., Manso, J.M.: Fiber-reinforced polymer bars embedded in a resin concrete: Study of both materials and their bond behavior. Polymer Composites 27(3), 315-322 (2006).
17. Singh, N., Singh, S.P.: Evaluating the performance of self compacting concretes made with recycled coarse and fine aggregates using non destructive testing techniques. Construction and Building Materials 181, 73-84 (2018).
18. EN-Euronorm, Rue de stassart, 36. Belgium-1050 Brussels, European Committee for Standardization (2020).
19. EC2, Eurocode 2: Design of concrete structures. Part 1-1: General rules and rules for buildings. CEN (European Committee for Standardization) (2010).
20. EFNARC: Specification Guidelines for Self-compacting Concrete, European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (2002).